Master Thesis

Master in Energy Engineering

Towards evidence-based policymaking: energy modelling tools for sustainable development

CCG-SAND Interface for OSeMOSYS

REPORT

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Date: 27 October 2020

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To Natali, curious soul,

who passed away before seeing the end of this work

Acknowledgement

I would like to express my sincere and deepest gratitude to my external supervisor, Mark Howells, for his mentorship and invaluable help in building up this thesis. Thanks for believing in me and this work, for making my curiosity grow and to keep me on track when I was not.

I want to extend my profound gratitude to my internal supervisor, Cesar Valderrama, for the constructive suggestions and advice to make this thesis coherent and cohesive from beginning to end. The completion of this report would not have been possible without your support.

I also wish to thank Francesco Gardumi, Will Usher and Agnese Beltramo from dESA department at KTH for providing valuable materials, feedback and critique along the way. A special thanks to Eunice Ramos for her advice and encouragements.

I gratefully acknowledge the assistance received from Thomas Alfstad and Abhishek Shivakumar from UNDESA department, in the development of the Interface and the teaching exercise.

A sincere thanks to Hillary Kassedde, from the Makerere University of Kampala, for proofreading, providing materials and insights in the Ugandan culture and challenges.

I would like to take also the opportunity to appreciate the valuable contribution of other Master students to the development of this thesis. Thanks, Lucy, Naomi, Edward, Ellie and Miles.

Thanks to my family, that never gives up, for your unconditional support and faith.

Last but not least, thanks to Davine, to be my backbone in the difficult times and to share my happiness in the good ones.

Abstract

Governments’ commitments to cope with climate change unpredictability, while ensuring an equal green transition, require clear plans to allocate resource better and estimate the impact of energy and social policies. Many energy models were developed to reach these goals. One of these is the Open Source Modelling System (OSeMOSYS), which uses the graphical Model Management Interface (MoManI). Feedback from MoManI users has shown unpleasant experiences and a steeper learning curve than desirable. In this study, the Simple And Nearly Done (CCG-SAND) Interface was developed to investigate whether an Excel-based tool could fasten and strengthen the process of evidence-based policymaking, reaching a wider audience of energy modelling practitioners. The potential improvements of CCG-SAND Interface compared to MoManI were tested and validated with an introductory Master course teaching exercise called Climate, Land, Energy and Water Systems for OSeMOSYS (CLEWS-O), four Master students from Imperial College London used CCG-SAND Interface for their energy models of Laos, Kenya, Nigeria, and Vietnam. To ensure a standardized collection and manipulation of data, replicable energy systems formats were created, respectively, for simple and more detailed analysis (Tier 1 and Tier 2 Models). Moreover, a case study on Uganda was analysed, including the validation of national energy policies which aim at diversifying the energy mix and reducing indoor pollution from the cooking applications of inefficient stoves. Analysis of the results obtained for the Ugandan case study showed massive enhancements of the quality of life if Improved Biomass and Electric Stoves are used. The results also indicated that the proposed electricity generation policy is not cost-effective. A revision of this plan could aim at reducing the dependency from nuclear energy. On these bases, CCG-SAND Interface proved to be a valuable and user-friendly tool for long-term energy policy modelling. Future work could aim at automatizing some processes of CCG-SAND Interface and reduce the computational time. Finally, CCG-SAND Interface has the potential to replace MoManI in universities Master programmes.

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List of Abbreviations

BaU	Business-as-Usual
BEST	Biomass Energy STrategy
CAPEX	Capital expenditure
CCG-SAND	Climate Compatible Growth - Simple And Nearly Done
CHP	Combined Heat and Power
CLEWS-O	Climate, Land, Energy and Water Systems - OSeMOSYS
CO2	Carbon dioxide
COVID-19	Coronavirus disease
CSV	Comma Separated Value
ETSAP	Energy Technology Systems Analysis Programme
EU	European Union
GAMS	General Algebraic Modeling System
GJ	Giga Joules
GLPK	GNU Linear Programming Kit
GUI	Graphical User Interface
GW	Giga Watts
HCI	Human-computer interaction
HPP	Hydro Power Plant
IAEA	International Atomic Energy Agency
IEA	International Energy Agency
IGA	Inter-Governmental Agreement
ILO	Intended Learning Outcomes
INDC	Intended Nationally Determined Contributions
IPCC	Intergovernmental Panel on Climate Change
KTH	Kungliga Tekniska högskolan (Royal Institute of Technology)
LEAP	Low Emissions Analysis Platform
LPG	Liquefied petroleum gas
MARKAL	MARKet Allocation
MoManI	Model Management Infrastructure
NASA	National Aeronautics and Space Administration
NGO	Non-Governmental Organisation

NPV	Net Present Value
OCGT	Open Cycle Gas Turbine
OPEX	OPerating EXpense
OSeMOSYS	Open Source energy MOdelling SYStem
OSINDA	OSeMOSYS Interface and Database
PJ	Peta Joules
PM_{10}	Particulate Matter diameter of 10 micrometres
$PM_{2.5}$	Particulate Matter diameter of 2.5 micrometres
PP	Power Plant
RES	Reference Energy System
SE4ALL	Sustainable Energy for All
SEI	Stockholm Environment Institute
SETIS	Strategic Energy Technology Information System
TIMES	The Integrated MARKAL-EFOM System
UETCL	Uganda Electricity Transmission Company Limited
UNDESA	United Nations Department of Economic and Social Affairs
UNDP	United Nations Development Programme
UNFCCC	United Nations Framework Convention on Climate Change
WHO	World Health Organization
WWF	World Wide Fund for Nature

1. Introduction

1.1. Background of the work

With a growing number of scientific studies linking a higher coronavirus spread to an increased level of pollution in some areas of the world, people are becoming more aware of the environment that surrounds them and of the effects that human activities are causing to the Earth. Lockdown measures limited our freedom, but they made us rediscover the pleasures of life, the beauty of nature and the importance of personal connections, a rediscovery of the human being and a consciousness of the consequences of our daily actions. The coronavirus crisis looks even more connected to the environmental one: as validated in a study of Harvard University, there is a higher risk of transmission and a +8% mortality rate in the United States for Covid-19, where fine particulate concentrations ($PM_{2.5}$) are higher than the levels considered safe by the World Health Organization (WHO) [1]. The WHO, a public health agency of the United Nations, estimated that 7 million deaths each year are attributable to air pollution [2]. Coker et al. [3], focused on finding evidence of a correlation between long-term exposure to air pollution and the death rate for Covid-19 in North of Italy, one of the most affected regions by SARS-CoV-2 infections and most polluted area of the world. This scientific correlation was mainly attributed to the fact the exposure to a high level of particulate matters make human bodies more vulnerable to chronic lung inflammation, therefore making people more fragile to SARS-CoV-2, as for the clinical characteristic of Covid-19 deaths reported by the Italian National Institute of Health [4]. However, while coronavirus is a new hot research topic, climate change effects have been observed since years. The environmental crisis is becoming more urgent worldwide, representing the next calamity to the human being. The interactive map developed by Carbon Brief [5], shows the anthropogenic nature of the majority of the extreme weather events happening around the world. Temperatures reached 38°C in Siberia [6], record wildfire devasted the West Coast of United States [7], extreme flooding made Venice uninhabitable [8] and recent studies found that ice melting in the Arctic rises sea level even if we meet Paris Agreement [9]. Global warming and its extreme effects on Earth are the drivers for what is called the climate migration or climate migrants: massive groups of people that are starting to move from some areas of the world due to drought, flooding, heatwaves, lack of food and water access, as supported by NASA findings [10]. If at a global level the effort to deal with climate change was not so successful as expected, a strong commitment was made by the European Union new Von der Leyen commission with the presentation of the ambitious European New Green Deal [11], a plan for the transformation of the European economy and energy sector, which mobilized 1 trillion Euro to be used in a time range of 10 years, for the resources needed for a Just and Sustainable transition as well as creating the enabling environment to increase the capital invested in sustainable projects [12]. This strategy accompanied the commitment of Europe to become the first climate-neutral continent by 2050. The pillars of the European growth plan are the preservation of the natural ecosystem, the revision of the targets to cut emission by at least 50% until 2030 over 1990 levels, and the fairness of this development mechanism to be just and equal for all the countries. This claim attracted the interest and the attention of the rest of the world [13] [14] [15] as a virtuous example to foster the transition towards a sustainable way of living and growing. However, as shown in Figure 1, European emissions account for 9% of the world global total.

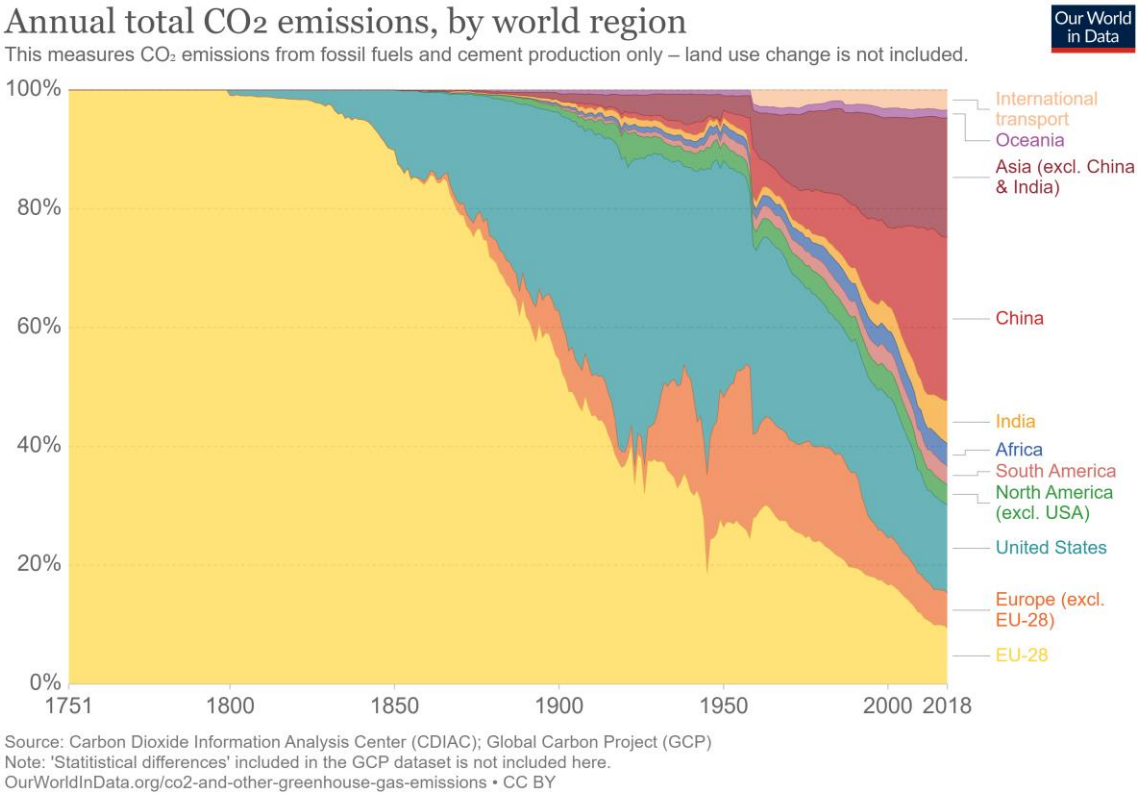


Figure 1: Annual total CO_2 emissions by region [16].

