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DIPLOMA THESIS

A GIS-based approach for productive uses of electricity

The case study of water and electricity demand for agriculture in Tanzania

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ΠΑΝΕΠΙΣΤΗΜΙΟ ΘΕΣΣΑΛΙΑΣ

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Εφαρμογή Γεωγραφικών Πληροφοριακών Συστημάτων (GIS) για παραγωγικές χρήσεις ενέργειας

Απαιτήσεις σε νερό και ηλεκτρική ενέργεια στον τομέα της γεωργίας στην Τανζανία

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Abstract

As an integral component of modern society, access to electricity plays a pivotal role in economic prosperity and growth as exemplified by the SE4ALL initiative and the corresponding SDGs. Its influence reaches to the foundations of human development, with the potential to enrich and trigger income generation and overall welfare enhancement from industrial, to commercial and agricultural development. Such activities are defined as “productive uses of energy”, and their incorporation constitutes a significant addition in the electrification planning process. Agricultural sector is usually the backbone of the economies in emerging countries, such as the United Republic of Tanzania, accounting for almost 32% of the GDP. With regards to agriculture, electricity is principally used to provide motive power for agriculture-based industries in order to power farm machinery for pumping irrigation. The alarming population and food demand projections, coupled with the general paucity of energy demand related georeferenced data, highlight the need for a holistic water-energy approach for national and sub-national planning. In this Thesis, an integrated GIS assessment combining a gridded water and energy balance model has been developed to assess and evaluate the water and energy demand for pumping irrigation from groundwater resources. It highlights the interactions between water use and energy consumption and focuses on the electricity demand impact associated with changes in irrigation technologies efficiencies and irrigated areas. For the dominant crop of maize in the country, irrigation accounts for 1.8 km^3/year of water abstraction, estimated to reach 13.3 km^3 by 2030. Electricity demand is estimated at 170 GWh as of 2013 and 1.3 TWh by 2030. This study is intended to create a generic framework aiming to facilitate sub-national energy planning in developing countries and it is expected that the findings will be complementary to already existing energy planning models but also the base for future research towards energy poverty elimination.

Περίληψη

Η πρόσβαση στον ηλεκτρισμό αποτελεί αναπόσπαστο συστατικό στοιχείο της σύγχρονης κοινωνίας, και διαδραματίζει κεντρικό ρόλο στην οικονομική ευημερία και ανάπτυξη, όπως εξηγείται από την πρωτοβουλία SE4ALL και τους αντίστοιχους στόχους SDGs. Η επιρροή του φτάνει στα θεμέλια της ανθρώπινης ανάπτυξης, με τη δυνατότητα να εμπλουτίσει και να προκαλέσει τη δημιουργία εισοδήματος και τη συνολική βελτίωση της ευημερίας από τη βιομηχανική, την εμπορική και τη γεωργική ανάπτυξη. Τέτοιες δραστηριότητες ορίζονται ως «παραγωγικές χρήσεις της ενέργειας», και η ενσωμάτωσή τους αποτελεί σημαντική προσθήκη στη διαδικασία σχεδιασμού μοντέλων ηλεκτρικής ενέργειας. Ο γεωργικός τομέας αποτελεί συνήθως τη ραχοκοκαλιά των αναπτυσσόμενων χωρών, όπως η Τανζανία, στην οποία αντιπροσωπεύει σχεδόν το 32% του ΑΕΠ. Όσον αφορά τη γεωργία, ο ηλεκτρισμός χρησιμοποιείται κυρίως για την παροχή κινητήριας δύναμης στις γεωργικές βιομηχανίες, για την άρδευση με χρήση αντλιών. Οι ανησυχητικές προβλέψεις σχετικά με τη μεγάλη αύξηση του πληθυσμού και της ζήτησης τροφίμων, σε συνδυασμό με τη γενική έλλειψη στοιχείων που σχετίζονται με τη ζήτηση ενέργειας, αντικατοπτρίζουν την ανάγκη μιας ολιστικής προσέγγισης για τη σχέση νερού και ενέργειας σε εθνικό και τοπικό επίπεδο. Στην παρούσα εργασία αναπτύχθηκε ένα ολοκληρωμένο μοντέλο GIS που συνδυάζει μοντέλα ισοζυγίων νερού και ενέργειας για την αξιολόγηση της ζήτησης ύδατος και ενέργειας για άντληση αρδευτικών πόρων από υπόγειους υδάτινους πόρους. Υπογραμμίζει τις αλληλεπιδράσεις μεταξύ χρήσης ύδατος και κατανάλωσης ενέργειας και επικεντρώνεται στον αντίκτυπο της ζήτησης ηλεκτρικής ενέργειας που συνδέεται με τις αλλαγές στις τεχνολογίες άρδευσης και τις αρδευόμενες περιοχές. Συγκεκριμένα για το καλαμπόκι, που αποτελεί την επικρατούσα καλλιέργεια στη χώρα της Τανζανίας, η άρδευση αντιστοιχεί σε 1,8 κυβικά χιλιόμετρα/έτος και εκτιμάται ότι θα φθάσει τα 13,3 μέχρι το 2030. Η ζήτηση ηλεκτρικής ενέργειας υπολογίζεται σε 170 GWh το 2013 και 1.3 TWh μέχρι το 2030. Η μελέτη αυτή αποσκοπεί να δημιουργηθεί ένα γενικό πλαίσιο που θα διευκολύνει τον τοπικό ενεργειακό προγραμματισμό στις αναπτυσσόμενες χώρες, και αναμένεται ότι τα ευρήματα θα συμπληρώσουν τα ήδη υπάρχοντα πρότυπα ενεργειακού προγραμματισμού αλλά θα αποτελέσουν και βάση για μελλοντικές έρευνες για την εξάλειψη της ενεργειακής φτώχειας.

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First and foremost, I would like to sincerely thank Professor Lefteri H. Tsoukalas, as well as Associate Professor Dimitrios Bargiotas, for undertaking the supervision of my Thesis on the side of my home University, and for "giving me the green light" to work on a hands-on, pragmatic project at KTH, which turned out to be perfectly aligned with my future expectations and goals. Their support, guidance and constructive comments were crucial for the completion of my work. I would also like to express my sincere acknowledgements to Emeritus Professor Elias N. Houstis for his persistent, educating and inspirational support and encouragement throughout the whole process.

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Last but not least, I would like to thank my family; my wonderful parents Maria and Apostolos, and my older sister Kelly, for supporting me spiritually, financially and showing me the way since day one. And above all, for their unconditional love.

I would like to dedicate this piece of work to the memory of my late grandmother Nafsika for her unwavering support and belief in me.

Konstantinos Filippos Pegios

Volos, July 2018

Acronyms

AfDB	African Development Bank Group
ASDP	Agricultural Sector Development Program
BRN	Big Results Now
CAADP	Comprehensive Africa Agriculture Development Program
CPF	Country Programming Framework
DIDF	District Irrigation Development Fund
dESA	Division of Energy Systems Analysis
KTH	Kungliga Tekniska högskolan
EAC	East African Community
FAO	Food and Agriculture Organization of the United Nations
FCFA	Future Climate for Africa
FYDP	Five Year Development Program
GADM	Database of Global Administrative Areas
GCM	Global Climate Model
GDP	Gross Domestic Product
GEF	Global Environmental Facility
GENI	Global Energy Network Institute
GIS	Geographic Information System
GTF	Global Tracking Framework
GW	gigawatt
GWh	gigawatt hour
ha	hectare
HDI	Human Development Index
ICT	Information and Communications Technology
IEA	International Energy Agency
kg	kilogram
kJ	kilojoule
km	kilometre
kPa	kilopascal
kWh	kilowatt hour

mm	millimetre
MW	megawatt
MWh	megawatt hour
MWI	Ministry of Water and Irrigation
NBS	National Bureau of Statistics
NEP	National Energy Policy
NIA	National Irrigation Act
NIDF	National Irrigation Development Fund
NIMP	National Irrigation Master Plan
OnSSET	Open Source Spatial Electrification Toolkit
PRODUSE	Productive Use of Energy
PSMP	Power System Master Plan
PV	photovoltaic
SAGCOT	Southern Agricultural Growth Corridor of Tanzania
SDG	Sustainable Development Goal
SE4ALL	Sustainable Energy for All
SPAM	Spatial Production Allocation Model
SSA	Sub-Saharan Africa
TANESCO	Tanzania Electric Supply Company Limited
TAFSIP	Tanzania Agriculture and Food Security Investment Plan
TDV	Tanzania Development Vision
TWh	terawatt hour
UN	United Nations
UNDAP	United Nations Development Assistance Plan
USDA	United States Department of Agriculture
US$	United Stated dollar
WB	World Bank
WFP	World Food Program
WGS	World Geodetic System
WHYMAP	Worldwide Hydrogeological Mapping and Assessment Programme
WRMA	Water Resources Management Act

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1. Introduction

1.1 Background

In a time when the world is working towards universal access to clean energy and sustainable development, the provision of reliable, secure, and affordable energy services has been defined as "the golden thread" connecting economic growth, social equity, and environmental sustainability [1]. As exemplified by the SE4All initiative [2], and the UN SDGs [3] on energy, "Access to modern energy" is considered key to poverty alleviation and growth strategies by policy makers and development practitioners alike [4]. According to WB & IEA's latest Global Tracking Framework 2017 [5], almost 1.1 billion people live without access to electricity, the vast majority of which live in rural areas, particularly rural Africa. In detail, over half of Africa's population (more than 620 million people) lack access to electricity and many more rely on poor electricity supplies [5] (Figure 1.1). Making reliable and affordable energy widely available for Africa, a region that accounts for 16% of the total world's population [1], is crucial to human well-being but has also become essential for modern civilization.

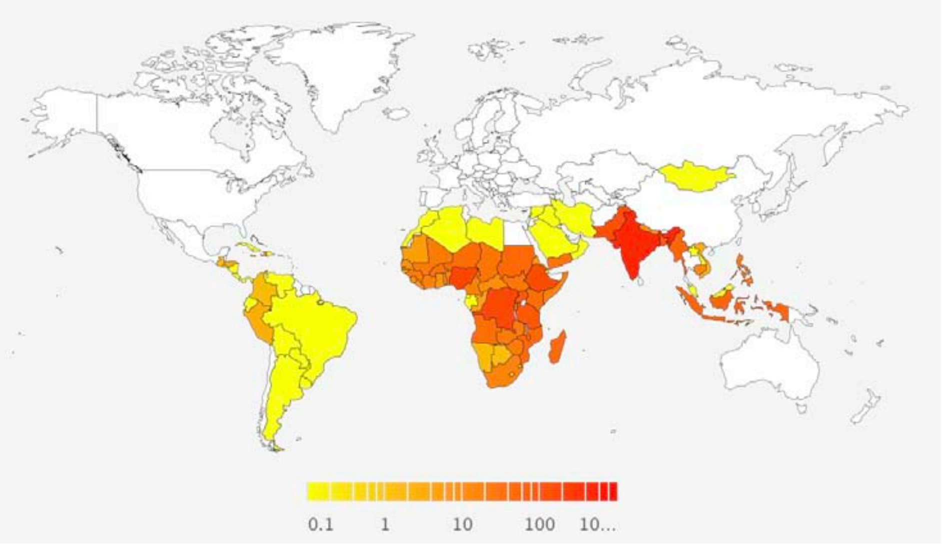


Figure 1.1: Population without access to electricity, 2016 (millions) (WB, 2016)

Thanks to its adaptable nature, electricity is currently considered as a preferred and convenient form of energy and has become an integral component of modern civilisation, playing a pivotal role in economic prosperity and growth. The main reasons for this lie on the fact that it can be easily converted into other forms of energy (such as heating, lighting, mechanical energy etc.) [6]. In additions to this, devices and systems powered by electricity usually operate under simple and convenient starting and control processes and are not associated with smoke or other poisonous gases reducing greenhouse emissions. Furthermore, electricity can be easily stored and transmitted from one place to another with the help of conductors and transmission lines [7].

While electricity itself is used for various consumption purposes such as household electrification, lighting, access to information, comfort and entertainment which are principally met in urban areas , it is not sufficient by itself to trigger development in a national level [8]. According to Cabraal et al. (2005), for rural development, energy was, and in some cases still is, classified and looked at as having two distinct uses: residential and productive. Residential uses of energy are expected to positively impact the rural quality of life or improve rural living standards, making significant inroads for household lighting, cooking and entertainment. Although electricity certainly provides improvements in the quality of life through these household applications, it is the productive uses of energy that can provide the desired development benefits to rural areas [9][10]. More specifically, the productive use of energy is expected to result in increased rural productivity, greater economic growth, and a rise in rural employment, which would not only raise incomes but also reduce the migration of the rural poor to urban areas [10]. The SDGs, however, emphasize not just poverty reduction in terms of income, but embrace a much broader definition of well-being by highlighting the importance of improved health, food security and responsible consumption and production, universal education and other welfare related activities, even gender equality [5].

Hence, since there is a high correlation between electricity access and human prosperity, and based on studies that point out that even the very first kilowatt-hours provided play a pivotal role, the usage of it should also be aligned in such a way that it will trigger development and bring about the desired socioeconomic impact.

1.2 Productive uses of energy

In the general discussion, there have been several attempts to come up with a clear definition of the term productive uses of energy. While in some cases productive use is mainly defined through income generating activities that are directly positively affected by the use of electricity, others draw a much broader definition by including the use of electric energy for education and health or other welfare related activities, even gender equality.

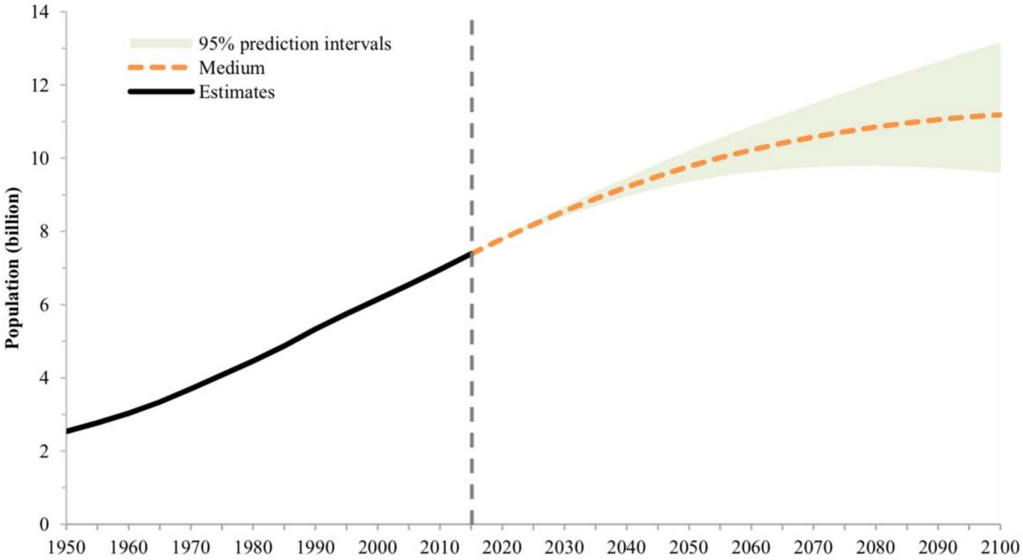
Ron White's paper presented at a GEF/UN FAO workshop on Productive Uses of Renewable Energy back in 2002, suggests a comparatively narrow definition of productive uses, taking into account only uses of energy that render outcomes that can be measured in monetary terms: “[activities that] involve the application of energy [...] to create goods and/or services either directly or indirectly for the production of income or value. The production of income or value is understood to be achieved by selling products or services at greater than their cost of production, resulting in an increase in the net income of the enterprise or the entrepreneur.” [11]. A similar definition is used in the Productive Use of Energy (PRODUSE) manual that defines productive uses of electricity as “agricultural, commercial and industrial activities involving electricity services as a direct input to the production of goods or provision of services.” [4]. By contrast, Jose Etcheverry (2003) outlines a different approach by classing as productive use projects in rural contexts those that “aim at enhancing income generation opportunities and productivity in rural areas [...] to improve quality of life and increase local resilience and self-reliance”, with education and health mentioned among the key sectors for productive use of energy in rural contexts [12]. In the same context, a World

Bank paper by Kamal Kapadia (2014) employs an even broader definition of productive uses of energy as activities "that involve the utilization of energy – both electric, and non-electric energy in the forms of heat, or mechanical energy - for activities that enhance income and welfare. [In rural contexts] these activities are typically in the sectors of agriculture, rural enterprise, health and education." [13] .

In this context, rural electrification is key for the socio-economic development of non-urban regions in developing and emerging areas of the world, such as Africa. With regards to agricultural production, electricity can be used principally to provide motive power for agriculture-based industries in order to power farm machinery for irrigation and post-harvest processing, such as water pumps, fodder choppers, threshers, grinders, and dryers. For the purposes of this research we will refer to the productive use and demand of electricity needed in terms of agricultural activities, with a focus in primary agriculture which includes inputs and on-farm mechanization for pumping irrigation, which constitutes the first step towards the modernization of agricultural production.

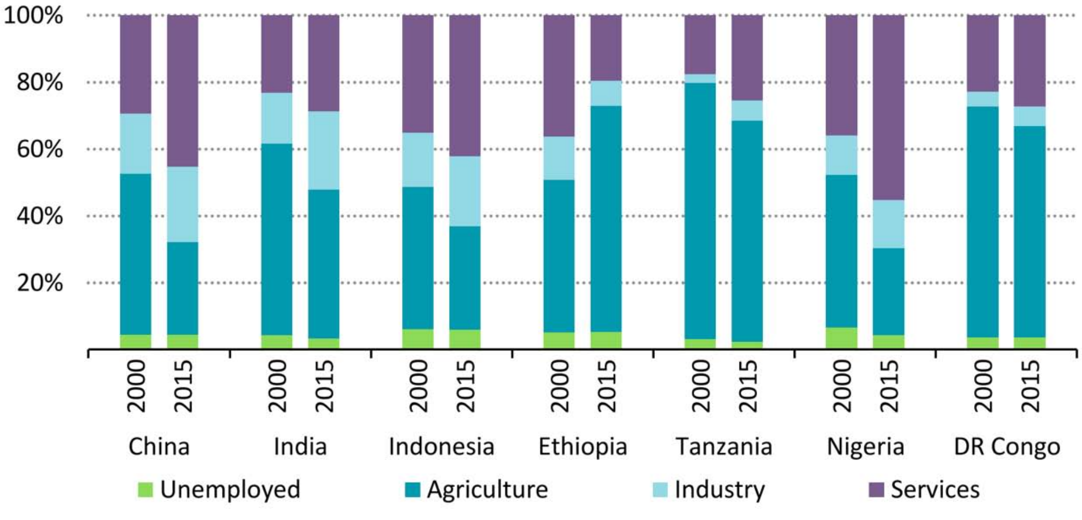
1.3 The Water-Energy-Food demand challenge

According to the UN (Graph 1.1), the current world population of 7.6 billion is expected to reach 9.8 billion in 2050, which means that the world will have to feed 2.5 billion more people than today [14]. FAO estimates that by 2050 current food production needs to rise by 70% to satisfy the expanding demand [15], to be met primarily through yield increases [16]. Given the planetary boundaries, especially limited energy and water resources, meeting this target is one of the century's biggest challenges.



Graph 1.1: Population of the world: estimates, 1950-2015, and medium-variant projection with 95 % prediction intervals, 2015-2100 (UN, 2017)

In most cases of emerging countries, food production and overall agricultural sector is considered as the backbone of the economies, accounting for a large share of their GDP and employing a large proportion of the labour force (Graph 1.2).

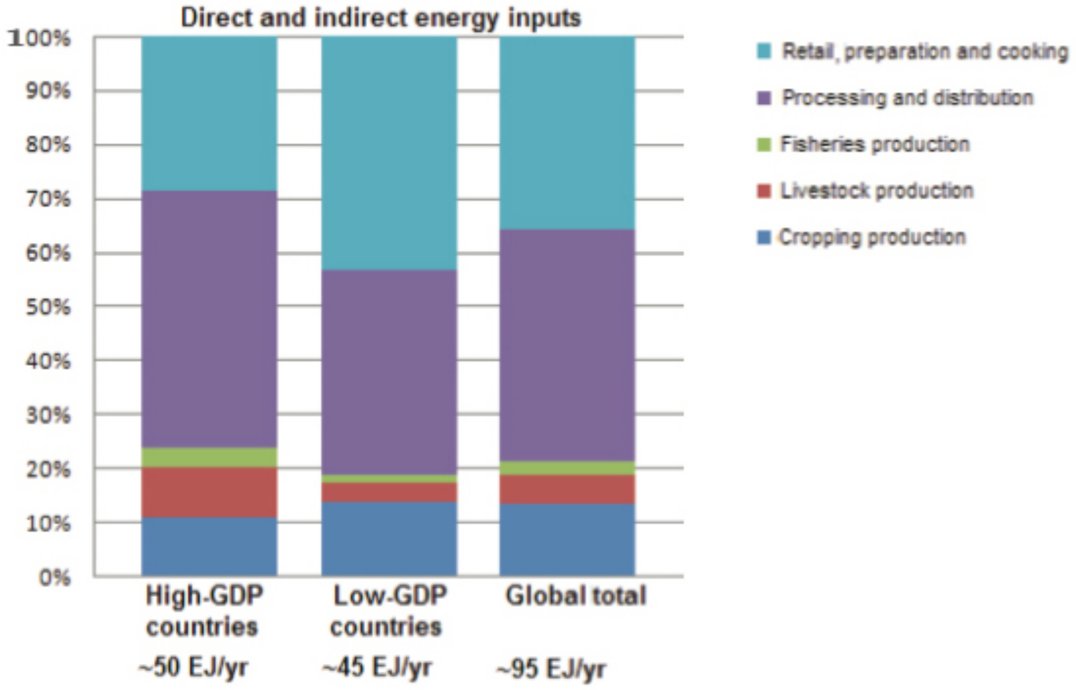


Graph 1.2: Share of employment by sector in selected countries, 2000 and 2015 (IEA, 2017)

At the same time, agriculture represents a major source of foreign exchange and constitutes the bulk of basic food providing subsistence and other income to the majority of their population. Increased productivity and the modernisation of agricultural production systems are the primary drivers of global poverty reduction and the contribution of energy is unarguably crucial in achieving this.

Energy and water inputs to modern and sustainable agricultural production and processing systems, is a key factor in moving beyond subsistence farming towards food security, added value in rural areas and expansion into new agricultural markets. Agricultural mechanization and intensification has been approached in a number of ways by different reports and studies [15], [17]–[20]. Perhaps the most appropriate and inclusive definition by Sims et al (2006) is that the term mechanization accounts for "the process of improving farm labour productivity through the use of agricultural machinery, implements and tools. It involves the provision and use of all forms of power sources and mechanical assistance to agriculture, from simple hand tools, to animal draught power, and to mechanical power technologies". It is, therefore, expected to result in improved productivity of labour and per unit area, as a result of improved timeliness of farm operations and potential expansion of the area under cultivation where land is available. It overall contributes, to a great extent, to the accomplishment of tasks that are difficult to perform without mechanical aids and to improvements in the quality of work and of products.