This graph shows that an effort in defining a clear roadmap is required from all the other countries to ensure the achievement of the Sustainable Development Goals set by the UN 2030 Agenda [17]. One of those goals, the 7th, which is strongly interconnected with many others, reflects the intention to ensure access to sustainable, reliable, modern and affordable energy to everyone. However, due to the energy cost fluctuation and uncertainty of technology development, it is very often challenging to predict the future and decide on what to invest and when. It is in this background that becomes urgent for policymakers to plan the allocation of financial (and other) resources accurately, in a way that assures an economic return but most importantly that can have a real impact when it comes to ensure energy security and achieve the country's emissions target. To fill the gap between policymakers and energy analyst, a high number of tools for energy planning were deployed in recent years by many international organizations. These instruments are used during highly specialized training organized around the world by numerous international organizations, to teach energy modelling skills and foster capacity building activities for government representatives. However, the main drawback is often related to the complex architecture of these tools, which results in frustration of the user when diving in an ocean of alternatives available. This can be seen as a ‘paradox of choice’, a theory first introduced by the psychologist Barry Schwartz, who believes that a greater degree of freedom of the user does not always translate in faster and more satisfying choices. Indeed, the multitude of possibilities creates immobility of action. This thesis starts with these premises and aims at analysing the state of the art of the modelling tools for sustainable development, encounter their limitations and develop an improved energy model interface for long-term energy planning. The user-friendliness of the tool is at the centre of attention to provide a more uncomplicated and straightforward instrument to perform the energy system analysis.

1.2. Literature review energy systems and modelling tools

In this thesis, only energy systems models for policy development are considered. It is worth mentioning that there also exist energy models to analyze the system operations and the engineering design. The system feasibility and the energy efficiency of the system are respectively, the outputs of these types of energy models. However, for the scope of this Master thesis, the focus was narrowed down only to energy policy models, which analyze an energy system and have as outputs, for example, natural resource use, greenhouse gas emissions and cumulative cost.

1.2.1. Energy systems

An energy system is a system that "*comprises all components related to the production, conversion, delivery, and use of energy*" as defined in the IPCC Fifth Assessment Report [18]. This system-level view is crucial to define better scenarios, assumptions and the effects of the implementation of a specific policy on the whole energy system. With the support of projection models, we can forecast future scenarios, simulate the different "what if?" questions and inform policymaking based on this evidence. An overview of the architecture of the energy system, adapted from Holger Rogner [19], is shown in Figure 2.

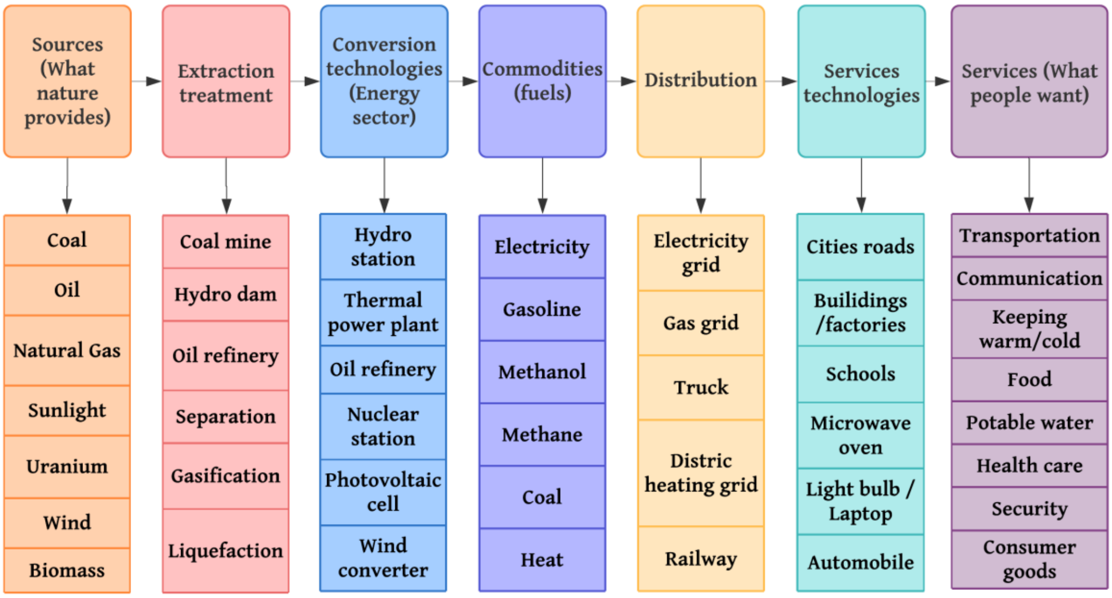


Figure 2: Energy System Architecture adapted from Holger Rogner [19].

1.2.2. What and why energy systems modelling for policymaking?

Energy modelling or energy system modelling is the process of mathematically analyze an energy system using computer programs to inform energy policy development, in a comprehensive, transparent and evidence-based manner. Energy planning is about finding trade-off solutions and dealing with future uncertainties: i.e. prices and availability of primary resources, technology development, governments commitments, growths of demands [19]. Comprehensive energy planning is, therefore, crucial to ensure sustainable growth and can play an essential role in informing decision making in different ways. Some advantages of using an energy model are i) optimal domestic resource allocation; ii) policy measures effectiveness; iii) compliance with environmental constraints and climate objectives; iv) financial viability and investment requirements, and v) social and public acceptance of a technology change.

1.2.3. Classification of models

Energy models can be categorized based on many different parameters, such as the mathematical program used, the modelling methods or the outcomes [20]. In this Master thesis, energy models were classified based on their results. As presented in Figure 3 and described above, energy models can focus on the system operations, on the engineering design or policy development. The first two have the system feasibility and the energy efficiency of the system as outputs. Whereas, the results of energy policy models emphasis the use of natural resources, the greenhouse gas emissions and the cumulative cost. For the scope of this thesis, only energy models for policymaking are considered.

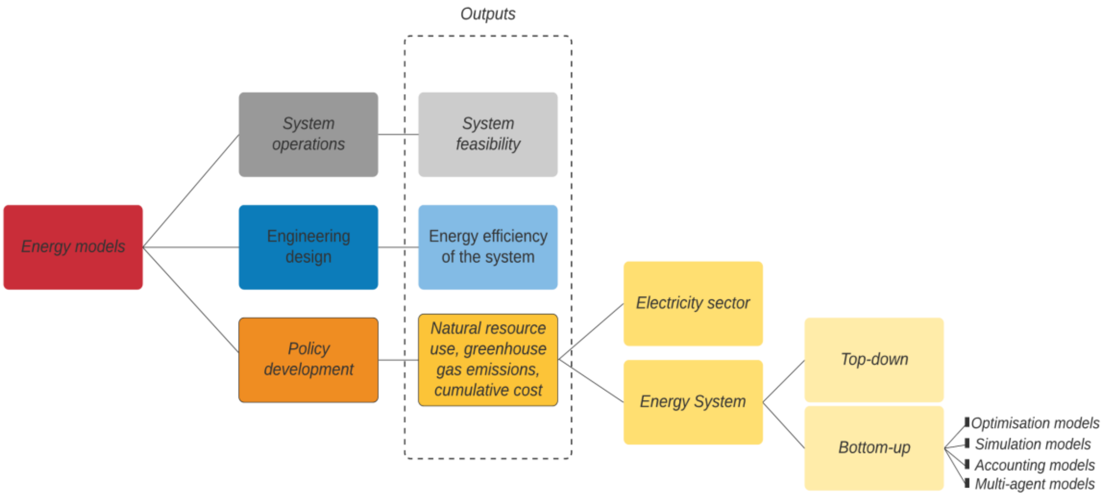


Figure 3: Classification of energy models by their outputs [20] [21].

Energy policy models can be further split up depending on how extensively the system is represented. Therefore, some models set their boundaries exclusively on the electricity sector, while others expand the analysis also to other sectors of the society (i.e. heating, transport, cooking) considering the entire energy system. As mentioned before, when developing a policy is crucial to have a holistic view of the energy system to account for the effects that energy policy has, not only on the electricity sector but on the whole society. Consequently, energy system models for policymaking are chosen for this work. The next level of classification presented in Figure 3 is related to two different approaches of energy system models to address the energy demand, namely the “top-down” and “bottom-up” perspectives, which respectively refer to aggregated or disaggregated models, to an economical or an engineering approach. How extensively described by Per Ivar Helgesen [21] and Böhringer et al. [22], “top-down” models consider the whole economic sector and the effects that policy has on prices and incomes in different markets. These economical models lack technicalities of the energy system and represent energy demand in an aggregated way. Therefore, “top-down” models are not well suited for analysing discrete energy technologies and cost projections. The latter task is optimally performed employing “bottom-up” models, that take into account capital cost (CAPEX), operation and maintenance costs (OPEX), efficiency curves and capacity factors for each technology included in the energy system model.

Although they do not include wide-economic interactions, the engineering approach of the “bottom-up” energy models performs best for command-and-control environmental policies [23] and technologies development over time. Therefore, as the ultimate interest of this thesis is to influence policy to promote sustainable development, the “bottom-up” approach is selected. Optimization, simulation, accounting and multi-agent are some of the types of “bottom-up” energy models for policymaking [21]. Optimization models find the optimal combination of technologies to address the energy demand at the lowest cost possible, while multi-agent models are the extension of the optimization models as they optimize simultaneously different objective functions. Accounting and simulation models do not consider prices change over time; therefore, they are less dynamic tools. The strength of optimization models lies in the possibility of finding optimal solutions to complex models and entire systems accounting for dynamic variations of prices and costs over time. Their output insights and the possibility to control each variable in the model make them the best-suited energy models for decision-makers [24].

1.2.4. Criticism of energy modelling for policy development

Significant criticisms to energy models are the lack of transparency, the difficulty in accessing the data and reluctance to collaborate and share the insights of research. Indeed, the majority of the models are licensed or closed, in other words, the user is required to purchase the license to be able to use the model or ask permission to the developers and authors to access the results of research. The choice of a closed model over an open-source one has to be reconducted to i) ensure the data privacy of individual consumers, ii) to a minor financial and time-consuming effort needed money to administrate and regulate a licensed infrastructure and iii) to avoid undesired critics on the research results, as outlined by the SETIS (Strategic Energy Technology Information System) Magazine of the European Commission [25]. To overcome this limitation of the modelling exercise, open-software projects have been developed. The well-known Open Source energy MOdelling SYStem (OSeMOSYS) is an excellent example of these kinds of initiatives, requiring no upfront investment and ensuring the retrievability of data, code and results [26].

1.2.5. The OSeMOSYS tool

OSeMOSYS is a linear optimization bottom-up model for long-term energy modelling, specifically designed as a tool to inform local, national or multi-regional energy strategies and support capacity-building activities. It was developed in collaboration with a range of institutions, including the International Atomic Energy Agency (IAEA), the United Nations Industrial Development Organisation (UNIDO), KTH Royal Institute of Technology, Stanford University, University College London (UCL), University of Cape Town (UCT), Paul Scherrer Institute (PSI), Stockholm Environment Institute (SEI), and North Carolina State University [27]. An overview of OSeMOSYS and its functionalities is presented in Figure 4 [28].

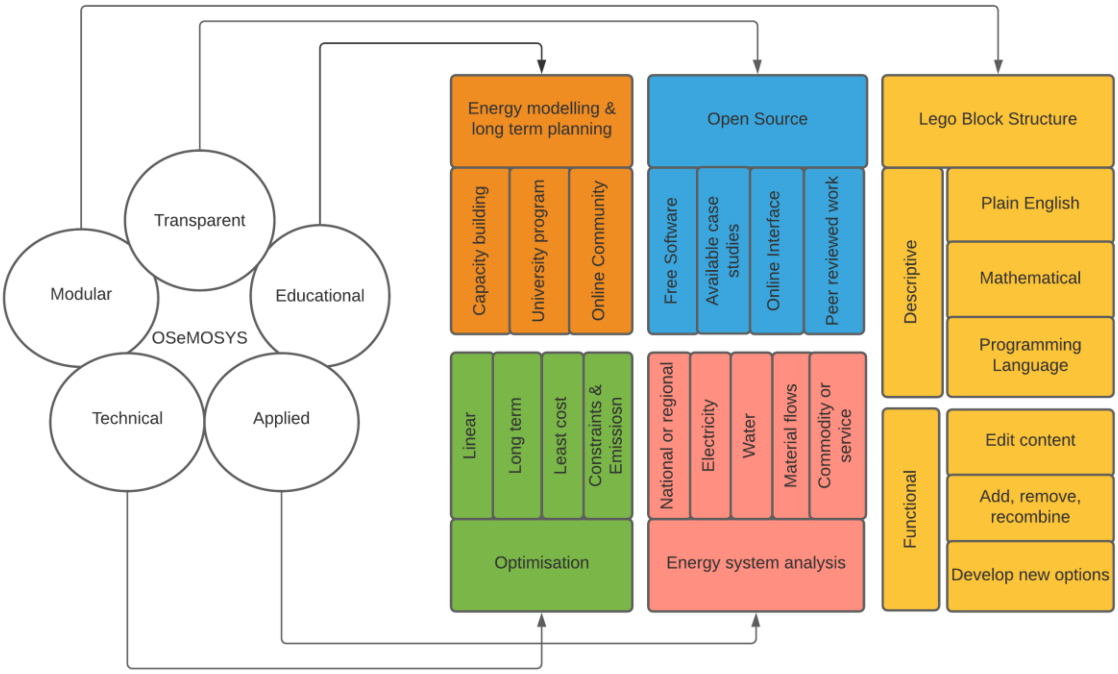


Figure 4: Overview of OSeMOSYS adapted from [28].

1.2.5.1. OSeMOSYS Lego-Block Structure

The structure of OSeMOSYS has been represented by different functional “lego-blocks” or components of functionalities, defined by the user through sets, parameters and variables. An overview of these functional components is presented in Figure 5. Each of the “block” is written in the mathematical language of the code, the GNU MathProg. This modular structure allows for easy edit and update of the code for specific analysis if needed.

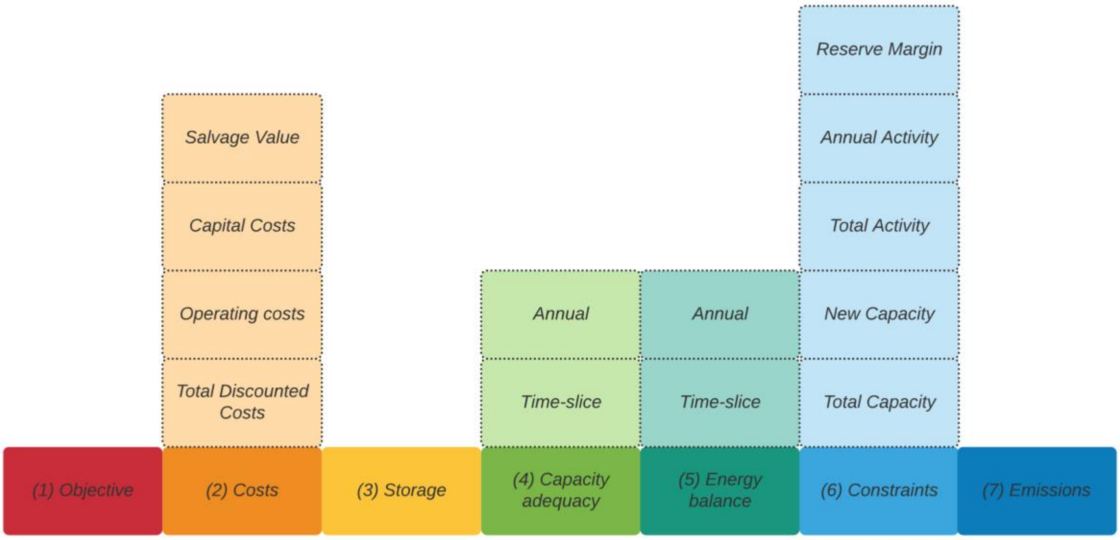


Figure 5: Overview of OSeMOSYS functional "blocks", adapted from [26]

The objective of the OSeMOSYS solver is to find the optimal combination of technologies able to meet the energy - or energy services - demand(s) at the lowest Net Present Value (NPV) possible of the energy system, taking into considerations the constraints (i.e. capacity, activity, emissions, operational life) set by the user. The costs (capital, fixed and variable, salvage value) are defined by the user per technology, year and timeslice. The salvage value is used to account for depreciation of power plants over the years estimating the capacities still available at the end of the modelling period. A timeslice represents the time split of each modelled year, therefore the time resolution of the model, which is necessary to assess the demand profile for fuels that are expensive to store (i.e. electricity) during the year. To reduce the computation time, these ‘slices’ are often grouped. Thus, the annual demand may be split into aggregate seasons where demand levels are similar (such as ‘summer, winter and intermediate’) [27]. Those seasons are made of days which may be further subdivided (such as into day and night) depending on the level of demand [28]. As block (3) shows, in OSeMOSYS, there is the possibility to add storage technologies in the energy system. Block (4) and (5) ensure that the capacity installed of a particular technology, as well as production, use and demand of a fuel or energy service, are feasible each year and in each timeslice [26]. Block (6) sets the constraints or the boundaries of the model in terms of capacity, activity and reserve margin. Finally, block (7) allows the user to account for emissions which are dangerous for the environment. As mentioned above, the mathematical language used is easy to understand and employs sets, parameters and variables which the user needs to define for its specific analysis.

1.2.5.2. Other OSeMOSYS characteristics

OSeMOSYS, being an open-source project, is entirely free and accessible to every user. It is worth remarking the importance of keeping the data transparent and accessible. This practice of sharing results, assumptions and data, enhances the possibility for collaboration between modellers and avoid duplication of work. Indeed, an open-source project could improve the quality of results, as a peer-reviewed work has a more solid basis and is more welcomed in the energy community [25]. OSeMOSYS has many other advantages compared to other tools such as TIMES [29], MARKAL [30] or LEAP [31]: the fact of being a fully open-source from code to the solver that does not require an upfront investment, the modular code allows for straightforward addition, the extensive documentation available online on the website help to get started and learn fast [26].

Furthermore, OSeMOSYS has an excellent policy impact worldwide, ranging from academia to governments and NGOs. To cite some examples, OSeMOSYS was used in the Republic of Cyprus to provide technical support in the definition of the National Energy and Climate Plan, which was submitted to the European Commission [32]. This work aimed at assessing the resilience and performance of the Cyprus energy system under different policy scenarios to achieve energy and climate targets set by the EU for 2030. When defining the Intended Nationally Determined Contribution (INDC) of Bolivia, OSeMOSYS was used to optimize each phase of the electricity generation and to account for CO_2 emissions [33]. In 2020, the Government of Costa Rica commissioned research on the optimal decarbonization pathways for the energy and transport sectors of the country. The Costa Rican National Development Plan included insights from the analysis of different policy scenario done with OSeMOSYS.[34].

Regarding the infrastructure and the channels that OSeMOSYS employs, it is good to mention that there is an active and collaborative community around the world. Figure 6 gives an overview of the locations interested and categorize the applications in scientific publication (red), thesis publication (yellow), research work (dark blue), university course (light blue), core scientific publication (black) and capacity building (green). This map was developed at the Department of Energy Systems Analysis at the Royal Institute of Technology of Stockholm (KTH), and it is available on the OSeMOSYS Community folder on Google Drive [35]. The interactive map sums up information from the complete list of publications available on the OSeMOSYS website [36] and the institutions that are actively using OSeMOSYS in their activities, openly available on the Google Forum [37].

Figure 6: OSeMOSYS Community around the world [35].