The aforementioned concerning numbers (Graph 1.1) highlight the rapidly growing demand in a world with limited resources, which cannot be replenished but rather are diminishing day by day. Specifically, the interdependency of water, energy and food is of concern and has become more and more evident, as the international debate progresses since the Bonn 2011 nexus conference [21]. Food production requires water and energy throughout the whole agricultural process. It is reported that 30% of global energy usage can be traced back to the food sector [15], [20]. This includes supply industry, agricultural production, processing, transport, merchandising and consumption. Agricultural primary production alone accounts for 20%, along with food processing (including transport), amounting to 40% (Graph 1.3). The agricultural and food sector thus contributes significantly to global energy consumption along the agricultural value chains.



Graph 1.3: Energy consumption in agriculture for low- and high-GDP countries (FAO, 2011)

Energy in the form of electricity, is an important –if not the most important- enabler for the agriculture sector to realize its growth potential, especially for power intensive value chains. Figure 1.2 shows that the need for electricity is distributed across the life of the crop—from mechanized irrigation to processing for final consumption. The power demand for irrigation primarily comes from (i) sourcing bulk water from a water body (e.g., a dam, river or groundwater aquifers) and (ii) distributing it over the cultivated area. Bulk water pumping is typically the major source of demand and depends on the vertical and horizontal distances of the scheme from the water source. Demand from distribution systems varies by the types of irrigation system, which range in scale from manual to surface flooding and localized ones to centre pivots. Post-harvest and primary processing (e.g., milling and drying) and secondary processing (e.g., packaging and bottling) represent a growth area. It is clear that milling is likely to increase significantly owing to the expected demand growth of dominant food crops such grains as maize, wheat, and rice [22]. In the same WB report by Banerjee et al. (2017), it is estimated that by 2030, electricity demand from agriculture in the Sub-Saharan Africa region is expected to double from today's level, to about 9 GW. The estimated incremental demand between 2015 and 2030 is 4.2 GW. Irrigation would provide about 75% of agriculture's demand, with the rest coming from agro-processing, constituting in this way the largest source of power demand in the sector. However, these are simplified estimates as the varying nature of product value chains and associated irrigation, processing, and storage processes make it impossible to develop comprehensive, region-wide or country estimates.

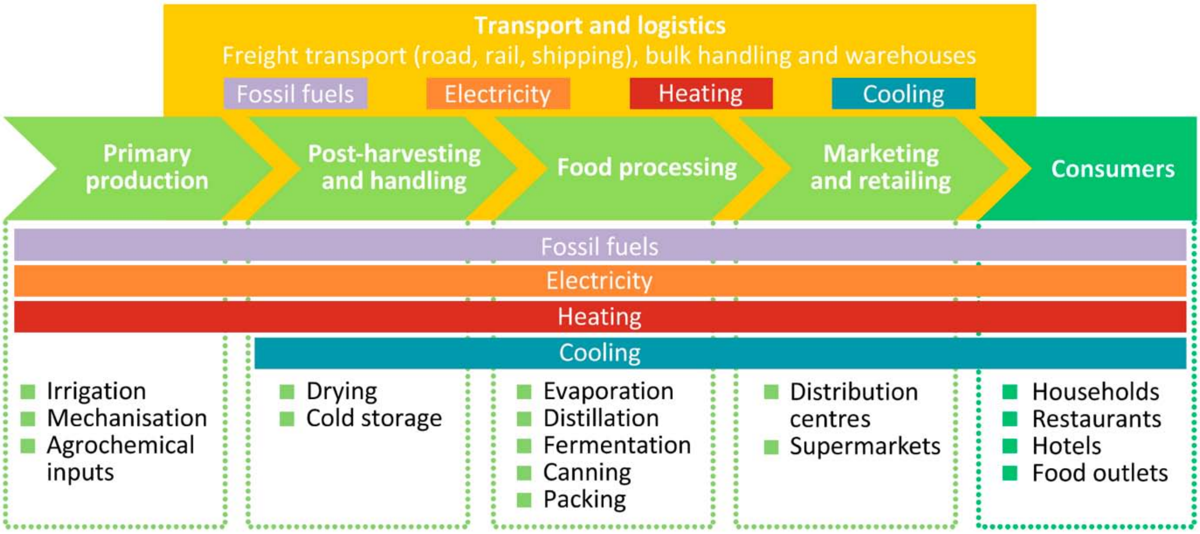
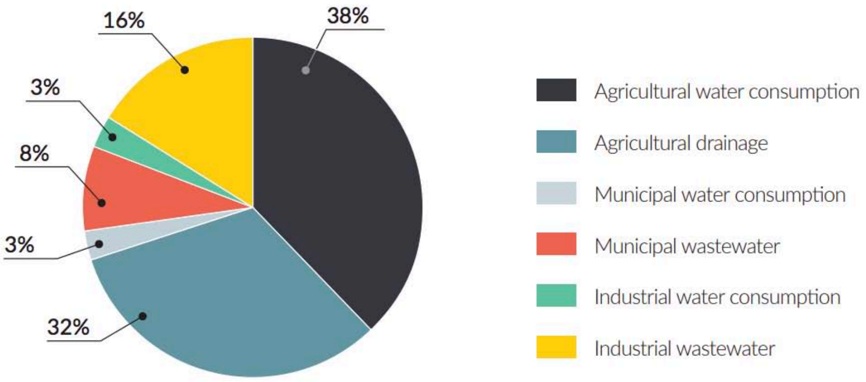


Figure 1.2: Agri-food processing chain and energy inputs (IEA, 2017)

In terms of water use, agriculture is currently the number one consumer of global water resources, accounting for 70% of all freshwater use [23] (Graph 1.4), required for land preparation, food production, processing and transport. Water abstraction would not be feasible without the contribution and use of energy which is a basic requirement for pumping, distribution and treatment of water. Overall, it is expected that, by 2030, population expansion, increasing food demand and economic growth will increase the global demand for energy and water by 40% [24], [25], which will play a critical role, both on farm and beyond the farm.



Graph 1.4: Global consumption and wastewater production by major water use sector (AQUASTAT; Mateo-Sagasta et al.,2015; FAO)

1.4 The geospatial dimension of the challenge

In order to outline and optimize the design of a comprehensive, region-wide, sustainable process within the agricultural production chain with regards to water and electricity demand, it is essential to assess the situation holistically: starting from exploring the desired region where the process will be based in, in a microscopic level, and finishing by optimizing individual process parameters according to the significant geographic parameters. Throughout this process, the use of energy models can be applied to answer questions and provide valuable insights. Computer models can process large amounts of data in order to generate demand forecasts, analyze energy supply strategies and impacts of energy policies. Mentis et al. (2015) also highlight the importance of the geo-spatial dimension in energy planning by the integration of GIS models in the energy modeling process. In their paper, they highlight that energy planning has a strong linkage to geographical characteristics of the area in which the planning is being conducted. Besides, it is commonly agreed that geospatial analysis is an effective tool for supporting the planning, implementation and monitoring of basic services delivery in developing countries [26]. As national statistics is often incomplete or lacking in many areas, especially in developing countries, GIS data can be used to help filling these data gaps. Furthermore, the ability to differentiate significant location specificities as well as visualizations and maps are also brought up as advantages of geospatial tools in energy planning [27]–[29]. However, the use of GIS data and associated analytical tools to conduct strategic energy planning remains at an early stage. Yet it has multiplied in recent years to support public and private sectors stakeholders in prioritizing and rationalizing decision making related to energy infrastructure [27].

There are many examples in the literature of GIS approaches employed for different dimensions of energy planning. GIS has been widely used for renewable energy resource assessments and optimal power plants location spanning from local, to national and continental scale assessments principally for household electrification and applications [28]–[37]. Besides these studies, there are few modelling models for electrification planning that utilize GIS tools to compare on- and off-grid technologies. Network Planner [38] and HOMER [39] are some of these models which compare grid-connection, diesel generation and standalone PV systems for given locations. The programs use GIS among other things to calculate the shortest distance for grid extension to multiple areas. GEOSIM [40] is another GIS based program which determines the optimal electrification option for areas which may function as centres for social and economic development. It also identifies which areas can be connected to the grid based on economics and grid capacity and compares several other technologies for. Lastly, OnSSET [41] uses GIS and allows the estimation, analysis and visualisations of the most cost effective electrification option based on grid-connection and six off-grid technologies (grid, mini grid & stand-alone) for the achievement of electricity access goals. OnSSET differs from the aforementioned tools in a sense that it considers all areas of a country or region instead of focusing on certain locations, considering location explicit resources' availability, infrastructure, economic activities and demand related parameters employing a large number of spatial datasets [27]. Nevertheless, one of the biggest assets of this tool is that the OnSSET code is open source, allowing for anyone to use and customize it based on the study area and the location dependent implications that come with it.

Most of these studies and models, however, focus on renewable energy supply and the optimal technology mix for household electrification without accounting for the location dependent energy demand and use. On the demand side of the energy planning infrastructure, most studies focus on the energy use in the built environment, employing models at an urban, district or even individual building level. ESMAP has already demonstrated that the concept of access to energy in a regional level does not lend itself to an easy definition [42]. In the same report, the locales of energy use are defined as "the broad locations of end use of energy for availing energy services" and are classified in household applications, community facilities and productive uses (Figure 1.3).

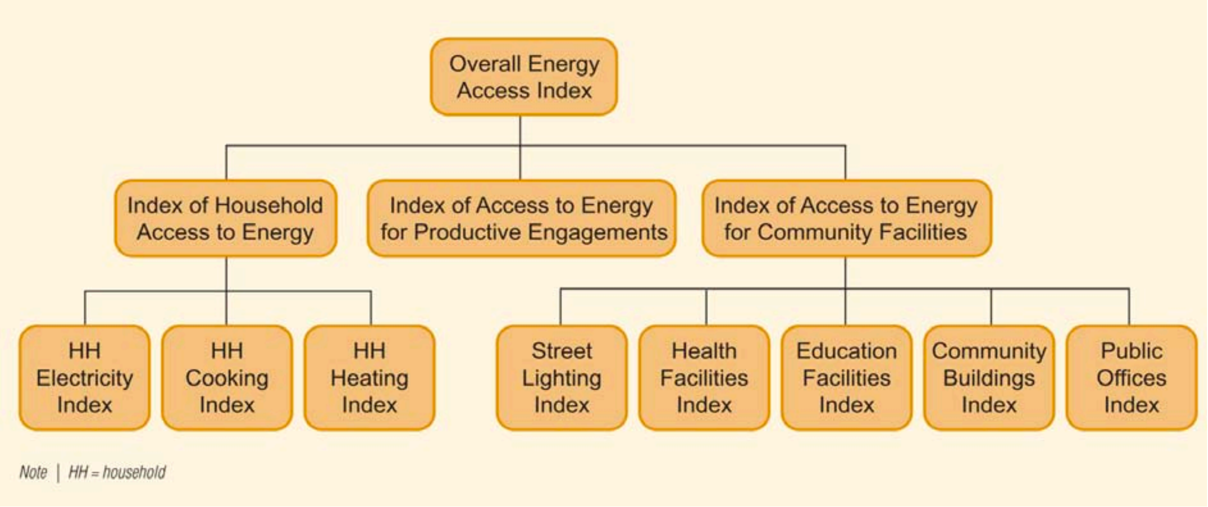


Figure 1.3: Hierarchy of energy access indices (WB/ESMAP, 2015)

In the aforementioned GIS models, the electricity demand (usually implying household access) is most commonly estimated based on demographics, national spatial statistics and energy targets. The electrification algorithm in OnSSET, for example, is based on the electrification tiers from the WB/ESMAP GTF report, under the SE4ALL initiative [2]. The Multi-tier Framework approach is based on residential electricity consumption and describes if the household has access to electricity as well as the level of access. It defines five tiers of access, each tier representing different levels of electricity services provided starting from basic lighting (lowest tier) to services that provide comfort, such as air-conditioning (See Appendix A). The electrification deficit, coupled with the tier of access to be targeted and the location dependent population allow the electricity demand to be estimated.

With regards to the location dependent access to energy for productive engagements, measuring electricity needs is more of a complex challenge, and research on the specific areas has been rather overlooked, hence the lack of GIS models in the literature. The wide variety of productive activities, with varying scales of operations and degrees of mechanization, make it very challenging to devise a common metric for energy access, and such a multi-dimensional modelling approach would incorporate numerous external factors that are volatile and highly interdependent; from climate and geographic parameters to individual activities and local policy and legislative frameworks.

1.5 Statement of objectives

The literature gap mentioned in the previous section and the general paucity of reliable georeferenced energy demand related information in developing countries hampers analysis and planning. Electricity access and associated infrastructure planning cannot be addressed without due regard of the spatial nature and dynamics of human settlements, activities and sources of economic production [43]. In the context of productive uses of energy, agricultural food production accounts for one of the largest shares in global energy consumption and water use, and therefore, its incorporation constitutes a significant addition in the electrification planning process. With regards to agriculture, electricity is primarily required for irrigation which is of the utmost significance in the agricultural production process and leads the way towards sustainable and efficient production systems. The first step towards this holistic integration of sustainable energy development and strategies is about understanding the origins of the challenge and addressing it to its core by answering the simple question *“What is the actual demand and the future projections?”*.

The scope of this Thesis is to develop a spatiotemporal demand model that will be able to perform a comprehensive, multi-criteria analysis which can be potentially replicated and applied on a national level for different study areas, and could also be integrated in electrification models, such as OnSSET. The main objectives are a) the geospatial estimation of water requirements for explicit food crops and b) the geospatial estimation of the electricity demand for groundwater irrigation, throughout the country's agricultural calendar in each 100 km^2 harvested area grid-cell. The output of this spatially distributed model leads to the estimation of a temporal and spatial variation of the water and electricity demand for irrigation purposes in the study area, and allows the development and assessment of scenarios highlighting the interactions and dynamics between water use and energy demand. These scenarios mainly focus on the impacts associated with changes in irrigated areas and different irrigation technologies. For the purposes of this work, the methodology is applied for the case study of the United Republic of Tanzania which will be presented in the following chapter.

1.6 Thesis organization

In Chapter 1, an introduction to the overall approach of the research topic is presented, highlighting the current socioeconomic framework and the rationale under which this Thesis was elaborated upon, outlining the specific research questions. Evidence and brief literature review of the state of the art are included in selected sub-sections if needed.

Chapter 2 focuses on the case study of the United Republic of Tanzania, describing the country's demographic, social and geospatial profile with regards to the research questions.

In Chapter 3, an in-depth description of the developed methodology is presented, including all datasets, tools and methods employed.

Chapter 4 discusses on the results of the application of the aforementioned methodology, specifically commenting on the dynamics of the outputs and the development of possible scenarios for further analysis.

Finally, conclusions and recommendations for future work are given in Chapter 5.

2. The case study of Tanzania

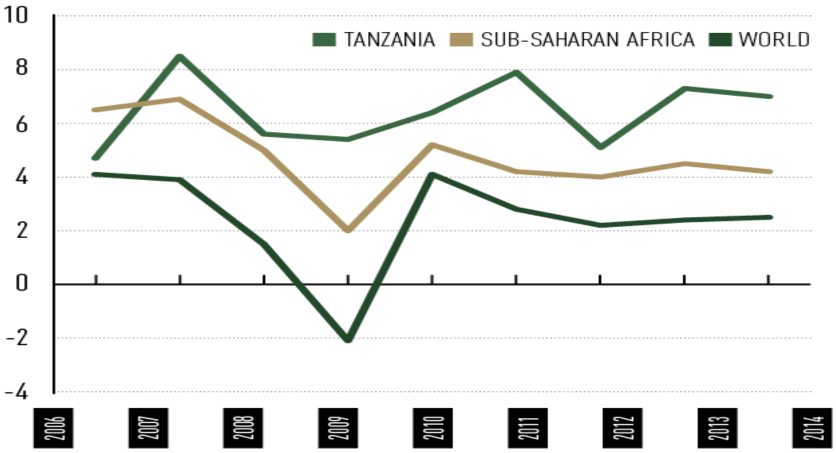
The rationale for selecting Tanzania as a case study for this developed methodology is based on the critical, far-reaching energy-related challenges facing the country, combined with efforts already undertaken by the Government of Tanzania, UN, FAO, the WB, and other global organizations to meet them. Key issues include a climate change–induced energy crisis, high rates of energy poverty, high population and economic growth, rapidly increasing energy demand, and diverse and abundant renewable energy resources that remain largely untapped. The government is strongly committed to developing the nation's renewable energy resources and has made significant efforts to create an enabling legislative and institutional framework. The country is also selected as a pilot emerging, low-income country to benefit from many global programs (FAO, WB, UN etc.) and was also of great interest during my internship and research tasks at KTH-dESA.

2.1 Area of study

The East African nation of Tanzania, officially the United Republic of Tanzania, lies on the East Coast of Africa between 1^o and 11^o S latitude and between 29^o and 40^o E Longitude. It is bordered by Kenya in the North and shares Lake Victoria with Kenya and Uganda in the West. Tanzania has frontiers with Rwanda, Burundi, and Democratic Republic of Congo in the Southwest, and Zambia, Malawi, and Mozambique in the South (Figure 2.1) [44]. With 947,300 km^2 of land, Tanzania is the 31st largest country in the world and the 13th largest in Africa. The area it occupies consists of the mainland and Zanzibar, which is made up of the islands Unguja and Pemba [45], [46], and is divided by region in 30 administrative areas which can be found in further detail in Appendix A [47]. According to the UN, the estimated 2016 population of Tanzania is 55.57 million, up from the 2012 official census estimate of 44.93 million, ranking 26th in the world. The vast majority of the population resides in rural areas, reaching up to almost 68 % of the total estimate [14]. The annual population growth rate is 3.1 % and the average population density is 62.7 inhabitants/km^2, with the population distribution varying significantly within different parts of the mainland and the islands.

Figure 2.1: Map of Tanzania (GENI)

Tanzania has registered an average economic GDP growth rate of 6-7 % in the past decade, which was well above the 6 % average for SSA and EAC members and the global average of 4 % [46] (Graph 2.1). Economic growth, which is estimated by the Tanzania NBS to have reached even 7.3 % in the first three quarters of 2016, largely thanks to the agriculture and manufacturing sectors as well as the emerging gold-mining sector, which was the fastest growing industry, driven by a strong performance in the information and communication sectors, public administration and defence, financial and insurance [46]–[48].



Graph 2.1: Tanzania GDP % growth change (WB, 2016)

According to WB, UN and national government data, under the social context, poverty has declined since 2007 and continues at a modest pace, with a fall in the poverty rate from 28.2 % in 2012 to 26.9 % in 2016. This decline has been accompanied by improvements in human development outcomes and living conditions. In 2014, the country's HDI score was 0.521, making it 151st of 188 countries, which puts the country in the low human development category. Between 1985 and 2014, Tanzania's HDI value increased from 0.371 to 0.521, an increase of 40.5 % or an average annual increase of about 1.18 %.

The energy sector in Tanzania is still dominated by traditional biomass for domestic uses, mainly harvested and processed in unsustainable ways. Electricity access and consumption are low but increasing at a fast pace. According to IEA, as of 2016, only 36.8 % of the population had access to different levels of electricity (37 million people without access), among which almost 17 % in the rural areas [49] [46]. Tanzania's per capita electricity consumption was estimated at 104.79 kWh per year in 2014, which is less than half of the consumption of low-income countries. TANESCO, which is the main electricity supplier of the country, anticipates major demand increases from several mining operations, factories and water-supply schemes for agriculture and other activities. Peak demand capacity is projected to increase rapidly, from about 1,000 MW in 2013 to about 4,700 MW by 2025 and 7,400 MW by 2035. Production is projected to increase ten-fold, from 4,175 GWh in 2010 to 47,723 GWh in 2035

Overall, despite the country's reported phenomenal improvement and growth, poverty and under-nutrition remain acute and widespread, particularly in rural areas where the majority of the population is found. While the poverty rate in the country has declined, the absolute number of poor has not because of the high population growth rate; more than 13 million people remained below the poverty line in 2016 along with many other significant geographical disparities.

2.2 Agriculture and crop production: the case of maize

Agriculture in Tanzania is considered as the backbone of the economy. In 2016, GDP was estimated at US$ 47.314 billion, with an annual growth rate of almost 7 % for the past decade. Agriculture contributed 31.5 % to the GDP, down from almost 50 % twenty years earlier. The sector still employs 66.7 % [45], [46], [50] of the active population (the majority of whom are found in rural areas) and thus continues to drive the economic growth of the country in spite of the emergence of the new high-growth sectors of mining and tourism [51], [52].

According to AQUASTAT [45], land cover is dominated by woodland, grassland and bushland which account for about 80% of the total area. Agricultural land is estimated to be about 44 million ha[1], or 42 % of the total area. In 2013, 15.65 million ha or 17 percent of the country was cultivated, comprising 13.5 million ha of arable land and 2.15 million ha of permanent crops. Smallholder farming covers almost 9 million ha, with an average farm size ranging from 0 to 5 ha, medium-scale farm owners (5-100 ha) cover an area of around 6 million while commercial farming (>100 ha) is spread in just below 1.3 million ha for just over 1,000 farms [53], [54] (Graph 2.2).

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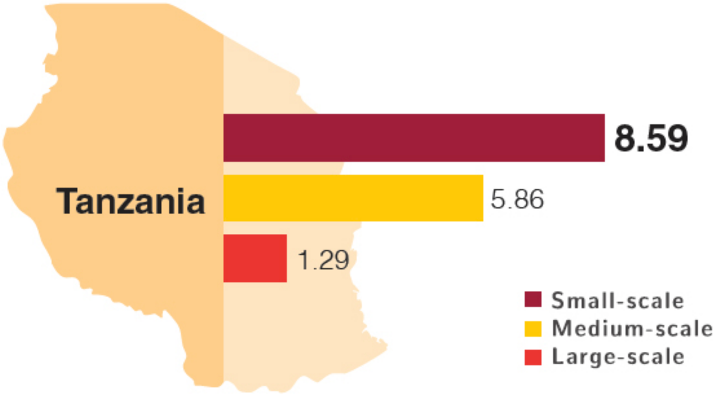
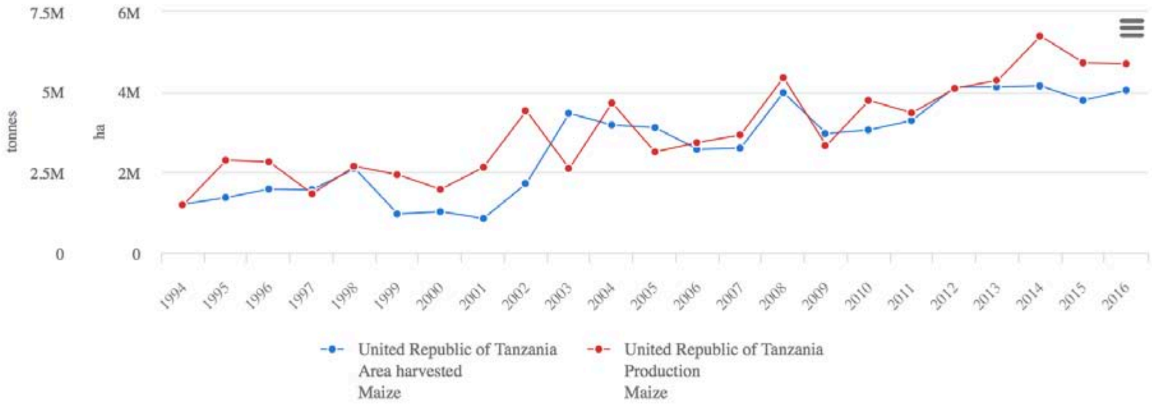
[1] 1 ha = 0.01 km^2



Graph 2.2: Area owned/controlled by small-scale (0-5 ha), medium-scale (5-100 ha) and large-scale (>100 ha) farm holdings in 2015 (Jayne et al.,2016)

Agricultural production remains predominantly based on smallholder production, with commercial farming concentrating on cash crops and productivity generally low with modest progress over the past two decades. Smallholder farmers principally depend on rain-fed production, limited use of improved seeds and fertilizers, and occupy a low share of cultivated over arable land.

The main food crops grown are maize, dry beans, rice, sunflower, cassava, sorghum, groundnuts, sweet potato and coconuts. According to the WB and the National 2018 USDA GAIN report, maize (or white and yellow corn) is the dominant crop with a planted area of over 4 million ha, followed by dry beans with over 1.1 million ha and rice with around 1 million ha (Graph 2.3). Traditionally, the country was a net exporter of agricultural products, but it has become a net importer in recent years. The main agricultural products exported are green coffee, tobacco, cashew nuts, cotton, sesame and tea, while the main agricultural products imported are soybeans, wheat and palm oil [45], [47], [55].

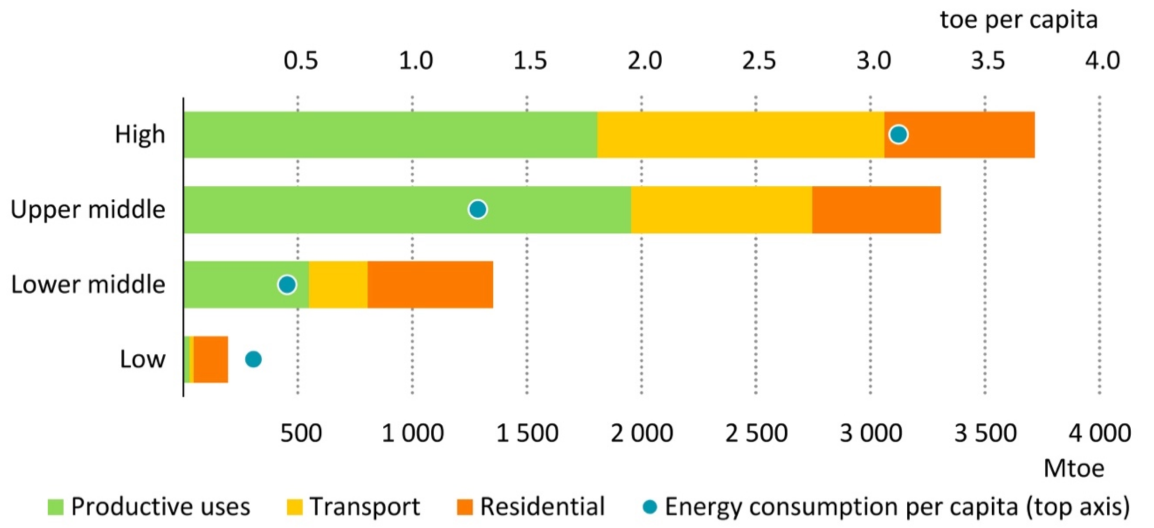


Graph 2.3: Harvested area and production of maize in Tanzania 1994-2016 (WB, 2016)

Although, maize comprises almost 45 % of the cultivated area and the country ranks as the first producer of maize in East Africa, Tanzania still faces lots of challenges of achieving full business operation and sustainable production to meet the increasing forecasted demand. The production of maize accounts for more than 70 % of the cereal produced in the country reaching almost 6 million tonnes (Graph 2.3). White corn is the main staple grain consumed in Tanzania, providing 80% of dietary calories and more than 35 % of utilizable protein to the population. The majority of smallholder farmers produce maize for their personal consumption and sell a portion to the market as a significant source of income. Typically, about 40 % of the production in Tanzania is sold in the market, mostly locally and annual per capita consumption is estimated at 135 kg per person per year.

2.3 The Water-Energy-Food approach

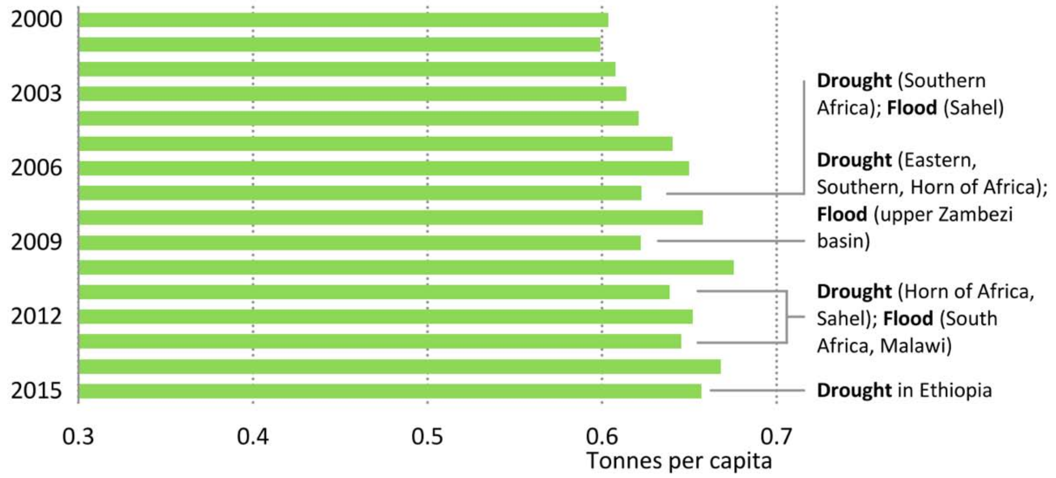
According to the latest WEO Special Report 2017, as a country undergoes a shift towards a more modernized and mechanized economic system that capitalizes on technological advancement and accounts for industry and services, it employs more energy. Hence, a larger share of total final energy is devoted to productive uses (Graph 2.4) [49].



Notes: Mtoe = million tonnes of oil equivalent; toe = tonne of oil equivalent. Productive uses include industry, services, agriculture and non-energy use.

Graph 2.4: Global final energy consumption by income group, 2016 (IEA, 2017)

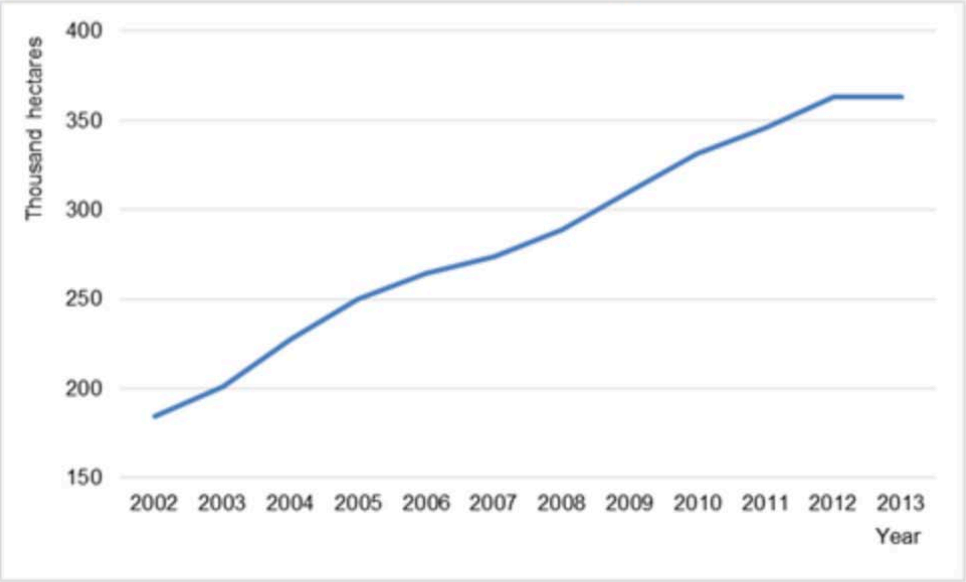
The above graph highlights the economic divide and the significance of improving energy access to stimulate economic growth in low-income countries, such as Tanzania. Despite agriculture's importance to the economy of the country, reliance on erratic precipitation, limited use of improved seeds and fertilizers, and the low share of cultivated over arable land have prevented Tanzania from reaching full production potential and have contributed to one of the lowest levels of productivity in Sub-Saharan Africa, which ranks among the last positions in a global level (Graph 2.5).



Graph 2.5: Total food production per capita in Sub-Saharan Africa (IEA, 2017)

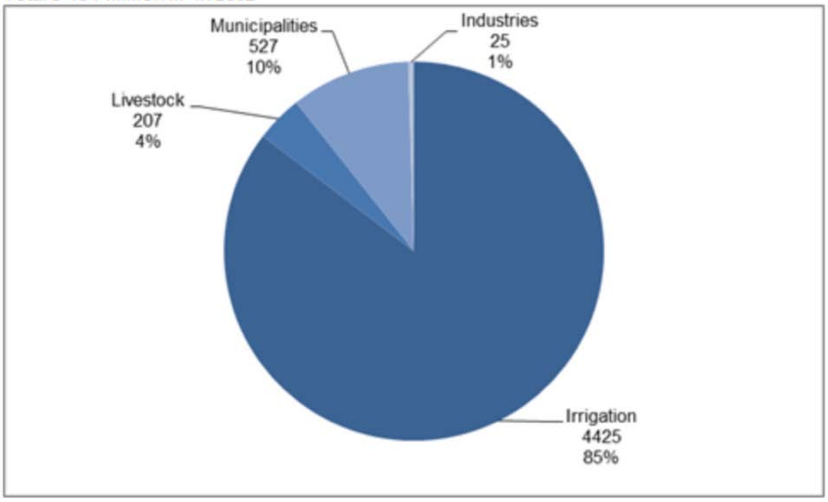
According to the WB and the AfDB [56], the electricity access rate in rural areas of the country in 2016, reached only 17 % . Animal and human power provide the main energy inputs for farms, while traditional use of biomass or direct solar energy (not to be confused with modern solar PVs) provide energy for the limited processing that takes place [49]. Limited access to electricity highly affects food production in the context of irrigation, resulting in large numbers of food loss since post-harvesting processing and storage options that require electricity are not available [20].

Irrigation can play a pivotal role to the intensification of the Tanzanian agricultural productivity, though it needs to be carried out in a sustainable fashion. IEA states that irrigated cropland can be two-times more productive than rain-fed land, improving yields, and irrigation can help to manage fluctuations that occur from a dependence on precipitation [57]. Based on data from FAO and AQUASTAT, the total area equipped for irrigation in Tanzania was 184,330 ha back in 2002. Geographically, 183,988 ha were located in mainland Tanzania and 342 ha in Zanzibar. On the same year, a study on the country's NIMP, estimated a total irrigation development potential of 29.4 million ha, of which 2.3 million ha as high potential in Tanzania mainland and Zanzibar [51], [58]. As of 2013, 363,514 ha are reported to be equipped for irrigation (Graph 2.6).



Graph 2.6: Evolution of the area equipped for irrigation in Tanzania, 2002-2013 (AQUASTAT, FAO)

The use of irrigation, especially groundwater irrigation, is highly dependent on access to energy to pump and move the required volume of water. According to AQUASTAT, total water withdrawal in mainland Tanzania was estimated to be 5.142 million m^3 for the year 2002. Irrigation for agriculture was reported to be the largest consumer reaching up to 86 % of the total amount (Graph 2.7). Without more recent data, the 2002 National water Policy [58] and the 2009 Water Resources Management Act [59] consider that irrigation withdraws an average of about 85 % of the total water withdrawals since then.



Graph 2.7: Total water withdrawal by sector in Tanzania, 2002 (AQUASTAT, FAO)

In 2010, groundwater withdrawals were estimated to be around 462 million m^3, mostly for domestic purposes (60 %), but also for livestock, fishing (28 %), irrigation (10 %) and industries (2 %) [45]. With regards to the energy intensity, it is estimated that roughly seven-times more energy is required to pump groundwater than is required for surface water extraction [24].

Overall, it is made clear that accounting for enhanced access to energy for irrigation can result in improvements in productivity. If inefficient pumps are used however, both water and electricity demand can increase, which depending on the availability of each resource, can lead to unsustainable irrigation practices. An emphasis on irrigation infrastructure efficiency and the use of groundwater in a sustainable manner is vital to ensure that improvements in yield do not have adverse impacts.

2.4 Legal and policy context

2.4.1 Energy policies and incentives

The first NEP for Tanzania was presented in 1992, in order to ensure an overall efficient practice within the energy sector. Since then, two new NEPs have been presented by the Ministry of Water and Minerals, replacing the one from 1992; one in 2003 and the most updated one in 2015. The NEP of 2003 resulted in, amongst other things, a large increase in installed capacity and an increase in the electricity consumption levels per capita. In this context, the country also managed to double the population connected to the grid. NEP 2015 aims for a larger and more active participation from private actors in the energy sector. Under the SE4ALL initiative, the new policy also focuses on improving energy conservation, efficiency and increasing the diversity within the energy mix, aligned with the SDGs framework. For the electricity sector, in particular, the aim is to increase the rural electrification rate and to enhance the reliability of the transmission and distribution network [60]. In the updated PSMP of 2016, six generation expansion scenarios, with different shares of power resources such as natural gas, coal, hydro and renewable energy were developed, and each one of them was evaluated under the economical, energy balance and environmental aspect. It was concluded that Scenario-2, which has the energy generation mix of 40% gas, 35% coal, 20% hydro and 5% renewable and others, was considered to be the best among six scenarios [61]. According to PSMP, the optimal generation plan has a total installed generation capacity of 5,011 MW (excluding renewable and import) by 2020 which is beyond the government target of 4,915 MW by 2020. The investment cost required for this, is calculated to a total cost of US$ 31.7 billion in the long term (2026-2040) and includes investment on generation, transmission and substation. It is interesting to point out that generation accounts for almost 80% of the total investment cost. The policy guidelines are aligned with the government's aspirations and targets to accelerate economic growth through the on-going Vision 2025, MKUKUTA and the Five-Year Development Plan–II (2016/17-2020/21, FYDP-II), which constitute the backbone of the legislative framework towards sustainable development and economic growth for Tanzania.

2.4.2 Water management for irrigation and agri-food policies

According to the updated NIP 2009 by the MWI, national irrigation development is constrained by the almost inexistent level of government funds for both irrigation and water storage infrastructures and by the low rate of contribution of the private sector [51]. As a result, irrigation development, together with sustainable water resources and land use management, was set as priority investment in the 2011 TAFSIP Plan for 2011 to 2021 development, along with the establishment of two funds; DIDF and NIDF, which have the objective of ensuring sustainable availability of irrigation water and its efficient use for enhanced crop production, productivity and profitability by promoting and financing mechanization for agriculture. The main regulatory framework for irrigation in Tanzania is the 2009 WRMA No.11 [59], which was completed by the 2013 NIA establishing a National Irrigation Commission [62].

Looking at the current status of agriculture intensifications policies, the Government has formulated TDV 2025, which envisages that by 2025 the economy will have been transformed from a low productivity agricultural economy to a semi-industrialized one, led by modernized and highly productive agricultural activities [63]. As an integral part of UNDAP II (2016-2021), the latest 2017 CPF includes the prioritization of four areas, under the guidance and aligned with FAO's global strategic objectives and striving to attain the SDGs under the SE4ALL initiative. The priority areas account for: i) *"evidence-based agriculture policy, planning, investment and sector coordination"*, ii) *"increasing agricultural production, productivity for food and nutrition security"*, iii) *"improving market access for increased incomes"*, and iv) *"strengthening resilience to* *natural and man-made threats and crises, such as climate change impacts; and unsustainable management of natural resources”* [63].

In order to reach TDV 2025, other significant policies include FYDP II, which among other key interventions, highlights the integration of modern technologies including ICT and the promotion of skills, expertise, research and innovation throughout the agricultural transformation procedure. In addition to this, TAFSIP 2011/2012 – 2020/2021 is highly prioritized since it aims to map the investments needed in order to meet the CAADP target of 6 % annual growth in the agricultural GDP. The Government together with development partners has also taken a number of initiatives, including ASDP II, SAGCOT, the Kilimo Kwanza initiative, and BRN, all of them intended to enhance technology uptake, market development, and an overall shift towards improved productivity, increased production, incomes and resilience, and ensuring food and nutrition security (Figure 2.2).

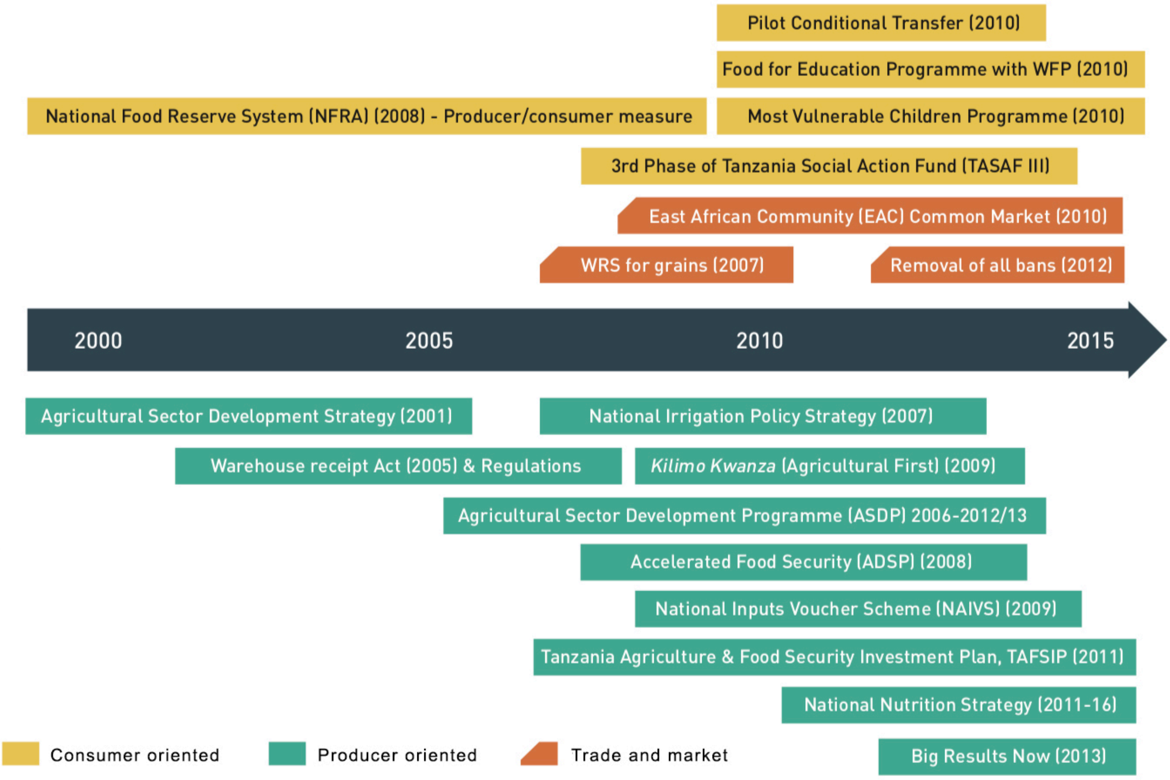


Figure 2.2: Main strategies related to irrigation and food security, 2000-2015 (FAO, 2014)

3. Methodology

3.1 Overview

This study describes a combination methodology developed to assess and compute agricultural water requirements and estimate the electricity demand associated with pumping irrigation from groundwater sources in Tanzania. It highlights the interactions between water use and energy consumption, and focuses on the electricity demand impact associated with changes in irrigated area and irrigation technologies. In order to comprehensively explore, analyze and assess the multi-dimensional aspects of this approach, GIS software and programming in Python language were employed as the main tools for this study.

At the core of this work is a monthly water balance model generated from spatial datasets and regional statistics in order to estimate the electricity demand for typical irrigated crops grown in the studied area. Water demand is computed from historical climate data and crop specific water needs according to national statistics, crop patterns, agricultural calendars and spatially explicit parameters. The electricity required to abstract and apply the required water is then calculated using national data on water sources, irrigation methods and sources of energy. The application of this spatially distributed water balance model leads to the estimation of the temporal and spatial variation of water and electricity demand for irrigation purposes in a selected area and allows the creation of scenarios for further dynamics analysis and insights.

3.2 Data approach and tools

Initially, historical geospatial data about croplands in the country and their reported irrigation status is collected in order to illustrate the temporal and spatial distribution throughout the agricultural calendar and the corresponding planting, growing and harvesting seasons accordingly. The differentiation between rain-fed and irrigated areas is the first step towards this direction and essential for addressing the core of our research questions. Proper temporal and spatial criteria regarding the crop water needs with regards to the various climate zones and land conditions are implemented. Historical monthly climate data as well as land and groundwater related data are collected and manipulated appropriately in order to come up with a monthly dynamic spatiotemporal model. All these criteria imply explicit agricultural zones and crop patterns which are discussed subsequently. Thereafter, it is required to quantify the monthly theoretical crop water needs and from there derive the actual water abstraction requirements and sustainable water management constraints that come along. Once the water needs are estimated, the monthly electricity demand is calculated based on the energy required for transfer, abstraction and water application. The latter highly depends on the morphology of the land, both underground and over ground, and needs to take into account the different operating and application pressure required under different irrigation technologies, as well as friction and transfer losses within the distribution systems. A description of the methods and datasets used are described in detail in the following sub-sections and summarized in Figure 3.1.

The multi-dimensional approach of this study highlights the need for inclusive energy planning and tools that can be aligned and adjusted to the local context in which they are applied, making it easier for the eye to recognize patterns such as distance, proximity, contiguity and affiliation. Drawing on the numerous advantages of GIS and the geospatial dimension of energy planning already discussed in Chapter 1, the methods followed rely solely on open-source software QGIS v3.2 [64] for geospatial analysis and cartography, and use Python 3.6 [65] for further data analysis, modelling and visualizations.