1.3. OSeMOSYS Interfaces

Currently, there are three OSeMOSYS interfaces available to a user who wants to create its energy model. In chronological order of development:

1. **Notepad ++**: a useful tool to work directly with the OSeMOSYS model and data files [38]. The drawback of using a data file to build up a model is that there is not a graphical interface which supports the user during each phase of the modelling exercise. Therefore, it is effort and time consuming to work with this type of file;

2. **OSINDA (OSeMOSYS Interface and Database)**, is a Microsoft Access-based environment created to replace the OSeMOSYS data files and to provide a user interface that facilitates the data management and automated representation of results [38]. For example, OSINDA was used to define the strategies for the development of Southern European countries following European policies for the reduction of greenhouse gas emissions [39].

3. **Model Management Infrastructure (MoManI)**, is a browser-based open-source interface for energy systems modelling. So far, it is the most common-used Interface based on OSeMOSYS. Indeed, the characteristic of being an open-source project fostered the creation of an OSeMOSYS Community of MoManI Users, whereas OSINDA does not have an active community. The existence of a Community allows users that are not geographically in the same place to collaborate simultaneously on a project, from editing the equations of the code to the improvement of results visualization. MoManI was developed to improve the user

experience compared to the previous OSINDA and data file. Despite being a powerful tool to perform an energy modelling analysis which is recognized and used worldwide, many suggestions for improvements and feedback were collected during the years.

1.4. Gaps and limitations of OSeMOSYS with MoManI Interface

Being the most used OSeMOSYS Interface, having an active community and representing the best alternative available right now to interact with OSeMOSYS, the analysis of the gaps focused only on MoManI Interface. To identify the limitation of OSeMOSYS with MoManI Interface analysis of the feedback was carried out. The users' feedback was collected from i) the OSeMOSYS Google Forum [37] and ii) surveys of Master students from the course "Introduction to Energy System Analysis" at the Royal Institute of Technology of Stockholm (KTH) [40]. Afterwards, this feedback and comments were categorized into eleven groups. Comments or discussion on a similar topic were aggregated and counted for the same category.

1.4.1. Feedback collection and categorization

To better identify the limitations of OSeMOSYS and in particular of its mostly used interface MoManI and to find out what is the need of this community, all the discussions of the OSeMOSYS Forum were analyzed and categorized. This Google Forum was set up in 2018 and aimed at fostering collaboration, support the users in the modelling exercise and avoid duplication of work [37]. This channel is actively used by the OSeMOSYS users representing the best environment to open a discussion on different topics, solve a debug or share results.

Besides, students' surveys of the course of "Introduction to Energy System Analysis" at the Royal Institute of Technology of Stockholm (KTH) [40], were also collected. During this course, the students have been using OSeMOSYS with MoManI Interface to develop long-term national energy models on real-case studies. It is worth mentioning that the majority of the feedback (around 90%) came from the OSeMOSYS Google Forum.

Figure 7 offers a breakdown of the results obtained: 34% of the comments refer to the modelling exercise itself. This macro-category includes questions related to the modelling exercise (i.e. How can I model storage technologies? Which parameter is the most appropriate to set multiple production targets within the same scenario for different years?), doubts about the data input needed by a specific parameter (i.e. What does the parameter X represents? Can you give me an example?) and finally information on the units of each entry (i.e. Which unit should I use for Residual Capacity?). With 13% of the questions related to this topic, the installation procedure represents a significant, painful, obstacle for smooth first user experience. However, explanatory teaching material and a step-by-step guide are available on the OSeMOSYS website [36].

Nonetheless, this part of the modelling process is still challenging for many OSeMOSYS users. Surprisingly, as much as 12% of the open discussion was related to Storage representation in MoManI Interface. Welsch et al. [41] offer a comprehensive description of the methodology to model storage options in OSeMOSYS. At the same time, Anjo et al. [42] included different storage technologies when analysing the impact of demand-response on the Portuguese electricity sector. Finally, Keller et al. research give insights on possible decarbonization pathways of the transport sector using electric battery storage or hydrogen fuel cells [42]. Nevertheless, storage representation in OSeMOSYS is a relatively new area of discussion, in line with the emphasis that this topic is gaining worldwide.

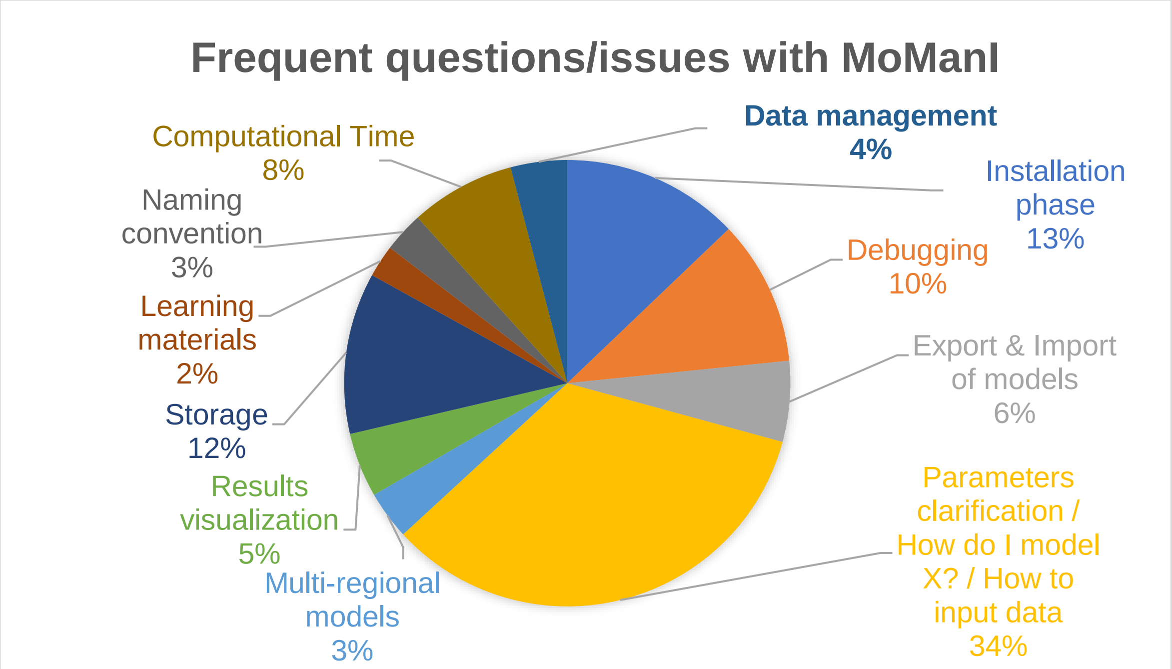


Figure 7: Break-down of the feedback collected from the Google Forum [37] **and the students' survey** [40].

It is essential mentioning that the 'Data Management' category constitutes a collection of answers of its own. Indeed, this group accounts for the discussions and the concrete suggestions for the development of a more user-friendly interface which could improve the collection and input of data. In particular, from the analysis of the feedback, it seems like many institutions and individuals are currently employing an Excel-based file to store, manipulate and adjust the data before adding them in MoManI. Unfortunately, these practices and efforts are scattered and, in the community, there is not a standardized and commonly recognized process for data management through an Excel Interface. Excel was identified as a "familiar tool" for many users, therefore being the "easiest way to manipulate and sort data and construct the datafile needed by the solver" – a user of the community said.

From the analysis of students' surveys, discussion on the OSeMOSYS forum and comments of experts users it was defined the purpose of this Master thesis: the need for a new interface based on OSeMOSYS which aims to smooth the learning curve and improve the user experience, addressing as many as possible of the frequently mentioned problems found in the results breakdown in Figure 7. From the etymology of the world, inter- (between) + face (shape, figure, form), it is clear that is needed "something" that helps the human being interacting with a machine. Therefore, the concept of Graphical User Interface (GUI) comes into play. Initially envisioned by Vannevar Bush in his essay, "As We May Think," published in July 1945, the idea of using computer-based machined controlled by buttons and controllers gained a foothold. It grew further as a multidisciplinary field of research and investigation called Human-Computer Interaction (HCI), which eventually culminate in the current Apps and software used Apple Inc.'s Macintosh and Microsoft Corporation's. It is commonly accepted that a GUI is "*a computer program that enables a person to communicate with a computer through the use of symbols, visual metaphors, and pointing devices"* [43].

1.5. Scope and objectives

The main objective of this thesis is the development of a user-friendly interface based on OSeMOSYS tool that serves as a platform to perform energy modelling calculations for a detailed and informative evidenced-based long-term policy and investment planning. The added value compared to existing tools and software is the user interaction and experience that has been optimized, tested and validated. The simplified, but accurate, interface offers excellent potential for policymakers, energy modellers and international organization who wants to visualize technical results as a basis for the formulation of energy security planning for their country. Simple design and functionalities, in the form of an Excel-based tool, aim at also allowing people with a low-medium digital skills and energy modelling knowledge to have valuable results and guidance in the definition of their country's roadmap in a time frame of 55 years.

1.6. Methodology

The thesis is structured as follows, as depicted in Figure 8: **Chapter 1** presents the background of this work, a literature review on the state of the art of the existing modelling tools, followed by an explanation of the OSeMOSYS tool and an overview of the weaknesses of the graphical interfaces that OSeMOSYS employs. In the same chapter are presented the scope, the objectives and the methodology of the thesis starting from the gaps identified. **Chapter 2** includes a description of the main functionalities of CCG-SAND Interface, its development and limitations. A description of the steps taken before reaching the final result of CCG-SAND Interface, which include the creation of an online Mock-up, are introduced in Annexe C.

Chapter 3 focuses on the methodology used for the construction of the Tier 1 and Tier 2 model. These are respectively, a model for a simple generation based on an energy balance and an extension of the first applied to the specific case study of Uganda. The development of these models aimed at proving the potential of CCG-SAND Interface and standardize the data collection process. The assumptions and limitations of the two models have also been included in this chapter.

Chapter 4 collects the full dataset employed in the Ugandan case study. The additional value of these data and the potential audience they could reach are presented in the same section. **Chapter 5** offers the background information needed to understand the Ugandan case-study, the ratio and the assumptions taken to develop each scenario. In this chapter, the results obtained are presented and compared. Economic and environmental analyses are presented, including recommendations for policymakers. Limitations of the model and potential future improvements of the work are also covered.

Chapter 6 is an independent section, which analyses the potential use of CCG-SAND Interface in a University Master Course program. It describes how CCG-SAND Interface was used to test a simple teaching exercise provided by United Nation Department for Economic and Social Affairs (UNDESA). This chapter includes potential future collaborations with universities to disseminate further CCG-SAND Interface.