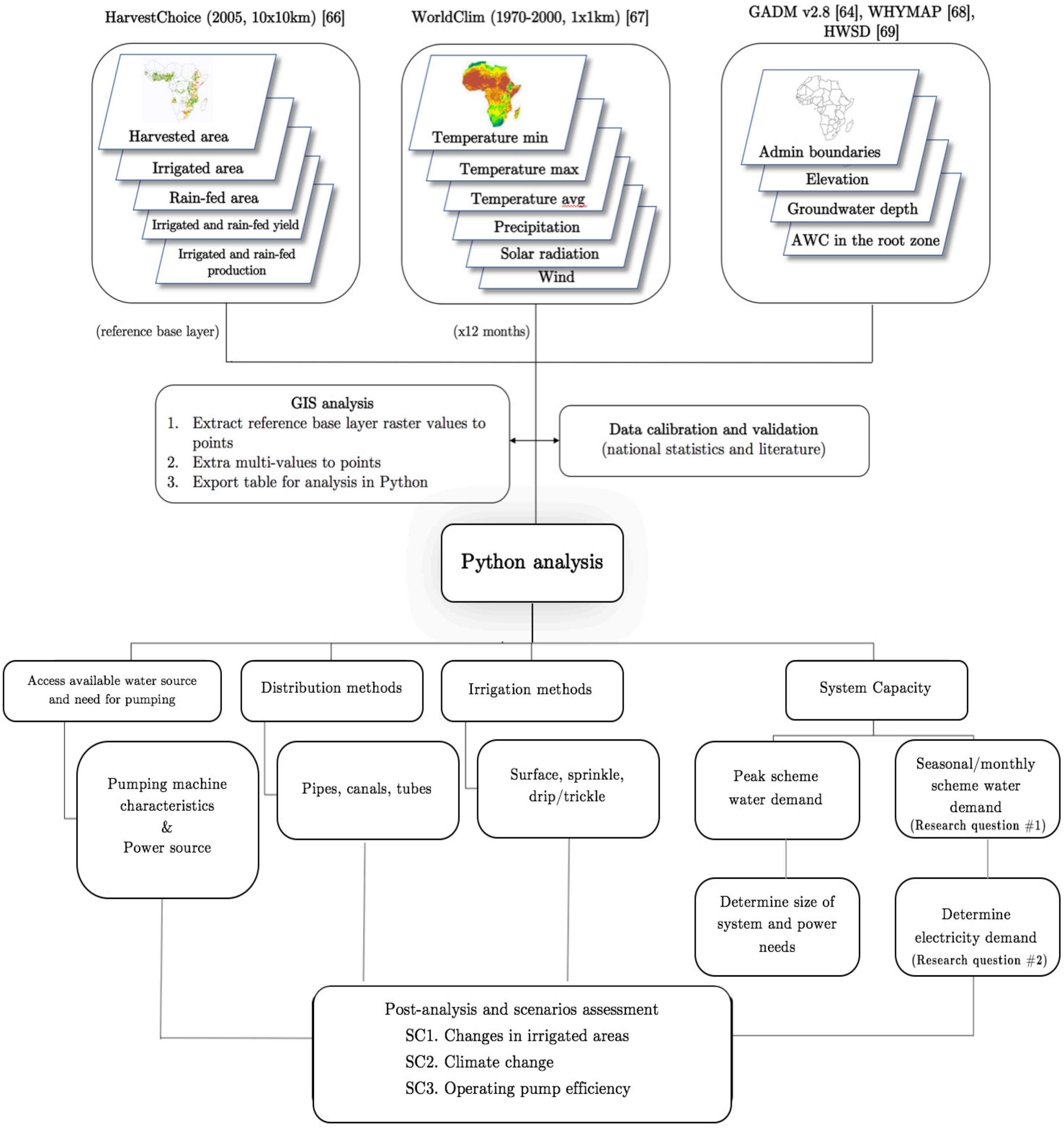


Figure 3.1: Schematic flowchart of the methodology

3.3 Data collection and description

In order to reach an accurate and reliable estimation of the water and electricity demand for irrigation purposes in a selected area, proper data should be collected, validated, potentially projected and analysed. Several sources are utilized not only for the crop and land cover data, but also for administrative country data, climatic conditions and groundwater parameters.

Table 3.1 below lists the datasets that are used and identified as useful for the estimation of water requirements and electricity demand for agriculture in the studied area. The type, resolution and the sources of the datasets are also provided. A more detailed description, along with all the data resources employed for the analysis, follows in the sub-sections below.

Table 3.1: Datasets used in the analysis

Dataset	Type	Resolution	GIS layer name	Source
Administrative boundaries	Vector polygon	-	adm0	[66]
Elevation (m)	Raster	1 km × 1 km	elev	[67]
Total harvested area (ha)	Raster	10 km × 10 m	harv_t	[68]
Irrigated area (ha)	Raster	10 km × 10 m	harv_i	
Rainfed area (ha)	Raster	10 km × 10 m	harv_r	
Total yield (kg/ha)	Raster	10 km × 10 m	yield_t	
Yield – irrigated (kg/ha)	Raster	10 km × 10 m	yield_i	
Yield – rainfed (kg/ha)	Raster	10 km × 10 m	yield_r	
Total production (t)	Raster	10 km × 10 m	prod_t	
Production – irrigated (t)	Raster	10 km × 10 m	prod_i	
Production – rainfed (t)	Raster	10 km × 10 m	prod_r	
Minimum monthly temperature (^{o}C)	Raster	1 km × 1 km	tmin_	[69]
Maximum monthly temperature (^{o}C)	Raster	1 km × 1 km	tmax_	
Average monthly temperature (^{o}C)	Raster	1 km × 1 km	tavg_	
Monthly solar radiation (kJ m^{-2} day^{-1})	Raster	1 km × 1 km	srad_	
Monthly wind speed (m s^{-1})	Raster	1 km × 1 km	wind_	
Monthly precipitation (mm)	Raster	1 km × 1 km	prec_	

Dataset	Type	Resolution	GIS layer name	Source
Groundwater depth (m)	Raster	10 km x 10 km	gw_m	[70]
Available water storage capacity (mm/m)	Vector	-	gw_m	[71]

3.3.1 Administrative boundaries

The administrative boundaries of the studied area should be clearly stated, so as to determine and quantify the main research objectives for each one of them. Including exact boundary locations, on a national or sub-national level, allows the classification into geospatial zones and the detection of similar patterns and dynamics among different areas. For this work, Level 1 data from the publicly available GADM version 2.8 database [66] was retrieved in shapefile format and manipulated subsequently in the GIS environment. (See Appendix B)

3.3.2 Crop data

Crop-related datasets, which constitute the base layer of our study, were extracted from the HarvestChoice database (2015). 5 arc-minute gridded data (~10x10=100 km^2 resolution) include crop-specific total irrigated and rain-fed harvested area (ha) , total irrigated and rain-fed yield (kg/ha), and total irrigated and rain-fed production (mt), all representing spatially disaggregated production statistics of circa 2005 using SPAM v2.0 [68]. You et al. (2014) used a variety of information sources to generate plausible, disaggregated estimates of crop distribution for 42 crops creating a global grid-space at the confluence between geography and agricultural production systems [72]. In addition to this, data was compiled for main crop characteristics based on experimental information reported in the FAO/AQUASTAT database [73]. These characteristics and insights are assumed to be representative for optimal planting, growing and harvesting conditions in the different agricultural zones of the studied region which are defined in the following sub-sections. Information on the land use, cropped and irrigated areas, as well as on the agricultural crop calendar were retrieved accordingly from national data in the FAO/AQUASTAT database and in FEWS NET [45]. These insights are followed by a calibration and cross-referencing procedure as explained later on, in order to ensure that the reported statistics are consistent with the aggregated spatial crop patterns obtained from the remotely sensed data mentioned above.

3.3.3 Climate data

Climate data is based on the high resolution (1 km^2 resolution) gridded climate dataset (WorldClim Version2) developed by Hijmans et al (2005) updated by Fick et al (2017). This is a spatially interpolated monthly climate dataset for global land areas aggregated across a target temporal range of 1970-2000, using data from between 9000 and 60 000 weather stations [69]. The primary variables used for this work are: minimum, maximum and average temperature (^{o}C), precipitation (mm), solar radiation (kJ m^{-2} day^{-1}) and wind speed (m s^{-1}). According to the authors, weather station data were interpolated directly using thin-plate splines covariates including elevation, distance to the coast and three satellite-derived covariates: maximum and minimum land surface temperature as well as cloud cover, obtained with the MODIS satellite platform [69]. Other climatic parameters such as net radiation at the crop surface (MJ m^{-2} day^{-1}), soil heat flux density (MJ m^{-2} day^{-1}), saturation vapour pressure (kPa), actual vapour pressure (kPa), slope vapour pressure curve (kPa $°C^{-1}$) and psychometric constant (kPa $°C^{-1}$) were arithmetically derived from the aforementioned dataset variables using functions from the open-source Mark Richards (2015) Python package PyETO [74]. Additional climatic input variables, such as effective rainfall (mm), are introduced in the irrigation water demand modelling section in the following paragraphs.

3.3.4 Groundwater resources and abstraction management

Regarding the water availability for irrigation, data about major groundwater resources was retrieved from WHYMAP [70]. The Groundwater Resources Map provides various characteristic groundwater environments in their areal extent and classified by their aquifer productivity and recharge potential. Additional groundwater related features such as depth to groundwater (m), aquifer recharge (mm) and available water content in the root zone (mm) were included in the methodology (source). Also, national data on water resources, withdrawal management (abstraction/pumping) and irrigation methods were obtained from the FAO global water information system AQUASTAT [73] and FAO's Irrigation Water Management Training Manual 1992 [75].

3.4 Data analysis

In this section, it is depicted how the collected required data are analysed and processed for the subsequent GIS and Python analysis. Before this comprehensive data analysis, it is essential to define the different GIS routines and methods used so as to gain a more detailed insight of the applied methodology and modelling process. Once data are manipulated in a convenient way, an aggregated data table is extracted for further analysis in a complementary Python code which was developed for reaching the objectives of this study. The combination of the quantitative modelling outputs with the qualitative research inputs allows the creation of evaluation scenarios in order to explore the dynamics among the input variables and draw conclusions and recommendations.

3.4.1 GIS concepts and analysis

Initially, the identification of the requirements of the objectives and the clear understanding of the processing tasks should take place so that the quality and reliability of the derived GIS outputs are not ultimately affected. Hence, the multi-criteria and geospatial character of this study highlights the need for a bottom up data handling approach which would not be feasible without the use of a GIS environment. All of the aforementioned datasets are imported in GIS allowing for geospatial analysis and multiple graphic representations of where the features are, explicitly and relative to one another.

On this basis, all data should be firstly organized and modified in a format that will facilitate the manipulation and analysis tasks that will be subsequently required. Each dataset is expressed and stored as a single, vertical layer in the GIS database prior to the application of common integrated database commands such as queries and statistical analysis. Once the datasets are properly named and overlayed within the GIS environment, it is essential to make sure that every single layer is in the same coordinate system and might need to be potentially projected into the suitable projection system in order for all of them to use common geographic locations for integration. For the purposes of this work, all layers are projected into the World Geodetic Datum 1984 (WGS84) which comprises of a reference ellipsoid, a standard coordinate system, altitude data and a geoid [76].

Input layers are distinguished into two primary data types; spatial data and attribute data. Spatial data describe the absolute and relative location of geographic features and represent either vectors (arcs/polylines, polygons or points) or rasters (georeferenced grid-cells). Attribute data, on the other side, describe characteristics of the spatial features which can be either quantitative or qualitative [77] and, simply put, they are represented as additional columns in a dataset table. The selection of a particular data model, vector or raster, depends on the source and type of data, as well as the intended use of the data [78]. As is often the case however, conversions from one type to the other are possible via GIS routines and tools. Total harvested area dataset (harv_t, ha) which is originally retrieved in raster format, is converted into a vector layer and constitutes the base layer of our model. In more detail, the 5 arc-minute resolution aforementioned raster layer is extracted into 4100 individual grid-cell points where each one of them represents a physical area of 100 km^2 or 10000 hectares (Figure 3.2).

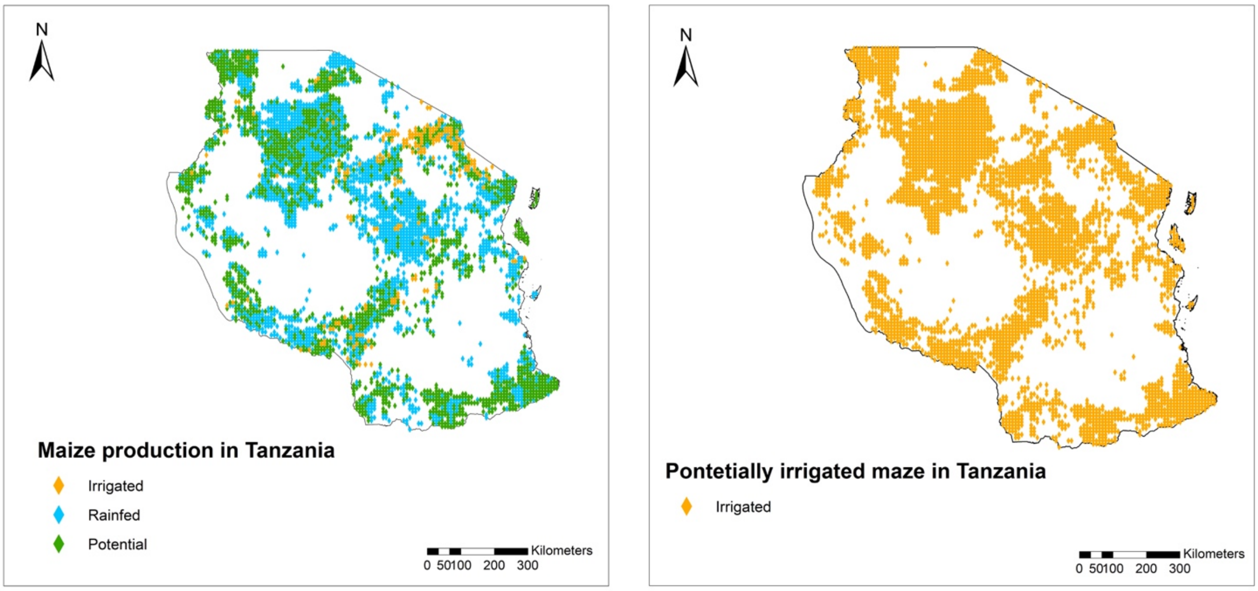


Figure 3.2: Maps of irrigated and rainfed land in Tanzania

The required output from the geospatial processing is a table built on top of the base layer where the rest of the raster layer values are extracted and assigned as additional attributes. Taking advantage of the GIS integrated Python console, a script was developed in order to extract all data into an indexed, aggregated table of 4100 rows and 86 columns (attributes) for further analysis.

3.4.2 Crop modelling

As already discussed in Chapter 2, maize was chosen for the purposes of this case study as it is considered the most dominant food crop in Tanzania, grown by 3.5 million households (60%) [79], accounting for 40% of calories consumed [80] and contributing to over 20% of the total agricultural GDP [52] and 31% of total production [81].

Crop calendar

First step of the crop modelling procedure, is defining the maize crop calendar. According to FAO, the crop calendar is basically a schedule for the crop containing information on planting, sowing and harvesting periods of locally adapted crops in specific agro-ecological zones. It provides both spatial and timely information allowing for better planning of the farm schemes activities and local crop production. Based on the country's complex rainfall patterns and on information drawn from the online FAO Calendar platform and the 2012 WFP/WB Food Security and Vulnerability analysis report [48], Tanzania is claimed to present at least seven (varying up to nine) recognized major agro-ecological zones. However, due to the complexity of the spatial and temporal identification of the sub-regions, they have been simplified into two main categories, unimodal and bimodal areas, based on the dual rainfall regime of the country. In more detail, the unimodal zone (Msimu rains) covers the south and west, and experiences one long rainy season from November to May with planting and land preparation taking place from October until January and harvesting from May until August. The bimodal zone (Vuli and Masika rains) – Tanzania's north, east and northern coast – experiences a short rainfall period from mid-September to January and long rains from March to June. Short rains harvesting occurs in late January and February and long rains harvesting in July until September (Figure 3.3). The bimodal areas, followed by two distinct rainfall seasons, allow two water demanding crop cycles per year to be grown and cover the regions of Kilimanjaro, Kigoma , Kagera, Mwanza, Mara ,Arusha, Tanga and parts of Morogoro, Mbeya and Coast/Dar es Salaam and transition areas such as Mwanza, Kagera and Kigoma, Masika where rains may begin in February, with sometimes no interruption between Vuli and Masika season [48]. (See Appendix B)

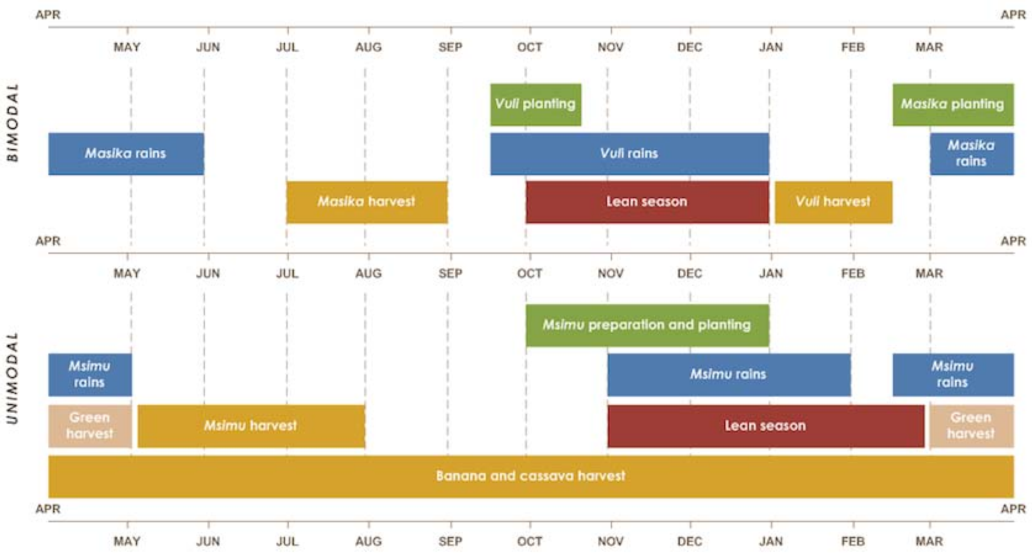


Figure 3.3: Tanzania crop calendar based on the rainfall pattern (FAO, FEWS)

Reference crop evapotranspiration (ET_o)

Having defined the spatial and temporal context of the crop modelling procedure, next step is the estimation of the reference crop evapotranspiration (ET_o). According to FAO's Irrigation and Drainage paper 56 [82], evapotranspiration (ET) is defined as the combination of two different processes whereby water is lost on the one hand from the soil surface by evaporation and on the other hand from the crop by transpiration. In detail, evaporation is the process whereby liquid water is converted to water vapour via the vaporization process and removed from the evaporating surface (vapour removal) while transpiration consists of the vaporization of liquid water contained in plant tissues and the vapour removal to the atmosphere [82], with no significant distinguishing between the two process since they occur simultaneously. According to Allen et al., there are multiple factors affecting evapotranspiration such as weather parameters, crop factors and various management and environment conditions

Reference crop evapotranspiration (ET_o) or potential evapotranspiration (PET) is defined as the evapotranspiration rate from a reference surface, not short of water, which is usually considered as a hypothetical grass reference crop with specific characteristics [82]. Unlike ET, the only factors affecting ET_o are climatic parameters and can be therefore computed from weather data without taking into account other crop characteristics or soil factors. Recent studies [83]–[86] found that more than 50 mathematical models are currently available to estimate ET_o which range from hydrologic or water balance models, to analytical methods based on climate variables (primarily temperature and radiation) and empirical estimates [82], [87]–[93]. There is also a plethora of literature and research [87], [94]–[99] on the evaluation and comparison of the varying calculation methods and their complexity. Even though the aforementioned research pieces are applied for significant crops in different parts of the world under different climatic and soil conditions, they all imply that there are not significant differences in the results and that the selection of the most suitable calculation method should be clearly based on the data availability and the needs and objectives of the given study. Some of the most widely used ET_o models include the temperature-based Thornthwaite (1948) [100] and Hargreaves-Samani (1985) [101] estimation formulas and the radiation-based Priestley and Taylor formula (1972) [102]. Several studies [17], [38-39] however, have shown that the physically based Penman-Monteith formula (1965) [105], which considers both climatic factors and their interaction with surface vegetation characteristics [99], is the most accurate and commonly used for estimating ET_o. Penman and Monteith combined the energy balance with the mass transfer method and derived multiple equations in order to compute the evaporation from an open water surface from standard climatological records of sunshine, temperature, humidity and wind speed [82].

For the purposes of this study, the widely used FAO-56 Penman-Monteith method is used, which was originally developed and adapted in May 1990 by a consultation of FAO experts and researchers in collaboration with the International Commission for Irrigation and Drainage and the World Meteorological Organization [82]. This method overcomes shortcomings of the Penman-Monteith method and provides values more consistent with actual crop water use data worldwide, referring to ET_o as the “evapotranspiration of a hypothetical reference crop with a height of 0.12 m, a surface aerodynamic resistance of 70 s m^{-1} and an albedo of 0.23, closely resembling an extensive surface of green grass of uniform height, actively growing, completely shading the ground and with adequate water" (Allen et al, 1998). The FAO-56 Penman-Monteith formula is the following (Equation 3.1):

$$\mathbf{ETo} = \frac{\boldsymbol{0.048\Delta(R_n - G) + \gamma \frac{900}{T + 273} u_2(e_s - e_a)}}{\boldsymbol{\Delta + \gamma(1 + 0.34u_2)}}$$

Equation 3.1: The FAO-56 Penman-Monteith equation

where ET_o is the reference evapotranspiration (mm day^{-1}), R_n is the net radiation at the crop surface (MJ m^{-2} day^{-1}), G is soil heat flux density (MJ m^{-2} day^{-1}), T is the mean daily air temperature at 2 m height (°C), u_2 is the wind speed at 2 m height (m s^{-1}), e_s is the saturation vapour pressure (kPa), e_a is the actual vapour pressure (kPa), e_s - e_a is the saturation vapour pressure deficit (kPa), Δ is the slope vapour pressure curve (kPa $°C^{-1}$) and g the psychrometric constant (kPa $°C^{-1}$) [82]. Climate data mentioned in section 3.3.3 are used as input variables in the calculation process drawing on the features offered in the "Pyeto" Python library [74]. Pyeto provides numerous functions for estimating missing meteorological data such as net outgoing longwave radiation, psychometric constant, soil heat flux, saturated vapour pressure, solar angles, daylight hours etc based on the methods described by Allen et al. (1998) in the FAO Irrigation and Drainage paper 56.

Crop evapotranspiration under standard conditions (ET_c) and single crop coefficient (k_c)

According to Allen et al. (1998), the crop evapotranspiration under standard conditions, denoted as ET_c, is the evapotranspiration from disease-free, well-fertilized crops, grown in large fields, under optimum soil water conditions, and achieving full production under the given climatic condition. ET_c is determined by the crop coefficient approach, whereby the effect of the various weather conditions are incorporated into

ET_o from the previous paragraph and the crop characteristics into the k_c coefficient which is defined in the following paragraphs. ET_c basically represents the crop water needs and is expressed as the product of ET_o and k_c (Equation 3.2).

$$\mathbf{ET_c} = \boldsymbol{ET_o} * \boldsymbol{k_c}$$

Equation 3.2: ET_c crop evapotranspiration equation (mm)

The calculation procedure consists of the identification of the crop growth stages, determination of their lengths and selection of the corresponding k_c coefficients by constructing the crop coefficient curve (Figure 3.4) allowing one to determine k_c values for any requested period or even specific day during the crop calendar [82]. Crop coefficient values mainly depend on the type of crop, the growth stage of the crop and the climate [106].

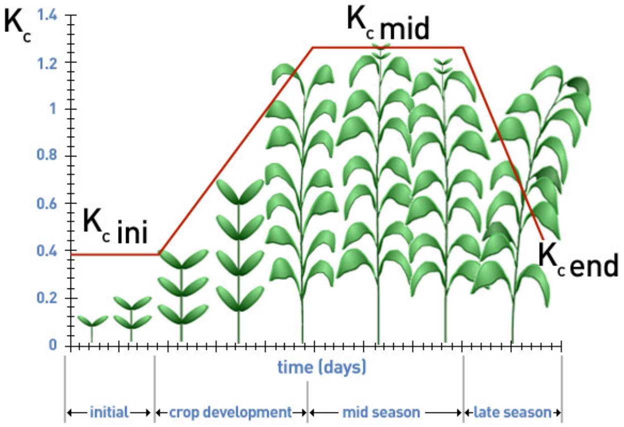


Figure 3.4: Crop coefficient (kc) curve (FAO)

FAO Irrigation and Drainage Paper 24 [107] and several other studies [108]–[110] provide general lengths for the distinct growth stages and total planting, growing and harvesting periods for various types of climates and locations. Growth stages are usually determined and distinguished into four different seasons (Figure 3.4). The initial stage is the period from sowing or transplanting until the crop covers about 10% of the ground. The crop development stage starts at the end of the initial stage and lasts until the full ground cover has been reached (ground cover 70-80%); it does not necessarily mean that the crop is at its maximum height. Following is the mid-season stage which starts at the end of the crop development stage and lasts until maturity; it includes flowering and grain-setting. Final is the late season stage which lasts until the last day of the harvest and usually includes ripening [107]. Brouwer et al. (1989) provide an indicative table with typical average values of aggregated growth stages, ranging from 80 to 180 days for maize. A more comprehensive assessment for maize in Tanzania [111], showed that the length of the season ranges from 131 to 150 days in Mbeya and Songea region in the south and Kigoma in the west. In Dodoma and Iringa regions, the duration was found to be as short as 93 to 97 days. Due to the complex variation and the inconsistency of the growth stages data sources within the different regions of the country, the crop calendar modelling classification explained in the previous paragraphs, is put in use in order to define the different growth stages for each one of the 4100 points on the map. Three instead of four growth stages are assumed for the purposes of this approach; the initial stage is introduced as the planting season, crop development and mid-season stage are merged into growing season, and final stage is expressed as harvesting season. By calibrating and consolidating the temporal information of the adopted crop calendar (Figure 3.3), fixed planting, growing and harvesting start and end dates, are joined and assigned accordingly as attributes in the entries based on the zone they belong in (bimodal or unimodal).

With regards to the three seasons assumed for this work, three corresponding crop factor coefficients are introduced as k_{cp}, k_{cg} and k_{ch} for planting, growing and harvesting season respectively. In FAO's Irrigation Water Management Training manual no 3 [106], indicative nominal values for maize are provided (0.4, 0.8, 1.15 and 0.7-1) for the different growth stages. In an attempt to get more realistic and accurate values throughout the different agricultural seasons, a function was developed in Python aiming to represent and fit the k_c curve presented in Figure 3.4. The numerical determination of the k_c given a specific day, lies on the idea that the crop coefficient for any period of the whole season can be derived by considering that during the planting and growing season, k_c is constant and equal to the k_c value of the season under consideration. Following this concept, during the growing and harvesting season, k_c varies linearly between the k_c at the end of the previous stage (k_{cprev}) and the k_c at the beginning of the next stage (k_{cnext}), which is k_{cend} in the case of the harvesting season (terminal condition) [82].

$$\boldsymbol{k_{ci} = k_{cprev} + \left[\frac{i - \sum(L_{prev})}{L_{stage}}\right](k_{cnext} - k_{cprev}}$$

Equation 3.3: k_c crop coefficient equation

where i is the day number within the growth stage, K_{ci} is the required crop coefficient on day i, L_{stage} is the length of the season under consideration (days), $\Sigma(L_{prev})$ is the sum of the lengths of all previous stages (days).

3.4.3 Irrigation water demand modelling

The methodology followed in this section is mainly adapted from the widely used work of Kay and Hatcho (1992) presented in FAO's Irrigation Water Management; Training Manual for small-scale pumped irrigation [75]. An irrigation scheme must be capable of supplying the water needed for the crop to be planted, then grow until it is harvested. In other words, the water supply must be equal to the demand throughout all the growth stages. The capacity to supply the required amount of water is called system capacity and implies the evaluation and identification of certain design criteria prior to the application of different irrigation techniques. Overall, it depends on the crop water requirements which are determined by the crop type and stage of growth (expressed in ET_c), climatic and land conditions, and the field application and distribution efficiencies which will be further discussed in the following paragraphs.

Monthly crop water needs

The outputs derived from the crop modelling process, are used as primary inputs in the estimation of the monthly aggregated crop water requirements variable (CWN_i) for each point in our dataset. Along with the monthly ET_c values, more climatic and land variables are either calculated or introduced from the literature, allowing for a more inclusive and accurate parameterization and estimation of the actual crop water needs at a given location. There are several approaches reported in the literature, from simple water balance models (sources) to more complex hydrological analysis (sources), based on the available data and research objectives of the study area. The method followed in this work relies on a simplified, yet comprehensive combination approach, that takes into account the effective rainfall (mm), the leaching requirements (%) and the available water content in the root zone (mm) at a given point, according to Equation 3.4:

$$\mathrm{CWN_i} = \boldsymbol{ET_{c_i} + ET_{o_i} * LR - eff_i - awc_i}$$

Equation 3.4: Monthly crop water needs equation (mm)

where i is the month, CWN_i is the monthly aggregated crop water need (mm), ETc_i is the product of the monthly ET_{oi} and k_{ci} from the previous sections (mm), LR is the percentage of leaching requirements (%), eff_i is the monthly effective rainfall (mm) and awc_i the monthly available water content (mm).

Effective rainfall according to FAO reports [106], [112] is defined as the effective part of the rainwater which can be retained in the root zone and can be used by the plant. When rain falls on the soil surface, some of it infiltrates into the soil, some stagnates on the surface, while some flows over the surface as runoff. From all the water that infiltrates into the soil, some percolates below the root zone, while the rest remains stored in the root zone. Numerically, it could be defined as the total rainfall minus runoff, minus evaporation, minus deep percolation. Most common calculation models for the estimation of the effective rainfall include the simplified FAO empirical formulae reported in [106] which can only be applied in areas with a maximum slope of 4-5%, the potential evapotranspiration/precipitation ratio method [113], and the USDA-SCS method [112] which is implemented in widely used models for planning and management of irrigation as the FAO CROPWAT model [114], [115]. The USDA method is based on a soil water balance model where cumulative monthly precipitation, evapotranspiration and irrigation application depth are considered to be the three factors to influence the effectiveness of precipitation, lying on the assumption that the average monthly effective precipitation can exceed neither the total average monthly rainfall nor the total evapotranspiration. In this study, the $\mathrm{eff_i}$ is calculated on a monthly basis by the following empirical expression (Equation 3.5):

$$\boldsymbol{eff_i = f * (1.253 * P^{0.824} - 2.935) * 10^{0.001 * ET_p}}$$

Equation 3.5: ***Monthly effective rainfall equation (mm)***

where $\mathrm{eff_i}$ is the effective rainfall per month (mm), P is the total precipitation per month (mm), ET_p is the total crop evapotranspiration per month (mm) and f a correlation factor which depends on the depth of irrigation water application (dimensionless). The factor f equals 1.0 if the irrigation water application depth is 75 mm while for other application depths, the value of f equals (Equation 3.6):

$$\boldsymbol{f = \begin{cases} 0.133 + 0.201 * \ln D_a, & D_a < 75\ mm \\ 0.946 + 7.3 * 10^{-4} * D_a, & D_a \geq 75\ mm \end{cases}}$$

Equation 3.6: ***f correlation factor equation***

where D_a is the water application depth (mm) for the irrigation system design and assumed to be accounted for 1.0 for the purposes of this work.

Available water content (awc) or maximum soil water deficit is the maximum amount of water stored in the plant's root zone that is readily available for use [116]. The available water storage capacity dataset was retrieved from the Harmonized World Soil

Database version 1.2 [71] and was used in order to gain insights on the availability of water in the root zone. The HWSD dataset is classified into 7 classes where each one of them represents different depths AWSC per soil unit (mm/m). Typical rooting depth (RD in m) value of 0.9 m for maize is assumed from Nyvall (2015) report and is used in Equation 3.7 for the estimation of the total soil water storage (SWS) in mm:

$$\boldsymbol{SWS = RD * AWSC}$$

Equation 3.7: Soil water storage equation (mm)

To prevent plant water stress, an allowable depletion factor (DF as of %) is used to calculate the manageable allowable depletion and is usually accounted for 50 % [116]. The product of the soil water storage (Equation 3.7) multiplied by the above depletion factor leads to the estimation of monthly available water content (Equation 3.8):

$$\boldsymbol{awc_i = SWS_i * DF}$$

Equation 3.8: Monthly available water content equation (mm)

Peak crop water demand (PWD) and seasonal scheme water demand (SSWD)

One of the most important design criteria, is the maximum discharge (in m^3/d/ha or l/s/ha) required to satisfy the peak water requirements of the scheme. In other words, it is the rate at which the water must flow to meet the peak demand. Kay et al. (1992) highlight its significant importance for the design of the irrigation scheme, stating that it basically determines the size of the pump and the distribution system and eventually the operational power demand for the scheme. The pipes, canals or channels must be large enough to carry this discharge and the pump and power unit must be capable to deliver the discharge at the pressure required. In the same FAO training manual, it is stated that due to the high variation of the demand throughout the season, the peak requirement might be at least double the average daily water needs. The following equations retrieved from [75] (Equation 3.9-12) are applied for units conversion in a convenient way so that they are easily manipulated in the next steps:

$$\boldsymbol{Monthly\ crop\ water\ needs\ (m^3/ha) = CWN_i\ (mm) * \ 10}$$

Equation 3.9 : Monthly crop water needs equation (m^3/ha)

$$\boldsymbol{Average\ daily\ crop\ water\ needs\ (m^3/d/ha)} = \frac{\boldsymbol{Monthly\ crop\ water\ needs\ (m^3/ha)}}{\boldsymbol{30}}$$

Equation 3.10: Average daily crop water needs equation ($m^3/d/ha$)

$$\boldsymbol{Peak\ crop\ water\ requirements\ (m^3/d/ha)\ =\ Average\ daily\ crop\ water\ needs\ (m^3/d/ha)\ * 2}$$

Equation 3.11: Peak crop water requirements equation ($m^3/d/ha$)

A discharge in m^3 /d/ha is not a very convenient unit to use for design purposes. A more common unit is l/s/ha, calculated by:

$$\boldsymbol{Peak\ crop\ water\ requirement\ (l/s/ha)\ =\ Peak\ crop\ water\ requirements\ (m^3/d/ha)\ * 0.012}$$

Equation 3.12: Peak crop water requirements equation (l/s/ha)

The peak scheme water demand is the discharge in litres per second (l/s) required to meet the peak crop water needs, plus the losses which occur in field application and the distribution system. The overall loss is called irrigation efficiency and can be calculated by Equation 3.13. (See Table 3.2-3)

$$\boldsymbol{Irrigation\ efficiency\ (\%) = field\ application\ efficiency * distribution\ efficiency * 100}$$

Equation 3.13: Irrigation efficiency equation (%)

Peak water demand (PWD) can be calculated from:

$$\boldsymbol{Peak\ water\ demand\ (l/s/ha)}\ =\ \frac{\boldsymbol{Peak\ crop\ water\ requirements\ (l/s/ha)}}{\boldsymbol{Irrigation\ efficiency}}$$

Equation 3.14: Peak water demand equation (l/s/ha)

This discharge in l/s/ha is called duty. The value assumes that 1 ha of land is being irrigated and the system will be running 24 hours every day to meet the water demand. In practice the irrigated area may be more or less than 1 ha, and pumping systems do not normally operate 24 hours a day, and may only operate during a few hours throughout day. To take account of areas with various size (<> 1 ha) and for different hours of operation, the following equation is used:

$$\boldsymbol{Peak\ scheme\ water\ demand\ (l/s)} = \frac{\boldsymbol{Peak\ water\ demand\ (l/s/ha)\ *\ cropped\ area\ (ha)\ *\ 24}}{\boldsymbol{hours\ of\ operation\ (h)}}$$

Equation 3.15: Peak scheme water demand equation (l/s)

Finally, seasonal scheme water demand (m^3) is referred to as the amount/volume of water needed over a season, taking into account the water losses in the distribution system and in field application [75]. It also constitutes the main responsible parameter for the estimation of the electricity demand required for pumping over a season as it will be further explained in the following section.

$$\boldsymbol{Seasonal\ scheme\ water\ demand\ (m^3)} = \frac{\boldsymbol{Monthly\ crop\ water\ needs\ (m^3/ha)\ *\ cropped\ area\ (ha)}}{\boldsymbol{Irrigation\ efficiency}}$$

Equation 3.16: Seasonal scheme water demand equation (m^3)

3.4.4 Electricity demand modelling

Water abstraction from underground aquifers typically requires energy for pumping. Electrical energy or electricity (kWh) is expended when a unit volume (m^3) of water passes through a pump during its operation. According to Ahlfeld et al. (2011), energy consumption for pumping irrigation purposes can be expressed as the energy required to lift the water from the groundwater source, followed by the energy required to overcome friction in pipes, pumps, and other elements of the distribution system used for conveyance of the water across the land surface [117]. As shown in Figure 3.5, an essentially linear relationship seems to exist between the electricity intensity value for ground water pumping and the depth from which it is pumped at a specific pressure [118].

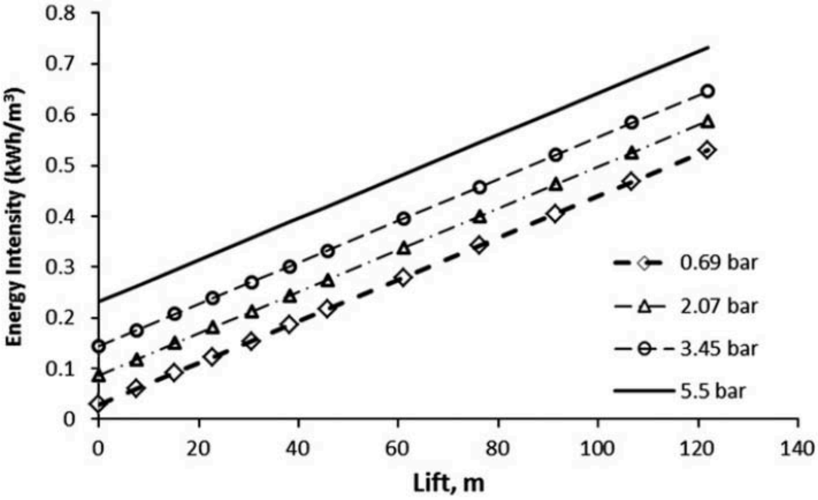


Figure 3.5: Electricity required for pumping 1 m3 of water as a function of lift with different discharge pressure requirements (Martin et al., 2011; Plappally et al., 2012)

It should be noted at this point, that the aforementioned lift depicted in Figure 3.5, does not represent the actual depth of the groundwater source, but it includes as well, the sum of the distance from the base of the pumping plant to the static ground water level and the ground water drawdown. Water drawdown, in simple terms, represents a potential cone-shaped depression in the aquifer ground water level that results from pumping in the long-term. The amount of energy consumed in lifting underground water is also highly affected by the location of the water source relative to the location of discharge [117], a significant parameter, which would not be easily accounted for without the use of GIS in the employed methodology.

In any case, nonetheless, a detailed review of the complete irrigation should be first taken into account, assessing the distribution and conveyance system and the explicit pump characteristics. Some of the general type of pumps used for drawing ground water are fixed speed, horizontal multi-stage centrifugal pumps, and submersible pumps [119]. Thus, the electricity demand depends on the efficiency of the pump, the pipeline

line and diameter, pipe material roughness or friction factor, and the volumetric demand for water. Electricity demand, E_D (kWh), can be therefore expressed as the following function:

$$\boldsymbol{E_D = f(d, V, P, t, f_l)}$$

Equation 3.17: Electricity demand function (adapted from Plappally et al., 2012)

where d is the distance through which the water is to be lifted, V is the required volumetric amount of water for pumping, P is the pressure requirement at the point of use, t is the time over which the water is pumped (assuming a constant head), and f_l is the friction loss along the distance d within the distribution system [117], [118].

In an attempt to interpret Figure 3.5 into a numerical example, a system with a pumping lift of 46 m and requiring a discharge pressure of 4 bar would consume around 0.367 kWh/m^3 of electricity. Similar energy consumption numbers have been reported in multiple case studies for pumping groundwater around the globe [120] [121], allowing for the translation to a value close to a specific groundwater pumping energy use of 0.004 kWh/m^3 per m of lifting [118] [122] (Figure 3.6). This figure is greater than what gravitational head alone would require; that being simply water density times gravity, or 0.00272 kWh/m^3 per m of lifting.

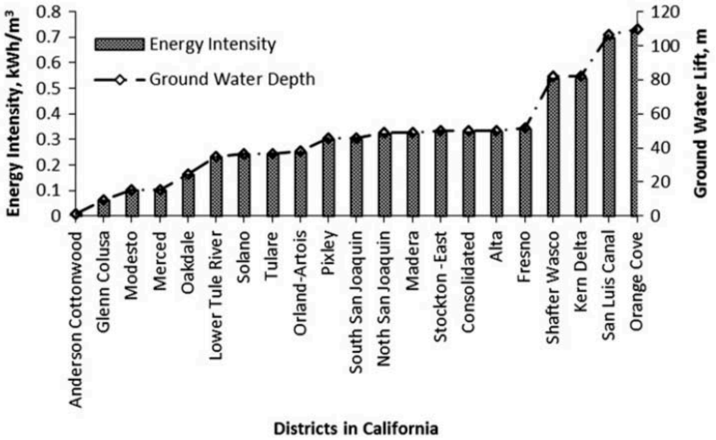


Figure 3.6: Groundwater energy intensity pumping values across California (Burt et al.,2008; adapted from Plappally et al., 2012)

Based on the above numbers and reports, the calculation of the electricity demand (ED_{gw} in kWh) for pumping water from groundwater resources, can be synopsized in the following equation:

$$\boldsymbol{ED_{gw}(kWh)_1} = \frac{\boldsymbol{Seasonal\ scheme\ water\ demand\ (m^3) * TDH_{gw}(m) * 0.00272}}{\boldsymbol{PP_{eff}}\ (\%)}$$

Equation 3.18: Electricity demand equation 1 (kWh)

where *Seasonal scheme water demand* (m^3) was defined in the previous section as the total volume of water required pumping over a selected season, TDH_{gw} *(mm)* represents the Total Dynamic Head which is basically a meter of pressure (Equation 3.19) and PP_{eff} *(%)* accounts for the Pumping Plant efficiency which is presented in Equation 3.20.

The calculation of the Total Dynamic Head is estimated using the following equation:

$$\boldsymbol{TDH_{gw}\ (m) = EL\ (m) + SL\ (m) + OP\ (m) + FL\ (m)}$$

Equation 3.19: Total Dynamic Head equation (m)

where *EL (m)* is the Elevation Lift which is the sum of the depth to the groundwater level of water and of the water table or drawdown, *SL (m)* expresses the Suction Lift which is assumed to be zero in groundwater vertical pumping, *OP (m)* stands for Operating Pressure and accounts for the pressure needed based on the application and conveyance system, and *FL (m)* expresses the Friction Losses in the piping systems.

The equation used for the estimation of the Pumping Plant efficiency is given below (Equation 3.20), while a detailed efficiency table for the overall irrigation pumping process can be found in the following sub-section in Table 3.4.

$$\begin{aligned}\boldsymbol{PP_{eff}}\ (\%) = {} & \boldsymbol{fuel\ efficiency * power\ unit\ efficiency * \ transmission\ efficiency} \\ & \boldsymbol{* pump\ efficiency\ x\ 100\%}\end{aligned}$$

Equation 3.20: Pumping plant efficiency equation (%)

The above electricity demand equation (3.18) is also validated and suggested, in a different form, by Kay et al. (1992) [75] in the corresponding FAO Training Manual, where the overall electricity need over a period of time is given by the equation:

$$\boldsymbol{ED_{gw}(kwh)_2 = \frac{Seasonal\ scheme\ water\ demand\ (m^3) * TDH_{gw}(m)}{367 * PPF_{eff}\ (\%)}}$$

Equation 3.21: Electricity demand equation 2 (kWh)

where the multiplier (1/367) is equal to 0.00272479564 as found in Equation 3.18.

Finally, the overall power demand for pumping water from the underground, is determined using the equation adapted from the aforementioned FAO manual [75]:

$$\boldsymbol{PD_{gw}(kW) = \frac{9.81 * discharge\ (m^3/s) * TDH_{gw}(m)}{PP_{eff}(\%)}}$$

Equation 3.22: Power demand equation (kW)

where *discharge* (m^3/s) is the *Peak scheme water demand (l/s)* (Equation 3.15) expressed in m^3/s.

A simple energy (EC) cost equation is finally formulated, taking into account the fuel consumption and the current or projected fuel or electricity grid price.

$$\boldsymbol{EC_{gw}(\$) = ED_{gw}(kWh) * fuel\ consumption\ (l/kWh) * cost\ per\ litre\ or\ energy\ unit\ consumed(\$/l\ or\ \$/kWh)}$$

Equation 3.23: Energy cost equation ($)

3.4.5 Scenarios under consideration

Baseline reference scenarios (Base year 2013)

In order to be able to comprehend and evaluate the dynamics of the output, as well as investigate how results change under different circumstances and parameters, a number of indicative scenarios was selected for further assessment. Within this context, the identification of scenarios which would allegedly be of the highest interest and impact for useful insights took place, having in mind estimated projections and potential situations that might arise in the future regarding irrigated agriculture. Because of the complex nature of the multi-dimensional approach described in the previous sections, the development of the scenarios was based on the intersection of three main categories: irrigation technology efficiencies and energy sources of irrigation water pumping, changes in irrigated land, and climate change.

The baseline reference scenario was calibrated and based on the most recent data from FAO AQUASTAT [45] for the year 2013. According to this, a total area of 4,120,269 ha of maize was planted in Tanzania, from which only 3 % being irrigated (124,000 ha). Out of the total area of 363,514 ha equipped for irrigation (2.3% of the total area cultivated) in Tanzania in the same year, the main types of irrigation schemes distinguished were: large irrigation schemes covering an area of 55,229 ha (15 %), usually managed by the Government, commercial farms and other external agencies, traditional irrigation schemes ran and initiated by the farmers themselves, with no external intervention, covering 117,000 ha (33 %), improved traditional irrigation schemes with the only difference of improved diversion structures for full control irrigation, drainage and flood protection, reaching up to 190,285 ha (52 %), and finally spate irrigation with only 1,000 ha (1 %), which basically use flash flood irrigation when available. With regards to the methods of irrigation, there are mainly three most commonly used, distinguished into surface (SU), sprinkler (SP), and trickle or drip (DR) irrigation (Table 3.2). Breaking them down, SU is the most common and less expensive method used for traditional, small schemes, and involves flooding water across the soil surface so that it can be infiltrated below the root zone and be used by the cultivated crop. It generally requires less energy than the other methods, mainly because of the low dynamic head required for distribution across the farm. SP irrigation is involves distributing water in pipes under pressure and spraying it into the air so that it falls to the soil surface like natural rainfall. Compared to SU, SP systems are generally more efficient, but pressure (or head) play an important for the successful operation, making them more energy intensive. Finally, DR irrigation systems involve dripping water onto the soil at a very low flow rate from small diameter, usually plastic, pipes with outlets, called emitters. In such systems, water is applied really close to the root of the crops so that only those parts are wetter. DR irrigation is supposed to be the most efficient method of applying water to the crops, requiring less operating pressure that SP, and therefore, less energy to operate successfully.