Finally, **Chapter 7** concludes this thesis doing a roundup of the outcomes, pointing at the limitations of this effort, setting the foundations for future improvements of this production and summarizing the dissemination activities carried out.

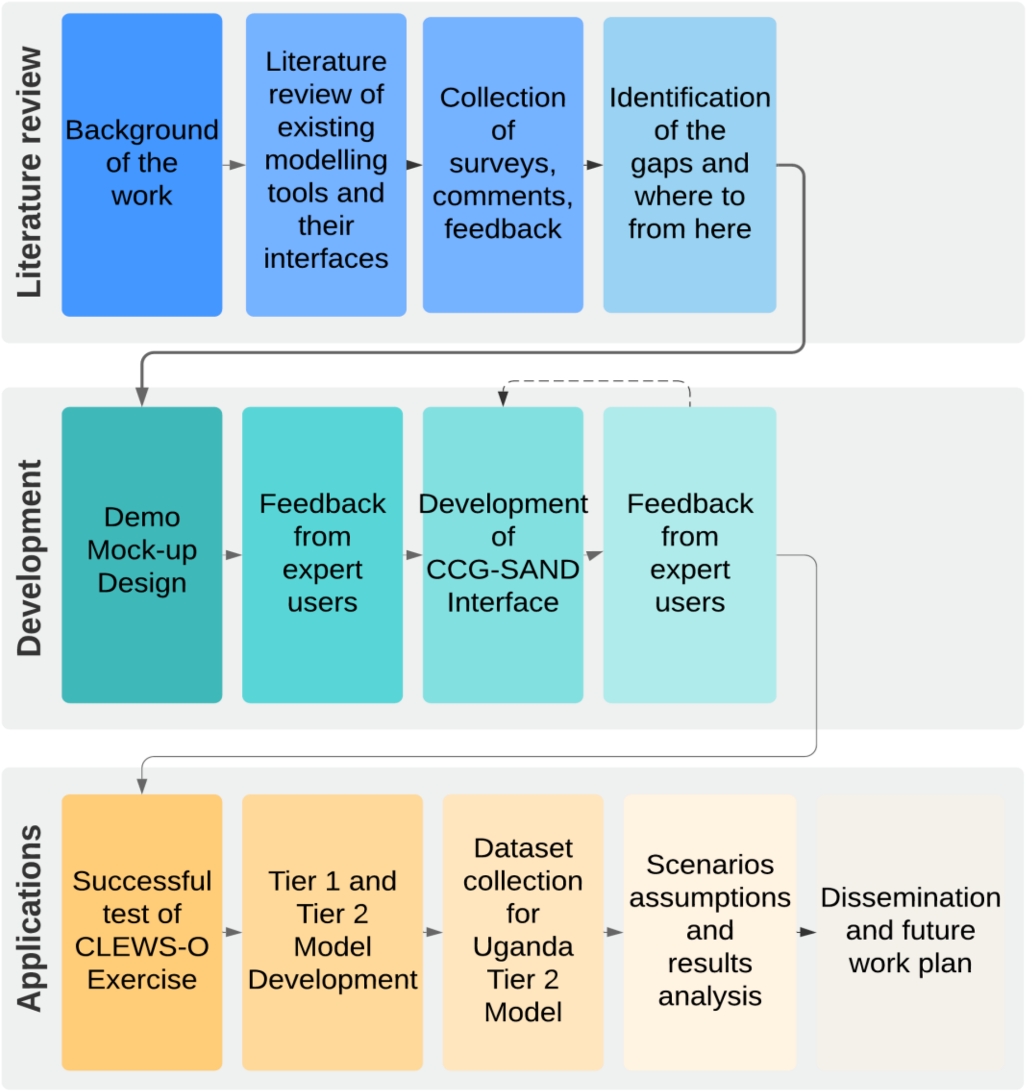


Figure 8: Thesis Structure

2. CCG-SAND Interface

As explained in chapter 1, the analysis of the feedback identified the “Data Management” category as the item most urgently requiring actions, according to the OSeMOSYS Community. Indeed, the development of a more user-friendly interface has the potential to impact all the other categories and solve many issues identified from the feedback. To do so, as a first step, an online Demo Mock-up was developed, which aimed at visualizing which functionalities the new Interface needs to have, and get feedback from expert users of the Optimus Community of Practices [44]. The latter includes academia and researchers whose works aim at promoting quantitative analysis to inform sustainable development policy. The functionalities included in the Demo Mock-up responded to a list of “User Stories” provided by UNDESA (who is part of the Optimus Community) and reported in Annexe A. It is a collection of opinions of OSeMOSYS Users that reports the main tasks that an interface should have. The Demo Mock-Up tool was shared with expert users of OSeMOSYS from international organization to academia.

The feedback received was collected in a Comment-Response Matrix to i) keep track of the improvements made on the development of CCG-SAND and ii) be sure to include all the functionalities in the Interface that were listed in these comments. In the right column of this Matrix, a colour was assigned to indicate the level of achievement of a specific item in the newly created CCG-SAND Interface: achieved (green), partially (orange) and not achieved (red). This method was used to support the transferability of the work, by accommodating for future improvements of the Interface. Annexe A includes the list of “User Stories”, a preview of the Demo Mock-up tool and the Comment-Response Matrix. The Comment-Response Matrix was the starting point for the development of CCG-SAND Interface, which aimed to include as many features as possible of the one listed.

2.1. Development of CCG-SAND Interface

In the upper-right part of the workflow diagram in Figure 9 is presented the methodology used to create CCG-SAND Interface. First of all, it was built an empty shell with 200 technologies, 50 commodities and five types of emissions, using the previous Interface (MoManI). Non-default values were added in each entry in MoManI, and then the file which contained all the data was downloaded in a comma-separated values (CSV) format, using this available feature in MoManI. The CSV file was then converted to an Excel Workbook. If no manipulation of the values is done, MoManI takes the default values, and therefore, no entry cells for the development of CCG-SAND are created. CCG-SAND is made of different Excel Sheets which have been connected to automatically input data in an easier way compared to MoManI. The most time-consuming part of this effort was to link the different sheets in CCG-SAND. A detailed explanation of each of them is provided in Annexe B.