Table 3.2: Typical values of irrigation methods application efficiencies (%) (adapted from FAO, 1992)

Irrigation method	Application efficiency (%)	Source
SU	60	[75]
SP	75	
DR	90	

For the water to be distributed from the pumping location across the soil surface, as well as taking into account the vertical distance to the groundwater level, different methods of distribution are employed. Earth and lined canals, and most often pipes nowadays, are used and losses may occur from the channels through seepage, evaporation, mismanagement and malfunction of the distribution systems. For design purposes and the development of potential scenarios, Table 3.3 below indicates indicative values of distribution efficiencies for the aforementioned structures.

Table 3.3: Typical values of distribution methods efficiencies (%) (adapted from FAO, 1992)

Scheme size (ha)	**Distribution efficiency (%)**			**Source**
	Earth canals	**Lined canals**	**Pipes**	
Large (> 2000)	60 - 80	95	95	[75]
Medium (200-2000)	70 - 85	95	95	
Small (< 200)	80 - 90	95	95	

With regards to the pump type and the source of energy, compatible pumps are usually driven by a power unit such as a diesel or petrol engine, or an electric motor. In the spotlight of sustainable development and the holistic integration of renewable energy sources in the electrification mix, solar and wind power are also used to provide the power source for pumps to operate; however, they are out of the scope of this study. The primary concern in this piece of work, and therefore the development of the corresponding scenarios, is the use of diesel (DP) and electric (EP) pumps. Pumps are classified into axial flow, centrifugal and mixed flow, accompanied by different characteristics regarding the pump size (diameter), discharge rates and efficiency of operation [75], [119]. It is really important to note that the study of the optimal pump selection and the differences among different kinds of pumps may go in very deep detail and have significant impacts on the efficiency of the overall irrigation system; however due to their complex nature, the scenarios are limited to their efficiency parameter only. The efficiency of the components of the pumping plant are distinguished into fuel efficiency (%), power unit efficiency (%), transmission efficiency (%), and pump efficiency (%), as seen in Equation 3.20. The overall pumping plant efficiency scenarios assumed for this work can be found in the following table (Table 3.4):

Table 3.4: Typical values of pumping plant efficiencies (%) (adapted from FAO, 1992)

Pump type		Fuel efficiency (%)	Power unit efficiency (%)	Transmission efficiency (%)	Pump efficiency (%)	Pumping plant efficiency (%)	Source
DP	Low-efficiency (WC)	90	30	90	40	10	[75], [119], [123]
	High-efficiency (BC)	100	40	100	80	32	
EP	Low-efficiency (WC)	90	75	90	40	25	
	High-efficiency (BC)	100	85	100	80	70	

Energy costs, and more specifically, grid electricity price (US$/kWh) and diesel pump prices (US$/l) are assumed to be the same across the whole country at a standard level of 0.11 US$/kWh and 1.9 US$/l respectively for 2013. Projected estimations for the following scenarios are retrieved from TEMBA-OSeMOSYS, a tool that describes the least cost power generation mix based on the net present value [124]. The grid electricity cost is estimated to be 0.062 US$/kWh, while the diesel pump price 0.81 US$/l in 2030 [24].

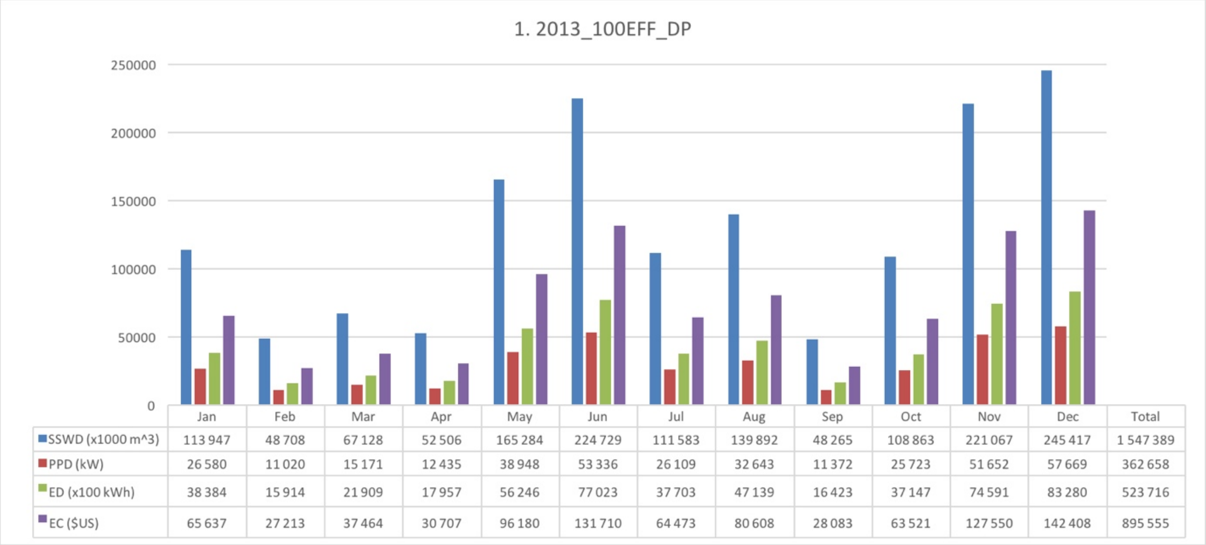
Projected future scenarios (End year 2030)

Based on the really low share of irrigated area over total cultivated area in the country of Tanzania (only 2-3 % of the total area is equipped for irrigation) and the irrigation development potential reported in the country's NIMP (2002), relevant scenarios are developed on the axis of changes in irrigated land. The irrigated land could increase substantially over the next years as the agricultural sector sees increasing investments from both public and private sector, as well as the Government's shift towards policies and development plans aiming at agriculture modernization, discussed in Chapter 2. Two scenarios are considered for the above reasons; a moderate development scenario following the past trends and patterns of irrigated land as seen in Graph 2.6 of Chapter 2 (estimated at an annual growth of 6.7 %), and an optimistic scenario trying to keep up and meet the high potential target of the total 2.3 million which could be potentially irrigated as reported in [51]. Assuming that irrigated maize will continue to comprise the 40 % of the irrigated land as in 2013, an average annual rate of 12.5 % is estimated in order to reach a total area of 920,000 ha by 2030.

4. Results

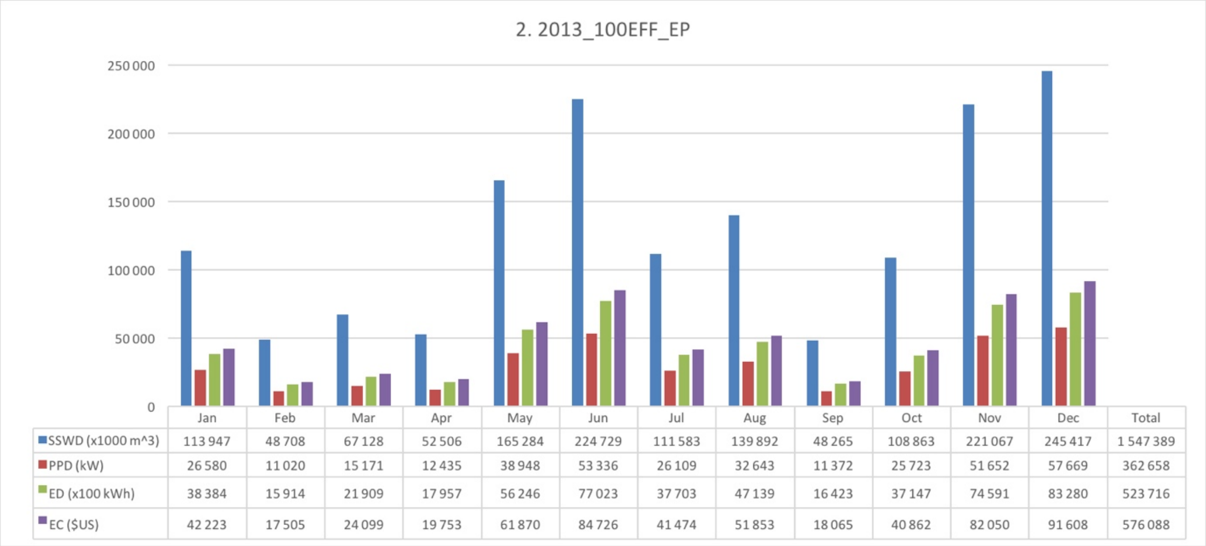
4.1 Baseline reference scenarios results

In total, 14 scenarios (Graph 4.1-14) were developed for the baseline scenario of the reference year 2013. The output of these scenarios is presented as aggregated tables representing monthly values for the water requirements (m^3), power demand (kW), electricity demand (kWh) and energy cost (US$). The parameterization of the aforementioned scenarios lies on the assumptions presented in the previous chapter, accounting for the significant application and distribution efficiencies of typical irrigation technologies, as well as for energy source and efficiencies of pumping plants.



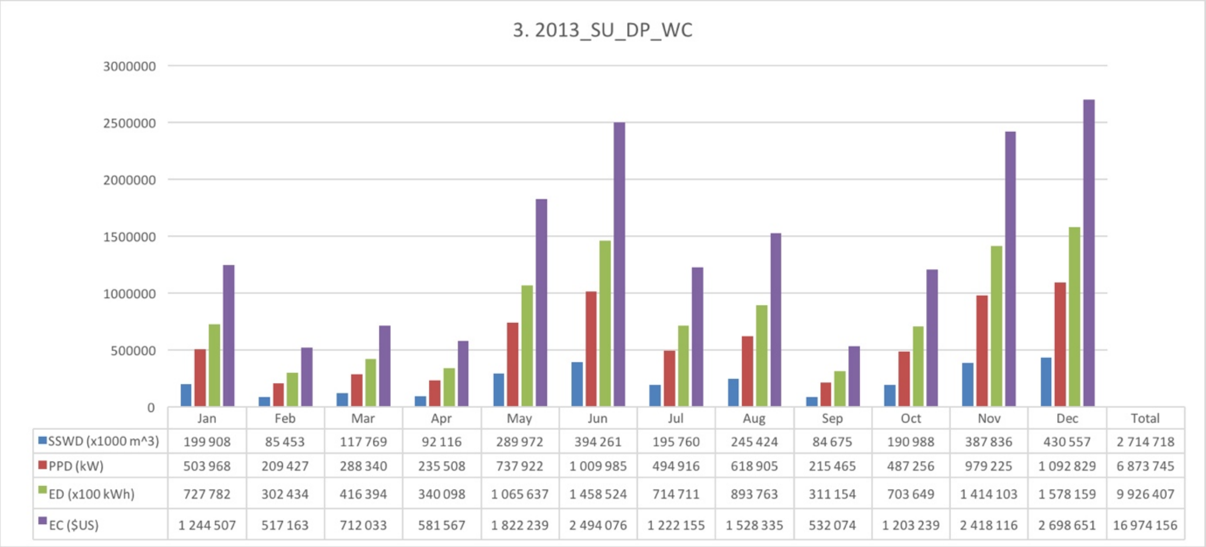
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
🟦 SSWD (x1000 m^3)	113 947	48 708	67 128	52 506	165 284	224 729	111 583	139 892	48 265	108 863	221 067	245 417	1 547 389
🟥 PPD (kW)	26 580	11 020	15 171	12 435	38 948	53 336	26 109	32 643	11 372	25 723	51 652	57 669	362 658
🟩 ED (x100 kWh)	38 384	15 914	21 909	17 957	56 246	77 023	37 703	47 139	16 423	37 147	74 591	83 280	523 716
🟪 EC ($US)	65 637	27 213	37 464	30 707	96 180	131 710	64 473	80 608	28 083	63 521	127 550	142 408	895 555

Graph 4.1: 1. 2013_100EFF_DP scenario



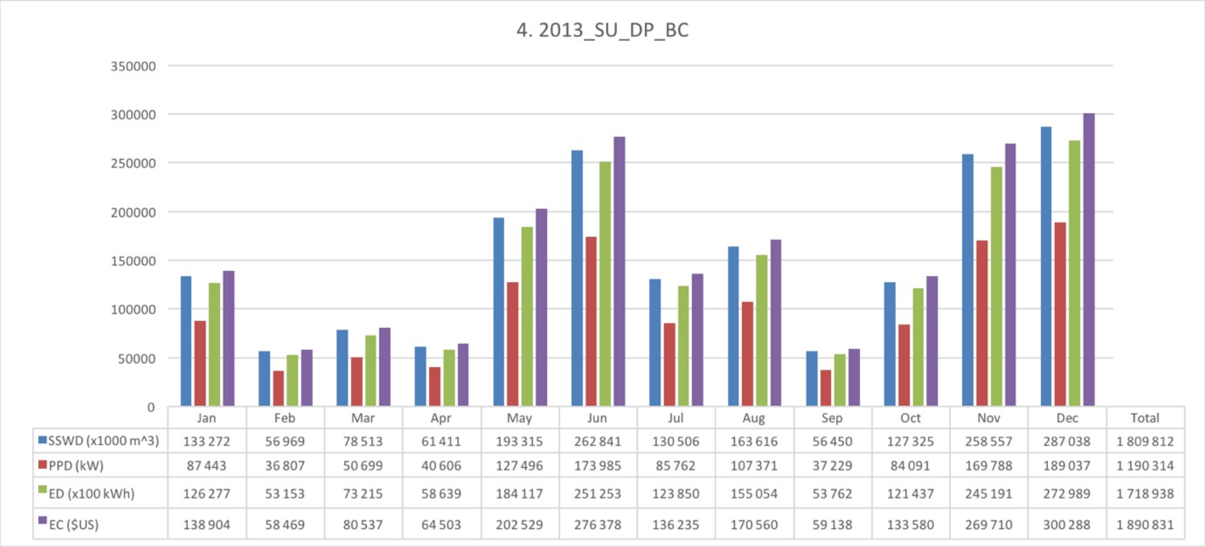
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
🟦 SSWD (x1000 m^3)	113 947	48 708	67 128	52 506	165 284	224 729	111 583	139 892	48 265	108 863	221 067	245 417	1 547 389
🟥 PPD (kW)	26 580	11 020	15 171	12 435	38 948	53 336	26 109	32 643	11 372	25 723	51 652	57 669	362 658
🟩 ED (x100 kWh)	38 384	15 914	21 909	17 957	56 246	77 023	37 703	47 139	16 423	37 147	74 591	83 280	523 716
🟪 EC ($US)	42 223	17 505	24 099	19 753	61 870	84 726	41 474	51 853	18 065	40 862	82 050	91 608	576 088

Graph 4.2: 2. 2013_100EFF_EP scenario



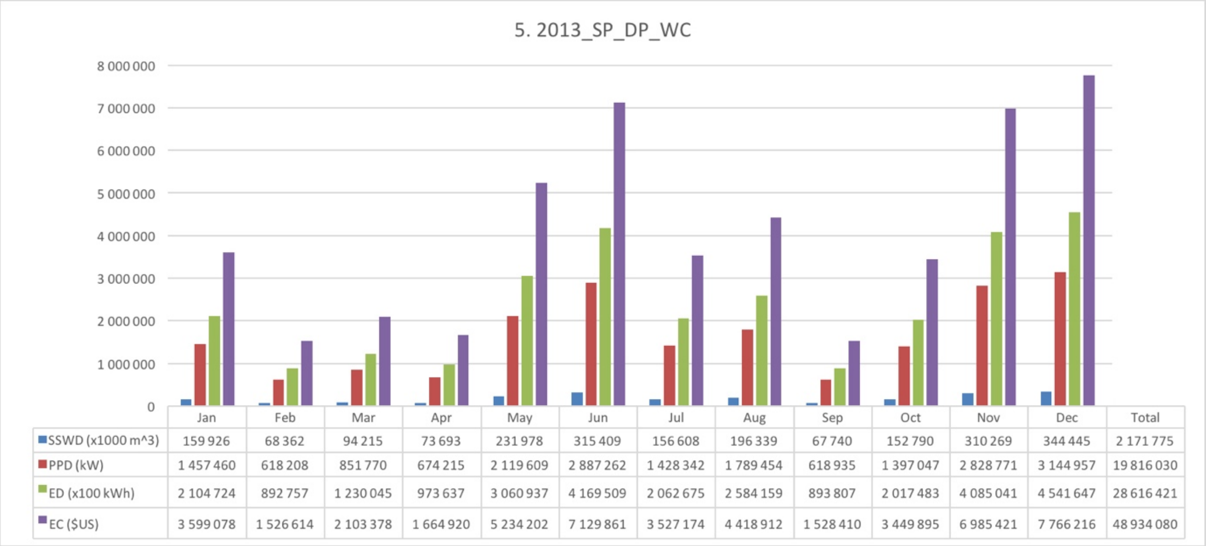
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
🟦SSWD (x1000 m^3)	199 908	85 453	117 769	92 116	289 972	394 261	195 760	245 424	84 675	190 988	387 836	430 557	2 714 718
🟥PPD (kW)	503 968	209 427	288 340	235 508	737 922	1 009 985	494 916	618 905	215 465	487 256	979 225	1 092 829	6 873 745
🟩ED (x100 kWh)	727 782	302 434	416 394	340 098	1 065 637	1 458 524	714 711	893 763	311 154	703 649	1 414 103	1 578 159	9 926 407
🟪EC ($US)	1 244 507	517 163	712 033	581 567	1 822 239	2 494 076	1 222 155	1 528 335	532 074	1 203 239	2 418 116	2 698 651	16 974 156

Graph 4.3: 3. 2013_ SU_ DP_ WC scenario



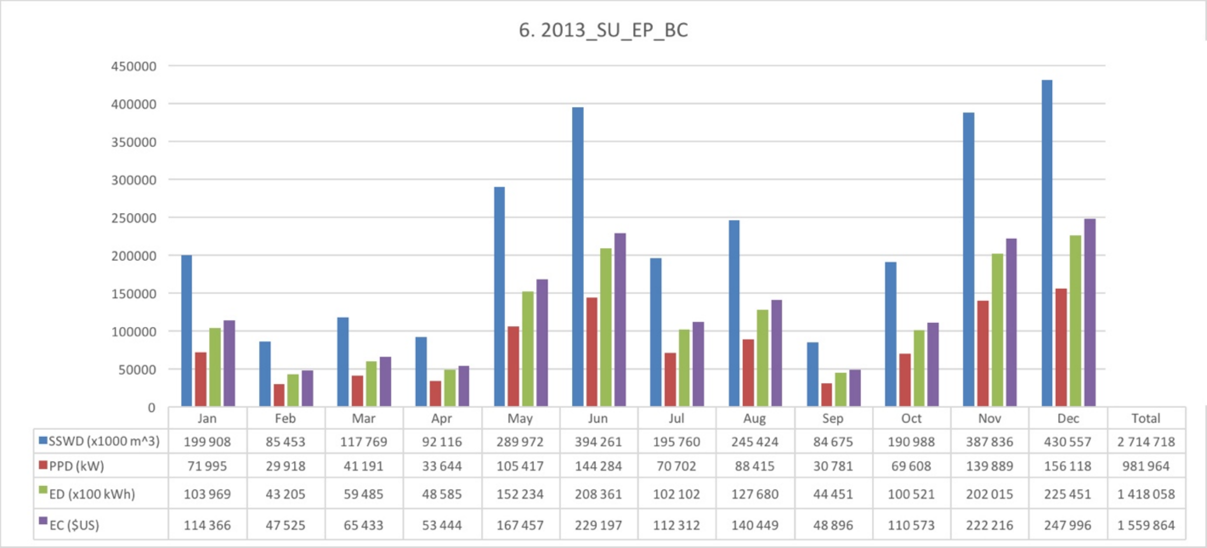
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
🟦SSWD (x1000 m^3)	133 272	56 969	78 513	61 411	193 315	262 841	130 506	163 616	56 450	127 325	258 557	287 038	1 809 812
🟥PPD (kW)	87 443	36 807	50 699	40 606	127 496	173 985	85 762	107 371	37 229	84 091	169 788	189 037	1 190 314
🟩ED (x100 kWh)	126 277	53 153	73 215	58 639	184 117	251 253	123 850	155 054	53 762	121 437	245 191	272 989	1 718 938
🟪EC ($US)	138 904	58 469	80 537	64 503	202 529	276 378	136 235	170 560	59 138	133 580	269 710	300 288	1 890 831

Graph 4.4: 4. 2013_ SU_ DP_ BC scenario



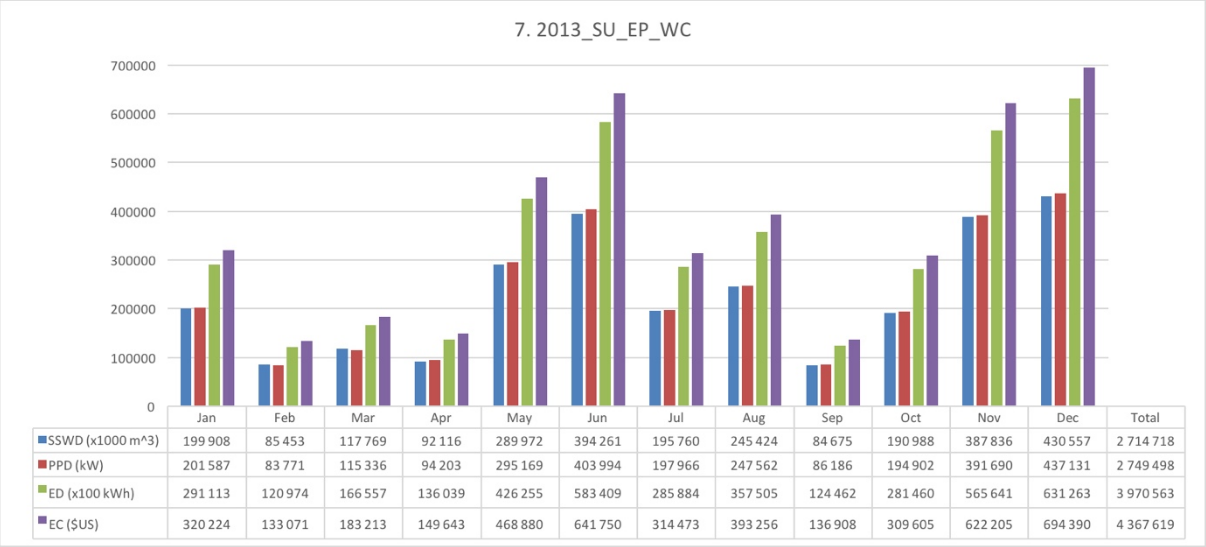
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
🟦SSWD (x1000 m^3)	159 926	68 362	94 215	73 693	231 978	315 409	156 608	196 339	67 740	152 790	310 269	344 445	2 171 775
🟥PPD (kW)	1 457 460	618 208	851 770	674 215	2 119 609	2 887 262	1 428 342	1 789 454	618 935	1 397 047	2 828 771	3 144 957	19 816 030
🟩ED (x100 kWh)	2 104 724	892 757	1 230 045	973 637	3 060 937	4 169 509	2 062 675	2 584 159	893 807	2 017 483	4 085 041	4 541 647	28 616 421
🟪EC ($US)	3 599 078	1 526 614	2 103 378	1 664 920	5 234 202	7 129 861	3 527 174	4 418 912	1 528 410	3 449 895	6 985 421	7 766 216	48 934 080