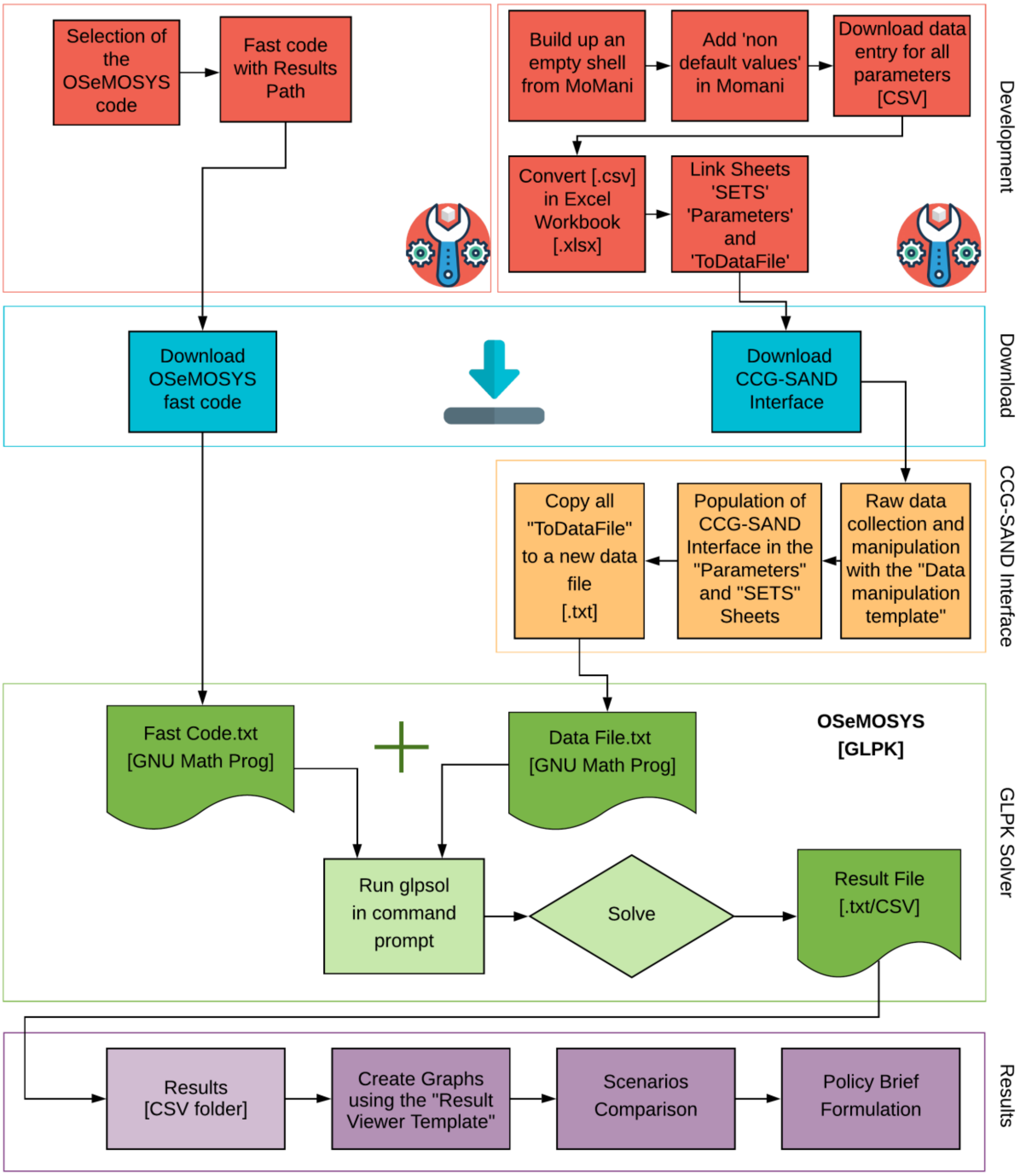


Figure 9: Workflow diagram of CCG-SAND Interface

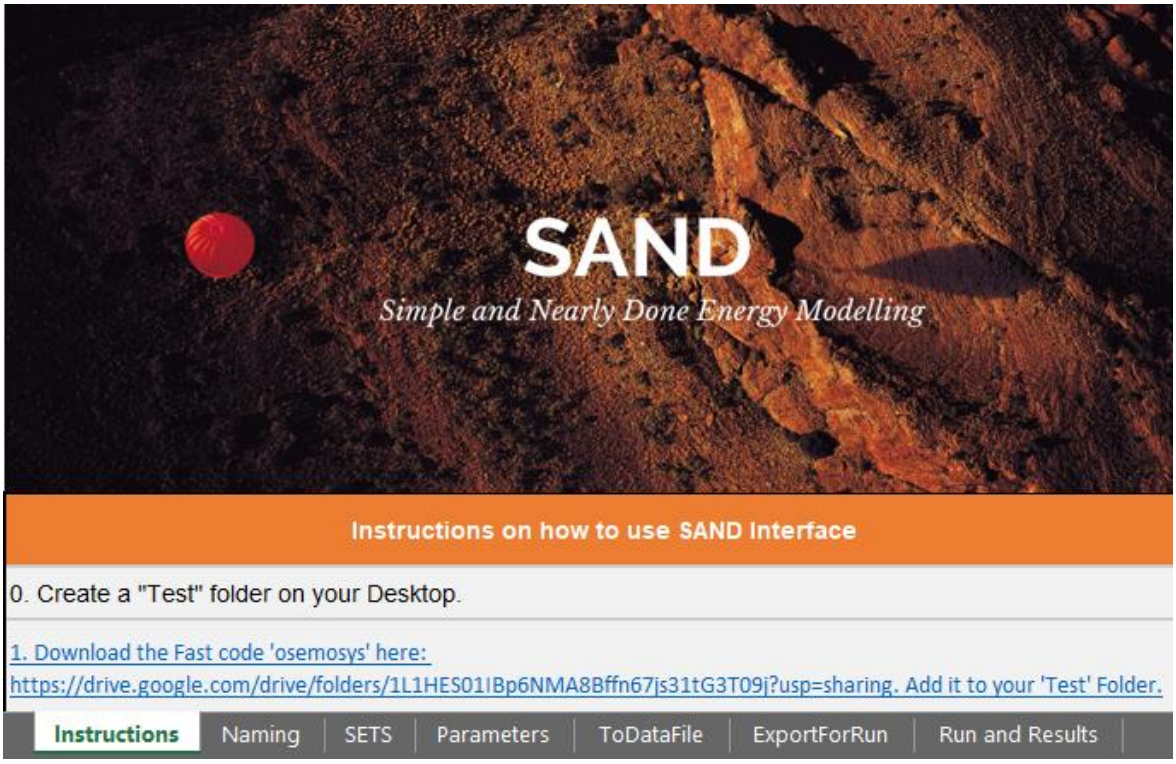
In parallel, it was evaluated which of the available OSeMOSYS codes, should be used to execute the data file created from CCG-SAND. OSeMOSYS code was initially written in GNU MathProg, a high-level language for creating mathematical programming models, and subsequently in GAMS and Python, to reach a wider audience of energy modelling practitioners [36]. To date, there are three available versions of the code: long, short and fast which give all the same output. The extended code includes equations that can be easily understood by a beginner user who wants to be aware of how the model works. A short version was created, which merges equations of the extended code and reduce memory usage of 10 times and processing time of 5 times. However, the most performing version of the code is the fast code, which merges equations from the long and the short codes, drastically reducing the computational time [44].

2.2. Downloading the files

From this phase onwards, the user needs to take actions to use CCG-SAND Interface. First of all, it is necessary to download the OSeMOSYS fast code and the Interface itself. The fast code is available for download on Github [45], and it was used to test CCG-SAND Interface in its applications. Instead, the latest version of CCG-SAND Interface is available for download from a Google Drive folder [46].

2.3. CCG-SAND Interface and “Data preparation template” overview

CCG-SAND Interface is the newly created energy modelling functional tool. An overview of the tool is offered in Figure 10. It is based on the widely used open-source OSeMOSYS for long-term energy planning and policy formulation. It keeps the same functionalities of the commonly used OSeMOSYS Interface, MoManI, but it employs, in this first version, an Excel-based Graphical User Interface (GUI).



Instructions on how to use SAND Interface

0. Create a "Test" folder on your Desktop.

1. Download the Fast code 'osemosys' here: https://drive.google.com/drive/folders/1L1HES01IBp6NMA8Bffn67js31tG3T09j?usp=sharing. Add it to your 'Test' Folder.

Figure 10: Overview of CCG-SAND Interface

CCG-SAND Interface aims at improving the OSeMOSYS user experience by shallowing the learning curve process. CCG-SAND Interface is an environment where the user can, in a straightforward manner, input data and automatically generate the data file needed by the GNU Linear Programming Kit, the GLPK solver, to find the lowest Net Present Value (NPV). To standardize the input data process, a supplementary material called “Data Preparation Template” was created, available for download on Google Drive [47]. The manipulation and preparation of the data is not a requirement to perform the energy modelling exercise, but it represents a useful addition for a beginner user. As shown in the orange block of Figure 9, the following step is to populate CCG-SAND with data using the Sheets called “SETS” and “Parameters”. When all the data have been inserted, the user is asked to copy-paste the entire “ToDataFile” Sheet in a new data file (i.e. Notepad) needed by the GLPK Solver. Detailed instructions on the steps needed to build, run and visualize results with CCG-SAND are provided in Annexe B.

2.4. GLPK Solver

The output of the Interface is a data file, which, together with the OSeMOSYS fast code, are needed to run the standalone GLPK solver. This *GLPK* solver finds the optimal solution of the linear program, "*the lowest Net Present Value (NPV) cost of an energy system to meet given demand(s) for energy or energy services"* [36]. The user is required to add monetary values for investments and operating costs of each technology per each year of the modelling period. The NPV accounts for the cost adjusted to represent the effect of the monetary inflation, as it includes in its formula the discount rate [26]. The solver is freely available for download at this link [48].

2.5. Results analysis and "Results viewer template."

As Figure 9 shows, the outputs of the GLPK solver are a "Results File" and a folder of "CSV Results". The "Results File" reports the optimal NPV. The CSV folder contains results for each OSeMOSYS variable. By copy-pasting these results in the other supplementary material called "Results Viewer", it is possible to visualize results in the form of graphs. The "Results Viewer" is available for download from the Google Drive folder [47].

2.6. Future work and improvements of CCG-SAND Interface

In CCG-SAND the user can freely modify the name of each Technology, Commodity and Emission and their descriptions in the "SETS" Sheet, as many times as needed. However, in this first version, for the scope of this work, it is not possible to change the name and the number of years and timeslices. Future improvements of CCG-SAND Interface could aim at completing the linking process between Sheets to offer an even more flexible tool to the user. Besides, the validation of CCG-SAND Interface with another solver is advisable to i) reduce the computational time and ii) automatize the process of exporting the data file from the Excel Workbook.

Another limitation of the current version of CCG-SAND Interface is the lack of the OSeMOSYS parameters linked to storage technologies. They were deliberately not included during the development of the Interface as the storage equations in the OSeMOSYS code are planned to be changed soon. Future work includes testing these different options and finding the optimal solution to represent storage technologies in the energy system. Detailed information on future improvements can be found in Annexe B.

3. Tier 1 and Tier 2 Models

If chapter 1 and 2 introduced the background of this work and CCG-SAND Interface, respectively, which is the primary outcome of this Master thesis, from chapter 3 onwards applications and validations of the tool are presented. Therefore, chapter 3 is organized as follows: Section 3.1. presents an overview of a simple and non-country specific energy system that is called Tier 1 Model. Section 3.2. introduces the extended Tier 2 Model, which represents the energy system of Uganda and the assumptions behind it.

3.1. Development of Tier 1 Model

Tier 1 model was created for a simple model generation using generic open data. Being not country-specific, it can be used as a structure for generation of a country model in a straight-forward manner, and it can be scaled-up in a standardized and fast way. Indeed, a beginner user can start building up its case-study using available public data and potentially compared it on an international basis. Tier 1 Model has the potential to be a format that can be picked-up easily to foster capacity building activities and improve the process of evidence-based policymaking.

To guarantee the replicability of this model, it was shaped on the format of a generic energy balance as in Table 1. The United Nations Energy Balance 2017 for Uganda was used as a reference [49]. It should be recalled that a United Nations Energy Balance has the following matrix format: commodities (energy sources) are represented in the columns, whereas energy flows such primary production (supply), transformation, trade and final consumption constitute the rows. The unit used is Terajoules (TJ) for all entries.

Table 1: Energy Balance of 2017 for Uganda [49].

Uganda

Terajoules

	Primary coal and peat	Coal and peat products	Primary Oil	Oil Products	Natural Gas	Biofuels and waste	Nuclear	Electricity	Heat	Total energy	of which: renewables
2017											
Primary production	--	--	--	--	--	*612049	--	12472	--	*624521	*624521
Imports	*4	--	--	74135	--	1	--	48	--	74189	-1
Exports	--	--	--	--	--	-1	--	-1140	--	-1141	-1
International marine bunkers	--	--	--	--	--	--	--	--	--	--	--
International aviation bunkers	--	--	--	-4498	--	--	--	--	--	-4498	--
Stock changes	--	--	--	--	--	--	--	--	--	--	--
Total energy supply	*4	--	--	69637	--	*612050	--	11380	--	*693071	*624522
Statistical difference	0	--	--	2678	--	0	--	-1	--	*2678	*12472
Transfers	--	--	--	--	--	--	--	--	--	--	--
Transformation	--	--	--	-2619	--	*-127159	--	1410	--	*-128368	*-127159
Electricity plants	--	--	--	-2619	--	*-3050	--	1410	--	-4259	*-3050
CHP plants	--	--	--	--	--	--	--	--	--	--	--
Heat plants	--	--	--	--	--	--	--	--	--	--	--
Coke ovens	--	--	--	--	--	--	--	--	--	--	--
Briquetting plants	--	--	--	--	--	--	--	--	--	--	--
Lequefaction plants	--	--	--	--	--	--	--	--	--	--	--
Gas works	--	--	--	--	--	--	--	--	--	--	--
Blast furnaces	--	--	--	--	--	--	--	--	--	--	--
NGL plants & gas blending	--	--	--	--	--	--	--	--	--	--	--
Oil refineries	--	--	--	--	--	--	--	--	--	--	--
Other transformation	--	--	--	--	--	*-124109	--	--	--	*-124109	*-124109
Energy industries own use	--	--	--	--	--	--	--	0	--	0	--
Losses	--	--	--	--	--	--	--	-2192	--	-2192	--
Final consumption	*4	--	--	*64339	--	*484891	--	10598	--	*559833	*484891
Final energy consumption	*4			*63535	--	*484891	--	10598	--	*559029	*484891
Manufacturing, const., mining	*4			11426		*42599		6449		*60478	*42599
Iron and steel	--	--	--	--	--	--	--	4893		4893	--
Chemical and petrochemica	--	--	--	--	--	--	--	--	--	--	--
Non-ferrous metals	--	--	--	--	--	--	--	--	--	--	--
Non-metallic minerals	--	--	--	--	--	--	--	--	--	--	--
Transport equipment	--	--	--	--	--	--	--	--	--	--	--
Machinery	--	--	--	--	--	--	--	--	--	--	--
Mining and quarrying	--	--	--	--	--	--	--	--	--	--	--
Food and tobacco	--	--	--	--	--	--	--	--	--	--	--
Paper, pulp and printing	--	--	--	--	--	--	--	--	--	--	--
Wood and wood products	--	--	--	--	--	--	--	--	--	--	--
Textile and leather	--	--	--	--	--	--	--	--	--	--	--
Construction	--	--	--	--	--	--	--	--	--	--	--
Industries n.e.s	*4	--	--	11426	--	*42599	--	1556		*55585	*42599
Transport	--	--	--	*46353	--	--	--	--	--	*46353	--
Road	--	--	--	*45063	--	--	--	--	--	*45063	--
Rail	--	--	--	1290	--	--	--	--	--	1290	--
Domestic aviation	--	--	--	--	--	--	--	--	--	--	--
Domestic navigation	--	--	--	--	--	--	--	--	--	--	--
Pipeline transport	--	--	--	--	--	--	--	--	--	--	--
Transport , n.e.s	--	--	--	--	--	--	--	--	--	--	--
Other	--	--	--	*5757	--	*442292	--	4149	--	*452199	*442292
Agriculture, forestry, fishin	--	--	--	*3506	--		--		--	*3506	--
Commerce, public services	--	--	--	*219	--	*47100	--	1234	--	*48553	*47100
Households	--	--	--	*2032	--	*395192	--	2252	--	*399477	*395192
Other consumers	--	--	--	--	--	--	--	*662	--	*662	--
Non-energy use	--	--	--	*804	--	--	--	--	--	*804	--