Graph 4.5: 5. 2013_ SP_ DP_ WC scenario



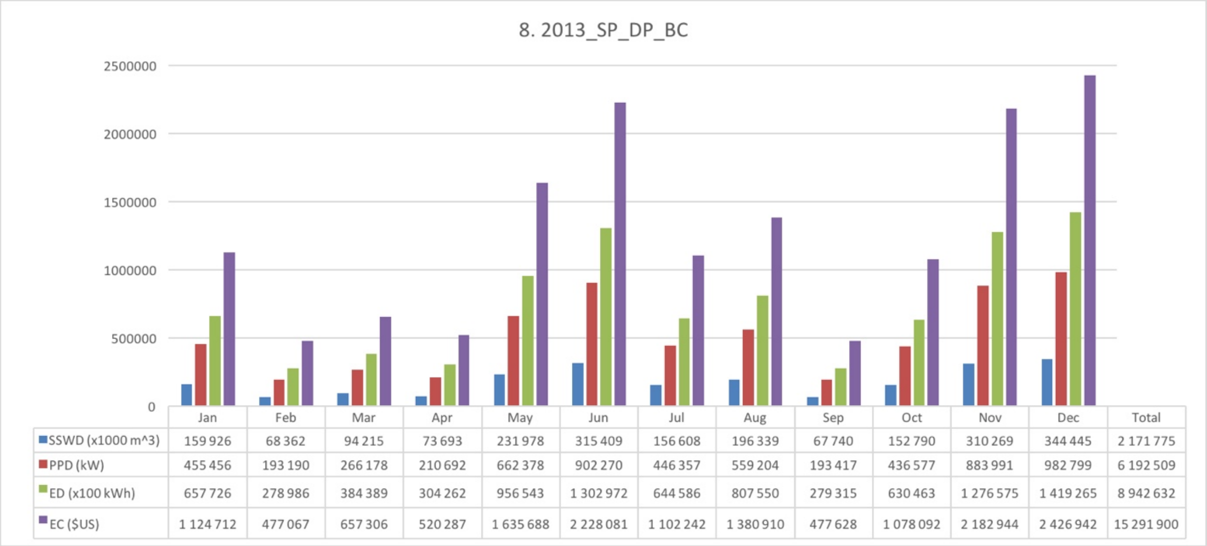
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
🟦 SSWD (x1000 m^3)	199 908	85 453	117 769	92 116	289 972	394 261	195 760	245 424	84 675	190 988	387 836	430 557	2 714 718
🟥 PPD (kW)	71 995	29 918	41 191	33 644	105 417	144 284	70 702	88 415	30 781	69 608	139 889	156 118	981 964
🟩 ED (x100 kWh)	103 969	43 205	59 485	48 585	152 234	208 361	102 102	127 680	44 451	100 521	202 015	225 451	1 418 058
🟪 EC ($US)	114 366	47 525	65 433	53 444	167 457	229 197	112 312	140 449	48 896	110 573	222 216	247 996	1 559 864

Graph 4.6: 6. 2013_SU_EP_BC scenario



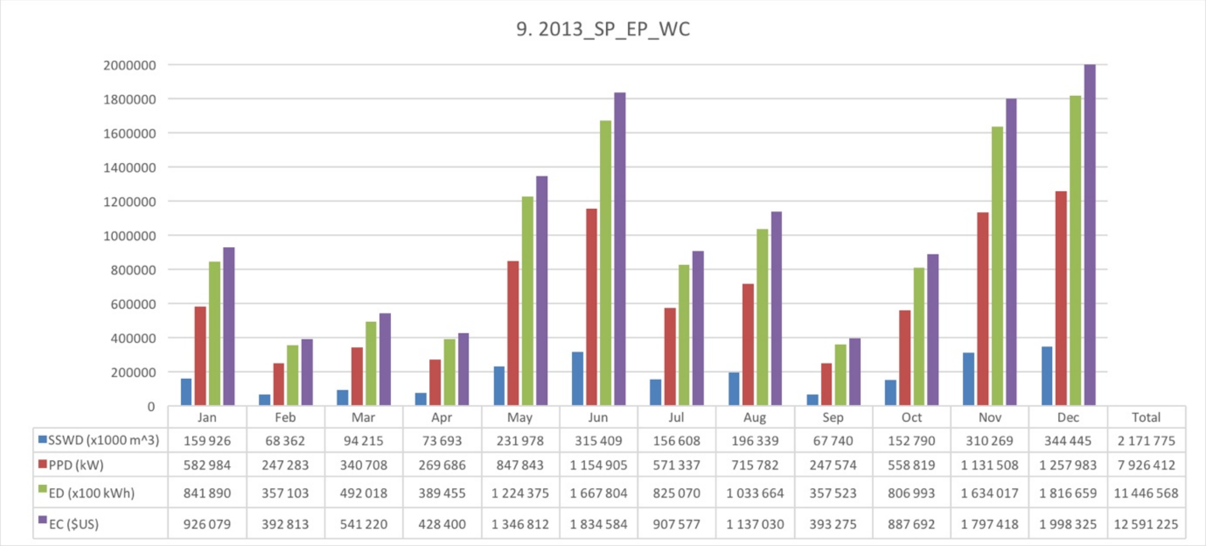
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
🟦 SSWD (x1000 m^3)	199 908	85 453	117 769	92 116	289 972	394 261	195 760	245 424	84 675	190 988	387 836	430 557	2 714 718
🟥 PPD (kW)	201 587	83 771	115 336	94 203	295 169	403 994	197 966	247 562	86 186	194 902	391 690	437 131	2 749 498
🟩 ED (x100 kWh)	291 113	120 974	166 557	136 039	426 255	583 409	285 884	357 505	124 462	281 460	565 641	631 263	3 970 563
🟪 EC ($US)	320 224	133 071	183 213	149 643	468 880	641 750	314 473	393 256	136 908	309 605	622 205	694 390	4 367 619

Graph 4.7: 7. 2013_SU_EP_WC scenario



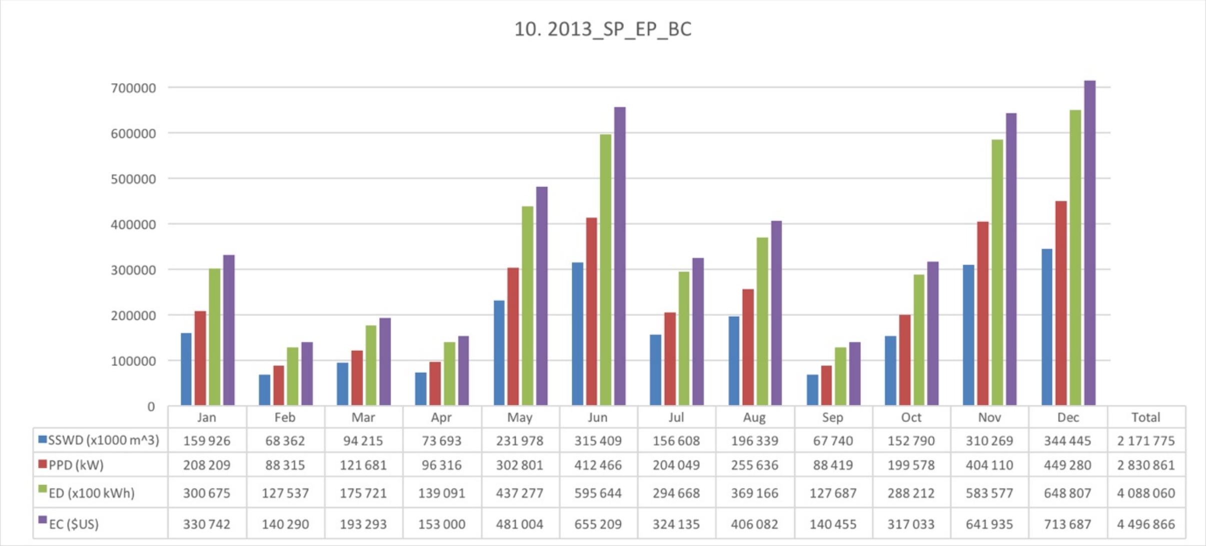
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
🟦 SSWD (x1000 m^3)	159 926	68 362	94 215	73 693	231 978	315 409	156 608	196 339	67 740	152 790	310 269	344 445	2 171 775
🟥 PPD (kW)	455 456	193 190	266 178	210 692	662 378	902 270	446 357	559 204	193 417	436 577	883 991	982 799	6 192 509
🟩 ED (x100 kWh)	657 726	278 986	384 389	304 262	956 543	1 302 972	644 586	807 550	279 315	630 463	1 276 575	1 419 265	8 942 632
🟪 EC ($US)	1 124 712	477 067	657 306	520 287	1 635 688	2 228 081	1 102 242	1 380 910	477 628	1 078 092	2 182 944	2 426 942	15 291 900

Graph 4.8: 8. 2013_SP_DP_BC scenario



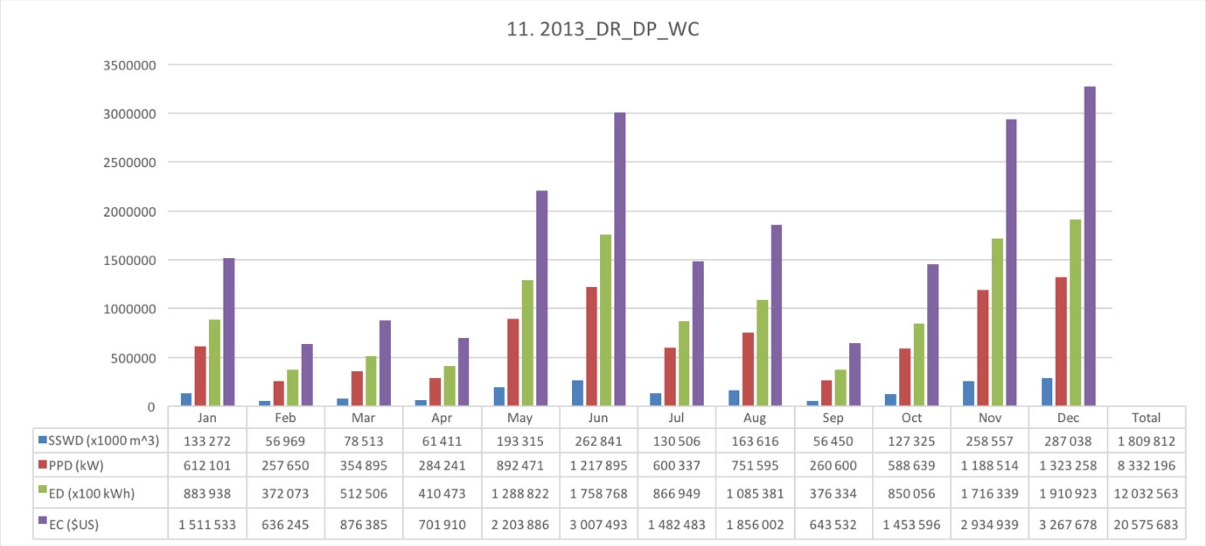
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
🟦SSWD (x1000 m^3)	159 926	68 362	94 215	73 693	231 978	315 409	156 608	196 339	67 740	152 790	310 269	344 445	2 171 775
🟥PPD (kW)	582 984	247 283	340 708	269 686	847 843	1 154 905	571 337	715 782	247 574	558 819	1 131 508	1 257 983	7 926 412
🟩ED (x100 kWh)	841 890	357 103	492 018	389 455	1 224 375	1 667 804	825 070	1 033 664	357 523	806 993	1 634 017	1 816 659	11 446 568
🟪EC ($US)	926 079	392 813	541 220	428 400	1 346 812	1 834 584	907 577	1 137 030	393 275	887 692	1 797 418	1 998 325	12 591 225

Graph 4.9: 9. 2013_ SP_ EP_ WC scenario



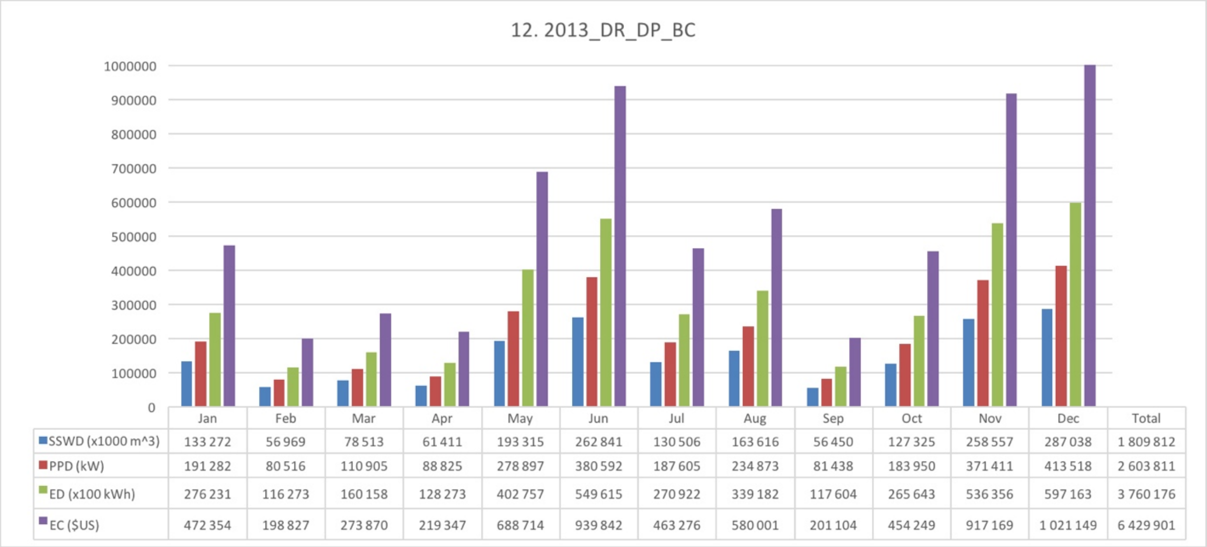
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
🟦SSWD (x1000 m^3)	159 926	68 362	94 215	73 693	231 978	315 409	156 608	196 339	67 740	152 790	310 269	344 445	2 171 775
🟥PPD (kW)	208 209	88 315	121 681	96 316	302 801	412 466	204 049	255 636	88 419	199 578	404 110	449 280	2 830 861
🟩ED (x100 kWh)	300 675	127 537	175 721	139 091	437 277	595 644	294 668	369 166	127 687	288 212	583 577	648 807	4 088 060
🟪EC ($US)	330 742	140 290	193 293	153 000	481 004	655 209	324 135	406 082	140 455	317 033	641 935	713 687	4 496 866

Graph 4.10: 10. 2013_ SP_ EP_ BC scenario



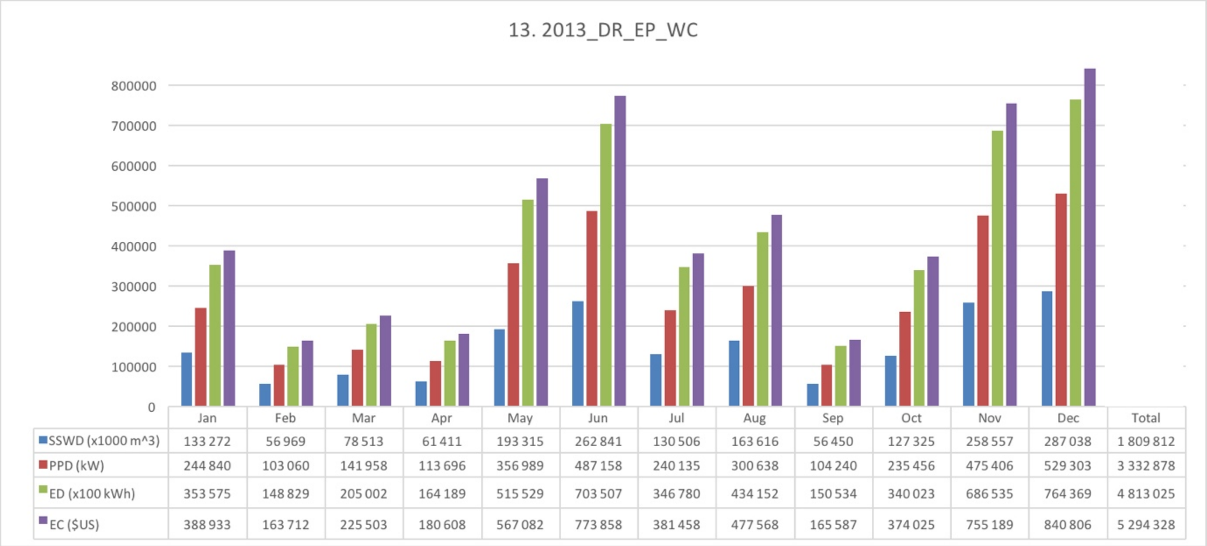
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
🟦SSWD (x1000 m^3)	133 272	56 969	78 513	61 411	193 315	262 841	130 506	163 616	56 450	127 325	258 557	287 038	1 809 812
🟥PPD (kW)	612 101	257 650	354 895	284 241	892 471	1 217 895	600 337	751 595	260 600	588 639	1 188 514	1 323 258	8 332 196
🟩ED (x100 kWh)	883 938	372 073	512 506	410 473	1 288 822	1 758 768	866 949	1 085 381	376 334	850 056	1 716 339	1 910 923	12 032 563
🟪EC ($US)	1 511 533	636 245	876 385	701 910	2 203 886	3 007 493	1 482 483	1 856 002	643 532	1 453 596	2 934 939	3 267 678	20 575 683

Graph 4.11: 11. 2013_ DR_ DP_ WC scenario



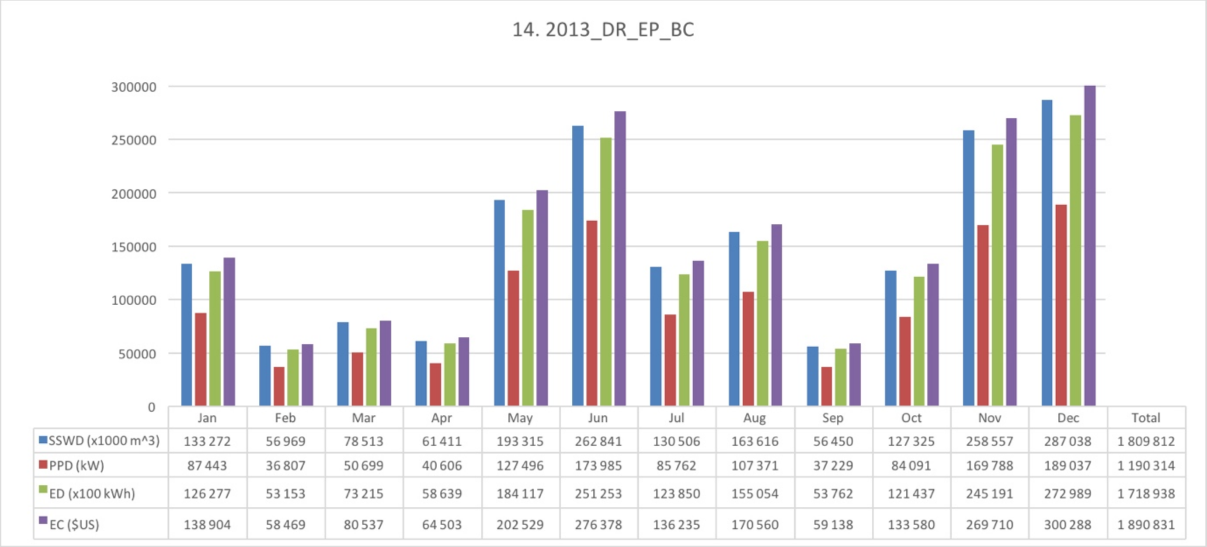
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
🟦 SSWD (x1000 m^3)	133 272	56 969	78 513	61 411	193 315	262 841	130 506	163 616	56 450	127 325	258 557	287 038	1 809 812
🟥 PPD (kW)	191 282	80 516	110 905	88 825	278 897	380 592	187 605	234 873	81 438	183 950	371 411	413 518	2 603 811
🟩 ED (x100 kWh)	276 231	116 273	160 158	128 273	402 757	549 615	270 922	339 182	117 604	265 643	536 356	597 163	3 760 176
🟪 EC ($US)	472 354	198 827	273 870	219 347	688 714	939 842	463 276	580 001	201 104	454 249	917 169	1 021 149	6 429 901

Graph 4.12: 12. 2013_ DR_ DP_ BC scenario



	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
🟦 SSWD (x1000 m^3)	133 272	56 969	78 513	61 411	193 315	262 841	130 506	163 616	56 450	127 325	258 557	287 038	1 809 812
🟥 PPD (kW)	244 840	103 060	141 958	113 696	356 989	487 158	240 135	300 638	104 240	235 456	475 406	529 303	3 332 878
🟩 ED (x100 kWh)	353 575	148 829	205 002	164 189	515 529	703 507	346 780	434 152	150 534	340 023	686 535	764 369	4 813 025
🟪 EC ($US)	388 933	163 712	225 503	180 608	567 082	773 858	381 458	477 568	165 587	374 025	755 189	840 806	5 294 328

Graph 4.13: 13. 2013_ DR_ EP_ WC scenario



	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
🟦 SSWD (x1000 m^3)	133 272	56 969	78 513	61 411	193 315	262 841	130 506	163 616	56 450	127 325	258 557	287 038	1 809 812
🟥 PPD (kW)	87 443	36 807	50 699	40 606	127 496	173 985	85 762	107 371	37 229	84 091	169 788	189 037	1 190 314
🟩 ED (x100 kWh)	126 277	53 153	73 215	58 639	184 117	251 253	123 850	155 054	53 762	121 437	245 191	272 989	1 718 938
🟪 EC ($US)	138 904	58 469	80 537	64 503	202 529	276 378	136 235	170 560	59 138	133 580	269 710	300 288	1 890 831