From the structure of the energy balance shown in, it was created the energy system for Tier 1 Model, which is called Reference Energy System (RES). As explained in 1.2.1, and defined in the IPCC Fifth Assessment Report [18], the energy system "*comprises all components related to the production, conversion, delivery, and use of energy*". In Figure 11, each box represents a Technology: on the left side there are the technologies for the extraction of primary energy sources, in the middle the conversion technologies which produce the useful fuels, and on the right side distribution technologies which have as output the final service or demand. The model, being "demand-driven", finds an optimal combination of operating technologies to meet the final demands.

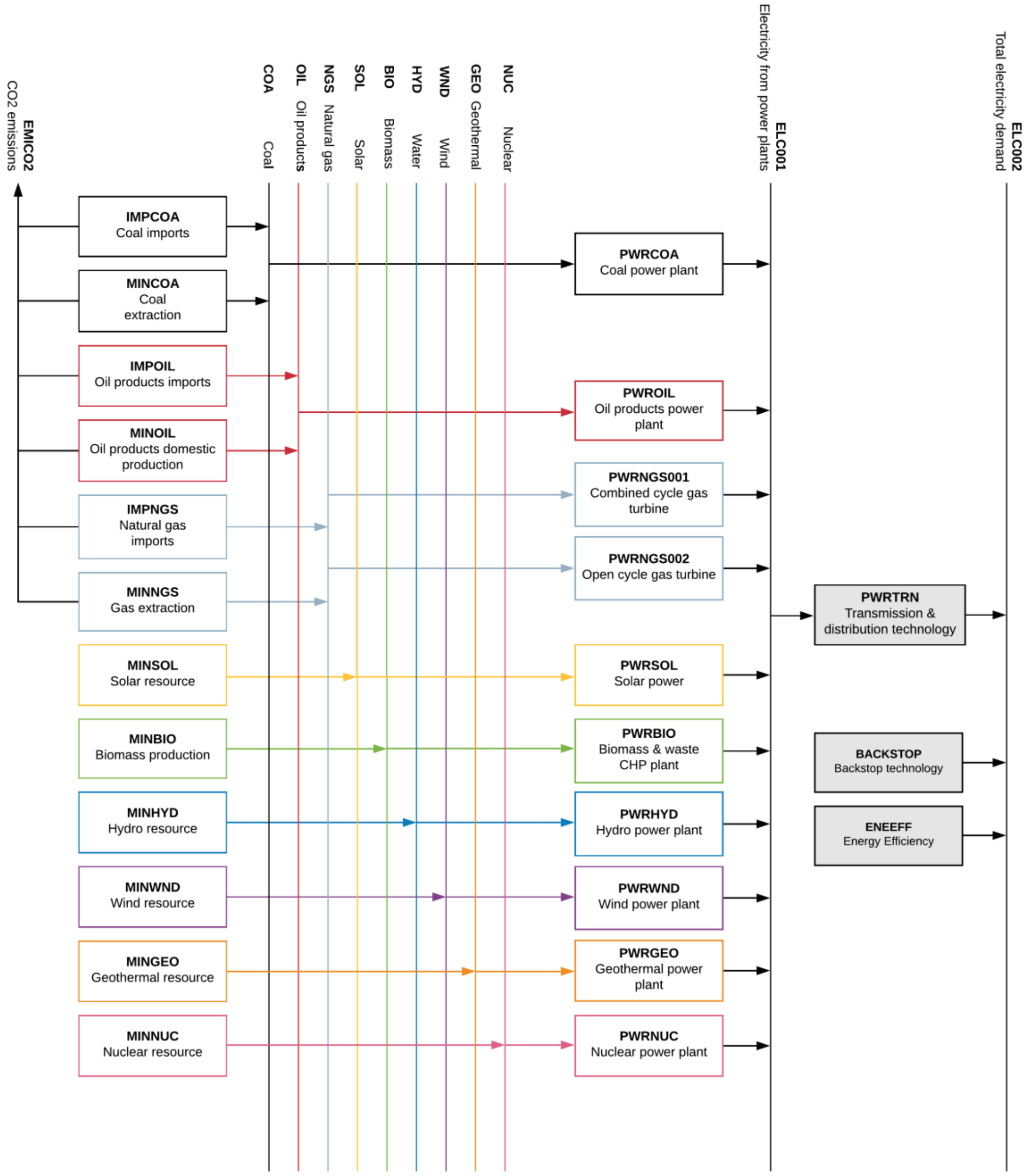


Figure 11: Reference Energy System for Tier 1

3.2. OSeMOSYS Parameters

In this sub-section, the main OSeMOSYS parameters are introduced. Those are needed to get started with the modelling exercise and building the Tier 1 Model in CCG-SAND Interface. Annexe C includes the specific assumptions taken for this study.

3.2.1. InputActivityRatio and OutputActivityRatio

Each technology is linked to its input and output fuel by two OSeMOSYS parameters, namely InputActivityRatio and OutputActivityRatio. By defining these two elements, the user includes the efficiency of each technology as described in Eq. 1:

$$\text{InputActivityRatio} = \text{OutputActivityRatio} / \text{Efficiency} \qquad (1)$$

It is common practice in the OSeMOSYS Community to set the OutputActivityRatio equal to 1 (unitarian product). To account for the efficiency, therefore for the losses, the InputActivityRatio value is increased accordingly. For example, assuming that technology has an efficiency of 54%. To obtain an OutputActivityRatio of 1, the InputActivityRatio has to be 1.852.

3.2.2. CapacitytoActivityUnit

The installed capacity of each technology is related to its energy generation with the OSeMOSYS parameter called CapacityToActivityUnit. If a 1 GW technology operates at full capacity the entire year:

$$1\text{ GW (installed capacity)} * 8760\text{ hours/year} = 31.536\text{ PJ/year}$$

Therefore, 31.536 PJ/year is the value that should be added to the CapacityToActivityUnit for every converting technology.

3.2.3. Division of the Year

To carry out a modelling exercise with OSeMOSYS, it is necessary to assign values to the set called Timeslices, which represents periods of the year with a similar demand. As explained in 1.2.5.1, a timeslice represents the time split of each modelled year, therefore the time resolution of the model, which is necessary to assess the demand profile for fuels that are expensive to store (i.e. electricity) during the year. To reduce computational time, these ‘slices’ are often grouped. Thus, the annual demand may be split into aggregate seasons where demand levels are similar (such as ‘summer, winter and intermediate’). Those seasons are made of days which may be further subdivided (i.e. day and night) depending on the level of demand [28]. In this model, the year was initially divided into 4 timeslices, representing four periods of 3 months each which have similar demand, further sub-divided in a day-night period and called: Summer Day (SD), Summer Night (SN), Winter Day (WD), Winter Night (WN). However, as in CCG-SAND Interface, it is possible to define up to 96 timeslices, these initial data were manipulated to obtain a 24-hour representation of a reference day for each of the four seasons (24 hours/season * 4 = 96 timeslices).

The parameter YearSplit was instead used to define the load curve of the electricity demand. The user can define the duration of each part of the day and the length of each season. The only requirement is that the sum of each entry over one modelled year should equal 1, being the YearSplit the duration of a modelled timeslices, expressed as a fraction of the year. Further information on YearSplit, timeslices and SpeficiedDemandProfile is collected in Annexe C.

3.2.4. Demands

Tier 1 Model includes only the electricity demand (ELC002) that is satisfied by an optimal combination of technologies from the Reference Energy Systems (RES) above (Figure 11). The demand can be found in the Energy Balance of the country of interest and estimated until 2070 (end of the modelling period in CCG-SAND Interface) with a projected growth rate. The units used for the ELC002 demand were PJ. The annual electricity demand (ELC002) is defined using the parameter SpecifiedAnnualDemand, which depends on a SpecifiedDemandProfile. The latter is equivalent to the daily load curve of the demand, in other words as defined in the OSeMOSYS Documentation [27], it is the “annual fraction of energy-service or commodity demand that is required in each time slice. For each year, all the defined SpecifiedDemandProfile input values should sum up to 1”.

3.2.5. Electricity supply system

The model is “demand-driven” meaning that the solver always finds a combination of technologies able to supply the required demand. For example, in the Tier 1 Model, to address the electricity demand, the model can choose between different types of power plants: Hydro, Solar, Nuclear, Gas, Coal, Biomass and Wind. Each modelling year (from 2015 till 2070), the solver finds the optimal generation mix of technologies. Therefore, there might be just a single technology operating or a different (optimal) share of each of the available one. Let us assume that the model chooses the Open-Cycle Gas-fired Turbine (OCGT). Then, following the Methane (Natural Gas) chain, the solver analyses, which is the best option to provide the input fuel to the technology, importing or locally producing it (if possible).