Graph 4.14: 14. 2013_ DR_ EP_ BC scenario

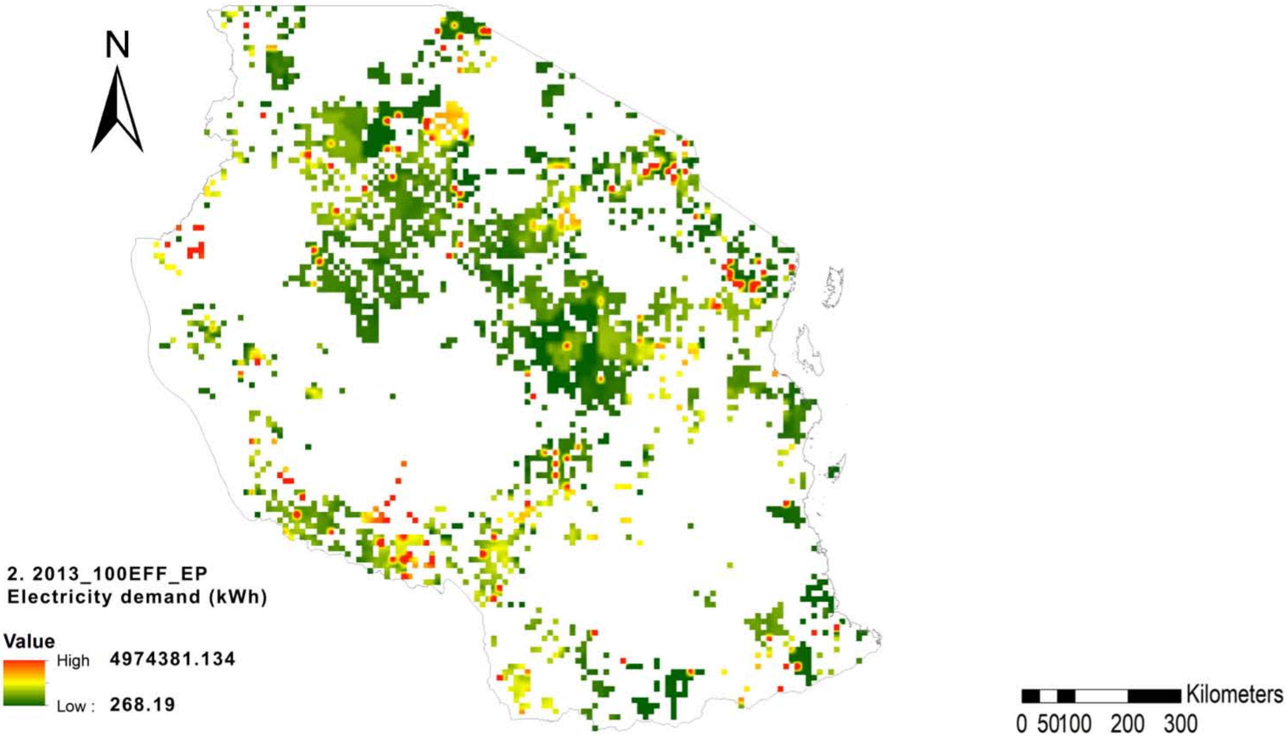


Figure 4.1: Aggregated heat map of ED - SC2

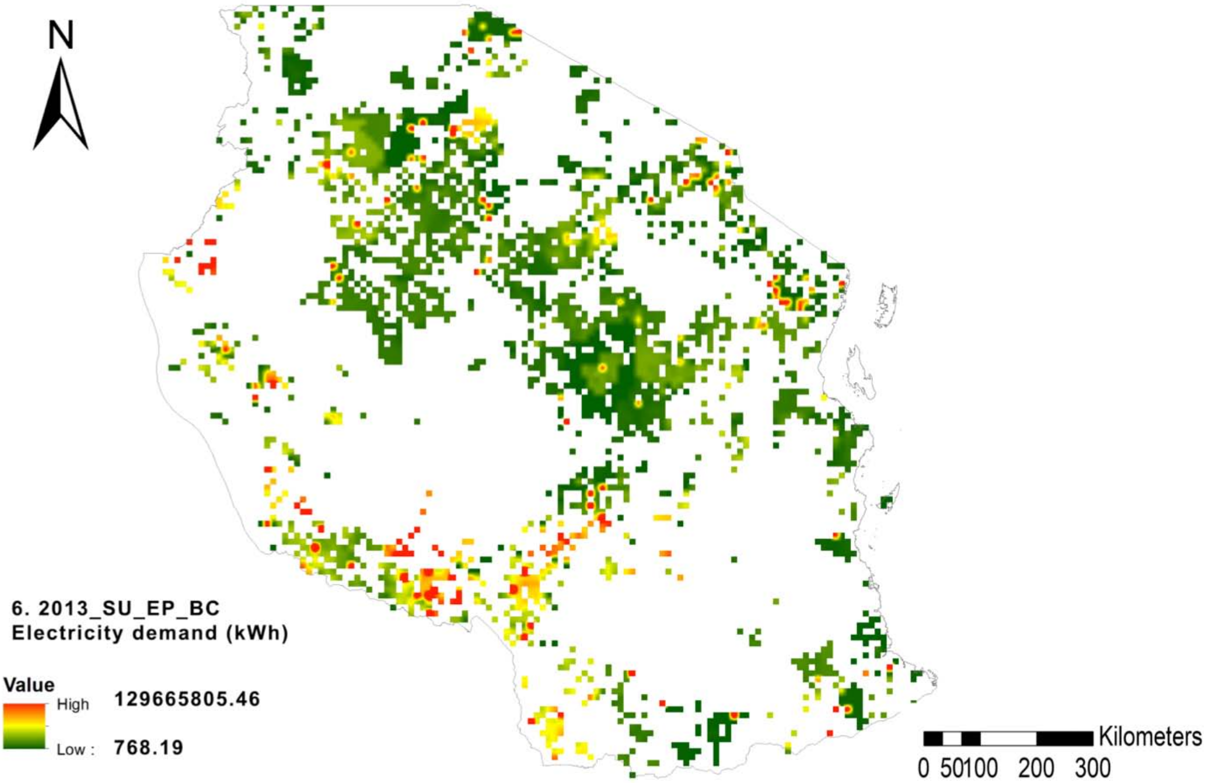


Figure 4.2: Aggregated heat map of ED - SC6

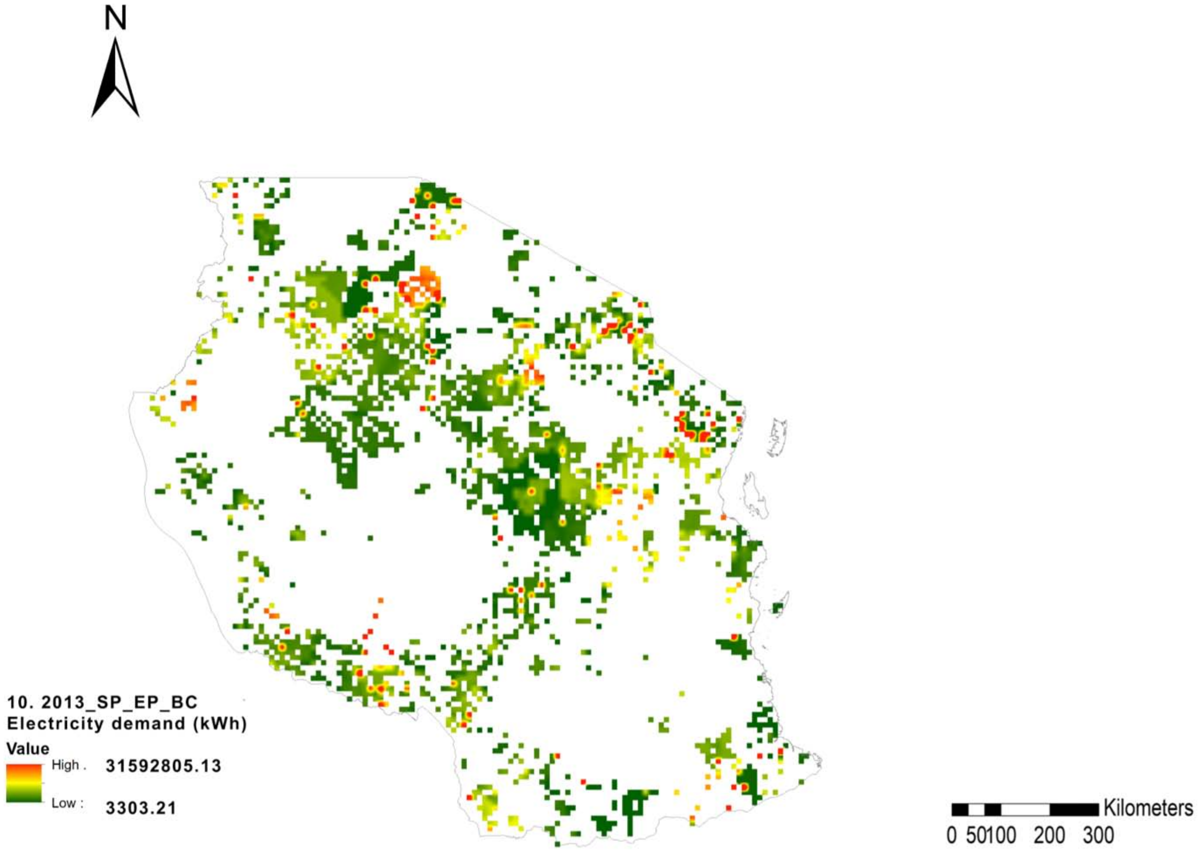


Figure 4.3: Aggregated heat map of ED - SC10

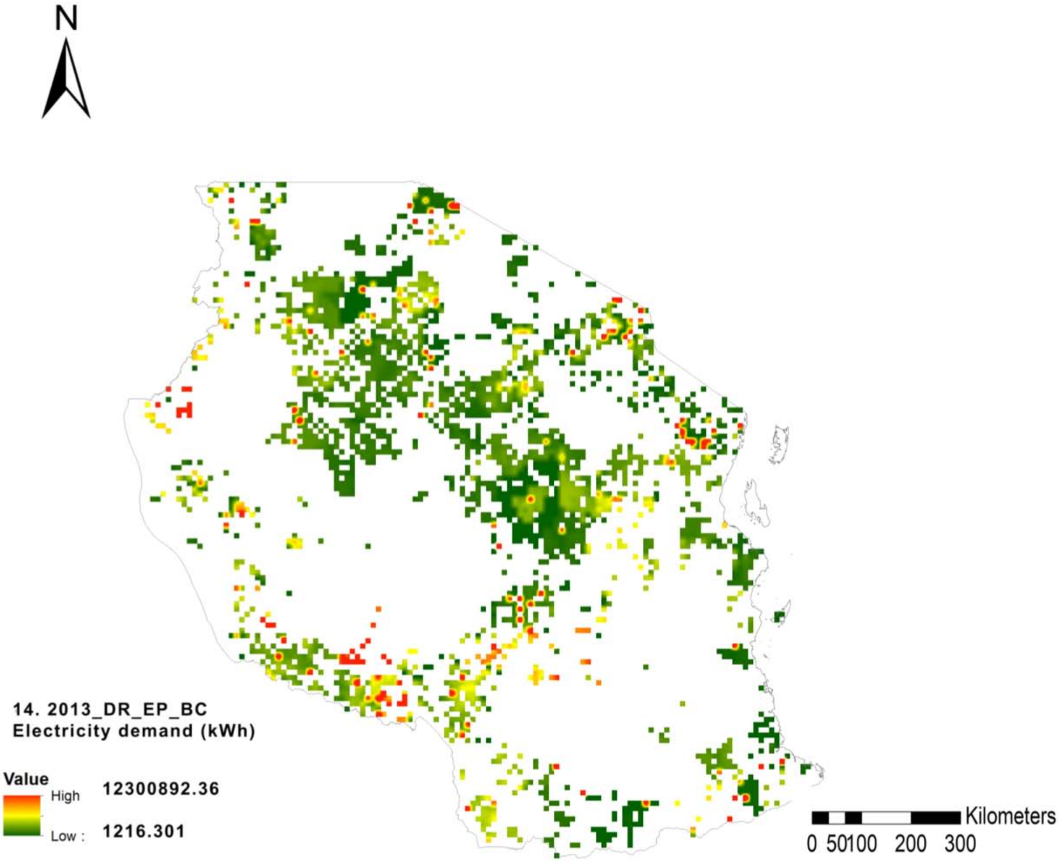


Figure 4.4: Aggregated heat map of ED - SC14

Overall, despite the significant changes in terms of the efficiencies applied, there is, as expected, a linear relationship between the total volume of water required and the energy demand for the depicted irrigated areas. Water and energy requirements for total irrigated land of 124,000 ha maize in Tanzania were subjected to different scenarios, and indicative developed heat maps are presented in Figures 4.1-4, in order to showcase the output features of the developed methodology. Electrically-driven pump scenarios seem to be less energy intensive than diesel engine pump scenarios. This is, generally, the case as electric pumps operate much more efficiently than diesel ones. The total aggregated electricity demand in an annual base, for the reference year of 2013, seems to present a significant range; from 170 GWh for DR irrigation powered by electric pumps, up to 28 TWh for the least efficient worst case scenario of SP irrigation powered by diesel pumps. Despite the relatively low water demand for the SP scenarios, the energy input is exponentially increasing due to the high operating and application pressure required, constituting those scenarios energy intensive compared to the rest, and therefore out of consideration. SU scenarios seem to perform well, with relatively low energy inputs due to the very low pressure levels required in order to convey and apply the abstracted water across the soil surface. SU irrigation methods applied may look promising to be accounted for, however field experience indicates that they are quite difficult to be managed efficiently, especially when it comes to large irrigation schemes. Unlike electricity, on the side of the volumetric demand of water, SU scenarios perform the worst, with water needs required for abstraction reaching up to 2.7 km^3, while SP and DR scenarios performance ranges between 1.8 and 2.1 km^3. It is interesting to point out, that the irrigation water withdrawal for maize in Tanzania in 2013 (FAO), was estimated at 2.7 km^3 in order to cover the crop water needs of 1.55 km^3 in total, for the reported year. Drawing on the advantages of GIS, heat maps or attribute maps are easy to be developed, as can be seen from the indicative maps of electricity demand. Higher inputs of energy are spotted in the north-east and south-west areas of the country, where the bimodal administrative regions happen to be located. The high water and energy needs are also explained during the months of May-June and November-December, since during these seasons of the agricultural calendar, Msimu and Vuli rains overlap within the dual rainfall pattern of the country.

4.2 Projected future scenarios results

Two additional scenarios were developed taking into account changes, and more specifically expansion, in the irrigated area under cultivation. A moderate (6.7 %) and an optimistic (12.5 %) development scenarios were employed in order to reach a potentially irrigated area of 373,437 ha and 920,000 ha of maize, respectively. From the baseline scenarios, scenario number 14 was selected as the optimal, thus the projected future scenarios are assumed to be irrigated under improved drip irrigation technology, powered exclusively by electric pumps. As estimated from the following maps, the aggregated volume of water withdrawal increased from 1.8 km^3 to 5.42 km^3 for the moderate development scenario, reaching up to 13.3 km^3 for the optimistic scenario. In terms of electricity needs, demand increased to 518 GWh for the moderate scenario, followed by the optimistic one which was estimated to almost 1.3 TWh.

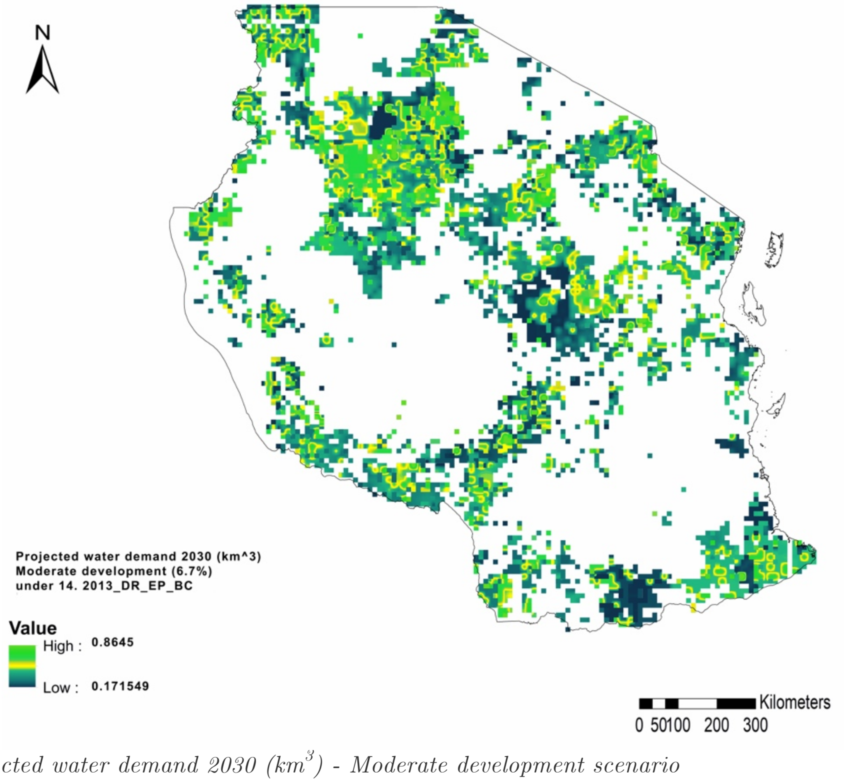


Figure 4.5: Projected water demand 2030 (km^3) - Moderate development scenario

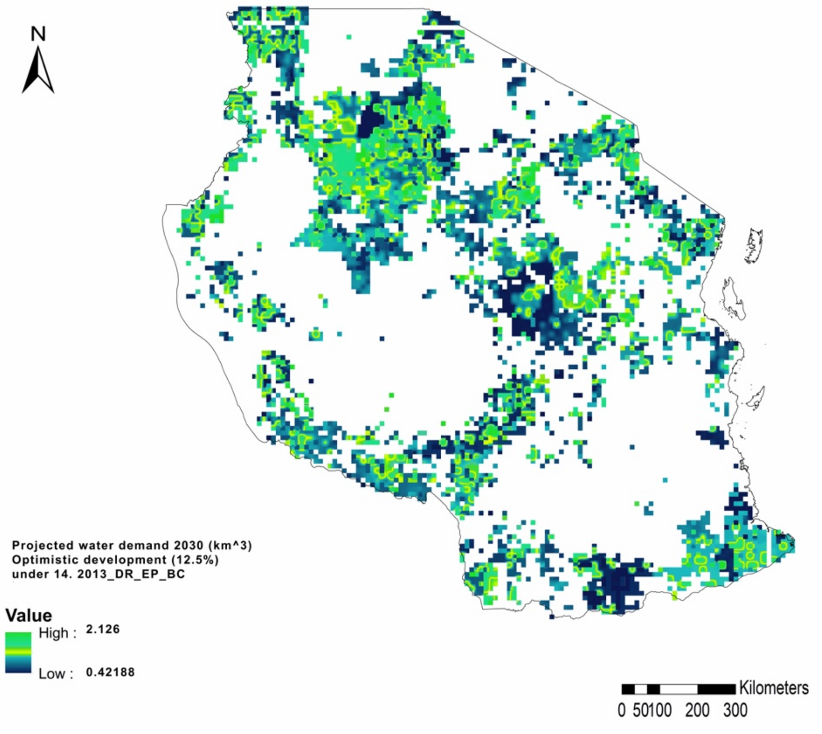


Figure 4.6: Projected water demand 2030 (km^3) - Optimistic development scenario

5. Conclusions and recommendations for future work

In this study, a GIS-based approach for the incorporation of productive uses of electricity, with regards to irrigation in agriculture, was conducted. The developed methodology was applied in the case study of maize for Tanzania. Lying on the rationale of the global growing energy demand towards global electricity access by 2030 under the scope of the SDGs and the SE4ALL initiative, the objectives of this work were focused on the estimation of water and electricity demand for pumping water from groundwater sources.

The study initiated with a base line collection of geospatial and national statistics data; however, the general paucity of georeferenced demand related information hindered the collection process to a great extent. As an outcome, a model accounting for climatic, spatial and temporal parameters was created, in order to answer the research questions under consideration. Additionally, 16 scenarios were developed in order to assess and evaluate the dynamics of the output, taking into account irrigation technology and energy source efficiencies, as well as projected changes in irrigated area aligned with the overall shift towards the modernization of agriculture. Namely, Tanzania's water demand for irrigating 124,000 ha of maize was estimated, under the optimal scenario, to be 1.8 km^3, projected to reach 5.42 km^3 or even 13.3 km^3 by 2030. Subsequently, irrigation electricity needs in 2013 were estimated at 170 GWh in the same optimal scenario, with a range subject to increase significantly under different irrigation method efficiencies and changes in irrigated area.

This piece of work was the first attempt in order to cover the reported literature gap and intended to create a generic framework aiming to facilitate national and energy demand planning in developing countries through a holistic approach. Paying respect to the global initiatives towards energy poverty elimination through sustainable development and promoting the continuous research on the field of energy assessment, planning and implementation, the recommendations and ideas for future work are suggested below.

The Thesis was elaborated on findings, estimations and assumptions derived mainly from literature review, which at times could be considered obsolete. Due to the lack related data, cross referencing was not always feasible, therefore validation of the data through a field study would contribute to a great extent, adding significant value to the developed methodology.

Further improvement of the water balance demand model is also recommended by including further water related information and parameters under the context of sustainable water management. Another option would be the incorporation of different sources of water (such as surface water, rivers, lakes, dams etc) for pumping irrigation, besides groundwater. A shortest path algorithm for the optimal selection of the water source in GIS would allow a more detailed and comprehensive approach of the water requirements and, subsequently, the implied energy needs.

With regards to the scenarios development and the future projections, there is unanimous belief that irrigation can play a pivotal role against the mitigation of climate change and variability impacts, enhancing agricultural productivity and profitability. Temperature, rainfall, solar radiation, and wind, are highly interconnected with the estimation of reference crop evapotranspiration and the required crop water needs throughout the agricultural calendar, and therefore with the overall seasonal energy needs. The estimation of crop production and potential yields is also recommended.

Finally, the results of the Thesis are expected to infer to critical improvements on the existing methodology behind geospatial energy planning for agricultural purposes and enhance the application of the model in similar studies of other countries in the future. The incorporation of the results of the case study of Tanzania in OnSSET in the future, is expected to show the optimal split between grid, mini-grid and standalone electrification solutions, as well as which energy resources should be used in order to achieve the lowest cost of electrification. This information could potentially be used by energy planners in the country, policy-makers or other organizations involved in electrification projects but also be the base for future research towards energy poverty elimination.

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APPENDIX A

Table A.1: Multi-tier Framework Matrix for household electricity access and services (ESMAP/WB)

Scope		**Tier 1**	**Tier 2**	**Tier 3**	**Tier 4**	**Tier 5**
Peak capacity	**Power capacity (W)**	Min 3 W	Min 50 W	Min 200 W	Min 800 W	Min 2 kW
	Power capacity (Wh)	Min 12 Wh	Min 200 Wh	Min 1 kWh	Min 3.4 kWh	Min 8.2 kWh
Availability (duration)	**Hours /day**	Min 4 hrs	Min 4 hrs	Min 8 hrs	Min 16 hrs	Min 23 hrs
	Hours /evening	Min 1 hr	Min 2 hrs	Min 3 hrs	Min 4 hrs	Min 4 hrs
Reliability					Max 14 hrs disruption per week	Max 3 hrs disruption/week of total duration <2 hrs
Tier criteria		Task lighting and phone charging	General lighting and phone charging and television and fan	Tier 2 and any medium-power appliances	Tier 3 and any high-power appliances	Tier 2 and any very high-power appliances

APPENDIX B

Table B.1: Tanzania administrative boundaries and rainfall pattern

ID	Administrative Area - Level 1	Rainfall pattern
1	Arusha	Bimodal
2	Dar es Salaam	Bimodal
3	Dodoma	Unimodal
4	Geita	Bimodal
5	Iringa	Unimodal
6	Kagera	Bimodal
7	Katavi	Unimodal
8	Kigoma	Bimodal
9	Kilimanjaro	Bimodal
10	Lindi	Unimodal
11	Manyara	Unimodal
12	Mara	Bimodal
13	Mbeya	Unimodal
14	Morogoro	Unimodal
15	Mtwara	Unimodal
16	Mwanza	Bimodal
17	Njombe	Unimodal
18	Pemba North	Unimodal
19	Pemba South	Unimodal
20	Pwani	Unimodal
21	Rukwa	Unimodal
22	Ruvuma	Unimodal
23	Shinyanga	Bimodal
24	Simiyu	Bimodal
25	Singida	Unimodal
26	Tabora	Unimodal
27	Tanga	Bimodal
28	Zanzibar North	Unimodal
29	Zanzibar South and Central	Unimodal
30	Zanzibar West	Unimodal