3.2.6. Backstop Technology

Backstop technologies are fictitious back-up technologies that are added as a common practice in the OSeMOSYS Community. They have high fixed, variable and capital costs, which make them the last resort option for the solver that is set to minimise the total discounted cost of the system (NPV). If the Backstop technology is running, it means that there are bugs in the data input by the user. In general, by gaining experience in creating a model, the frequency of this error decreases, if not disappear.

3.2.7. Costs

In CCG-SAND Interface as well as in OSeMOSYS, it is possible to specify per each technology (represented with boxes in the RES) the value of its overnight (capital) investment, fixed cost and variable cost of operation. The parameters used in this case are the CapitalCost, FixedCost and VariableCost, expressed in $/GJ.

3.2.8. Capacities

There are many parameters in OSeMOSYS, which give the user the freedom to define capacities in the model. For example:

a) ResidualCapacity is the parameter used to define a capacity already in operation before the beginning of the modelling period;

b) TotalAnnualMaxCapacity and TotalAnnualMinCapacity are parameters used to apply upper or lower constraints on the installed capacity of a specific technology each year.

The demand for energy changes during the year, during a specific season and even during a single day. For this reason, it is necessary to manipulate the data and increase the installed capacity to cope with the peaks in demand, using the ReserveMargin parameter.

3.2.9. Energy Policies

Energy policies can be translated into constraints and specific data that can be set in CCG-SAND Interface and later visualized in the results obtained with the OSeMOSYS code and the "Results Viewer Template". For example, a policy aiming at phasing-out fossil fuels results in an applied constrain on the emissions produced by the entire energy system. It is possible to define the specific emission value of each technology with the EmissionActivityRatio parameter. The constraint is then applied on the AnnualEmissionLimit, which if it is set to 0 makes sure that the solver finds an optimal mix of technology which do not emit CO_2 emissions. EmissionActivityRatio and AnnualEmissionLimit are time-dependent meaning that each modelling year the user can define a specific value for both. These OSeMOSYS functionalities are essential to include time commitments or country-target.

3.2.10. Emissions

To account for CO_2 emissions, it was assigned a specific EmissionActivityRatio value to diesel import (IMPDSL) and diesel locally produced (MINDSL), to gasoline import (IMPGSL) and gasoline production (MINGSL), to coal import (IMPCOA) and coal extraction (MINCOA), to natural gas import (IMPNGS) and natural gas production (MINNGS).

3.2.11. Operational Life

The last parameter here analysed is the OperationalLife which represents the lifespan of technology, and it is a parameter independent of time.

3.3. Overview of Tier Model 1

The specific characteristics of the Tier 1 Model are the following:

a) For each primary source are provided two alternatives paths of production: the commodity can be either imported or locally produced in the country of interest;
b) The transformation between energy source and energy flows was accounted for in the efficiency of each technology;
c) To each energy source was assigned a specific CO_2 emission value, which was considered as another flow of energy. Further information on the emissions is provided in 3.2.10;
d) Two competing gas-fired power plants (technologies) were included, one representing an Open-Cycle gas-Fired turbine (PWRNGS001) and a more efficient option such as the Closed-Cycle Gas-fired Turbine (PWRNGS002).
e) For simplicity, Transmission and Distribution lines of the electrical grid were aggregated in a single technology (PWRTRN);
f) A backstop technology (BACKSTOP1) was added as a common practice in the OSeMOSYS Community. Further information on the Backstop technologies is provided in section 3.1.3.4.
g) A fictitious technology, namely Energy Efficiency (ENEFF), was added. It provides virtual electricity and represents energy efficiency measures to provide electricity efficiently.
h) The aggregated primary source called “Renewables” in the United Nations Energy Balance 2017 [49] was disaggregated in the following competing technologies Wind Power Plants (PWRWND), Hydropower Plants (PWRHYD001) and Solar Power Plants (PWRSOL001);
i) Only the final electricity demand is included in Tier 1 Model (ELC002), while in Table 1, many more demands are presented. Future improvements of this work could aim at adding final demands for oil, coal, gas and biomass and further divided them in commerce, residential, industrial, agriculture.

3.4. Development of Tier 2 Model – Ugandan case-study

Tier 2 Model is an extension of Tier 1 Model, and it is a representation of the Uganda energy sector, which was chosen as a case study to validate CCG-SAND Interface, due to the numerous collaborations with the local institutions, to the existence of an extensive literature review and the availability of open-source data. The higher level of detail of this model is, therefore linked to assumptions related to the Ugandan energy sector and its challenges and constraints. In this section, a descriptive presentation of the model is provided, whereas chapter 4 collects all the data needed to carry out the modelling exercise. Chapter 5 introduces the Ugandan case-study, the background information and the research questions analysed. Figure 12 introduces the Reference Energy System for Tier 2 Model.

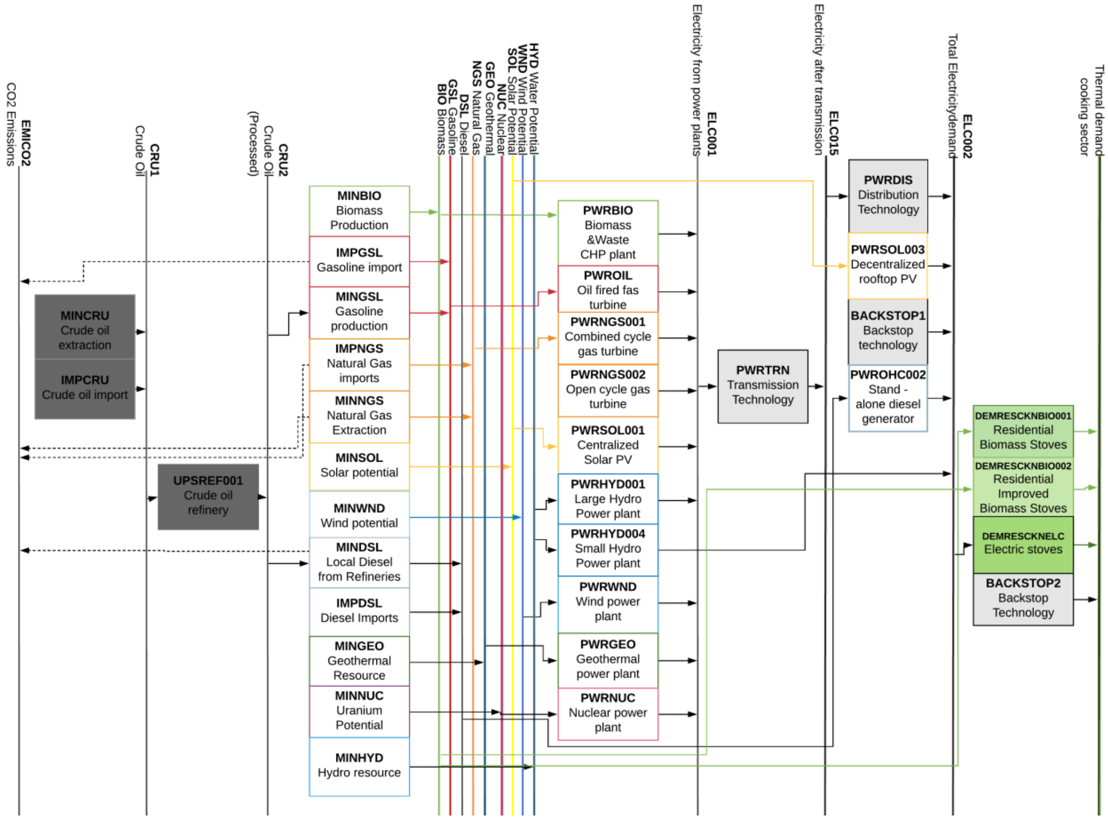


Figure 12: Reference Energy System for Tier 2 Model

3.4.1. Tier 1 and Tier 2 comparison

As it is depicted in Figure 12, the main differences between Tier 1 and Tier 2 Models are the following:

a) To account for their specific losses, Transmission and Distribution are now represented by two different technologies. New flows of electricity are now defined: i) Electricity from power plants (ELC001), ii) Electricity before Transmission (ELC015) and iii) Electricity after transmission (ELC002);

b) The hydrothermal power plants (HPP) were further classified in Small, Medium and Large. Medium and Large HPP were aggregated for simplicity (PWRHYD001); whereas PWRHYD004 represents small HPP.

c) Power plants transforming solar potential in electricity (PV) were divided into Centralized (PWRSOL001) and Decentralized (PWRSOL003) Photovoltaic Power Plants. Further improvement of the model could aim at including Solar Thermal and research its potential in the country;

d) Geothermal Power Plants (PWRGEO001) and Geothermal Potential (MINGEO) constitute a new line which exploits this alternative energy resource;

e) Oil products Power Plants were differentiated into Decentralized Diesel Generator (<1kW) (PWROHC002) and Oil products power plants (PWROHC001);

f) The chain of oil products production reached a new level of detail: crude oil extraction (MINCRU), import (IMPCRU) and refineries (UPSREF001), which were added to the model as oil deposits were recently discovered in Uganda;

g) Oil products were split in Diesel (DSL) and Gasoline (GSL) and for each of them was added the option of locally producing it or importing it.

h) A new energy demand (RESCKN) representing the thermal demand for residential cooking was included, and three alternative cooking stoves were also added as explained in 3.4.1.1.

i) The chain of coal was not included as Uganda is not endowed with this natural resource.

3.4.1.1. Thermal demand for cooking applications extension

As mentioned in the previous subsection, two competing energy demands are supplied by different combinations of technologies. It was added the demand for thermal energy for residential cooking purposes. Being time-independent, RESCKN is defined using the parameter AccumulatedAnnualDemand instead of employing SpeicifiedAnnualDemand as done previously in Tier 1 Model with the final electricity demand (ELC002). The assumptions behind the choice of including this new demand are related to the fact that biomass represents the first energy source (90%) of the Uganda energy balance, while electricity accounts only for 2% of the total [49]. The aim was, therefore, to not cut off from the exercise, the major contributor to the energy needs of the population. Three types of cooking stoves were added [3]:

a) Residential Solid Biomass Stoves (DEMRESCKNBIO001, efficiency 18%);

b) Residential Solid Biomass Improved Stoves (DEMRESCKNBIO002, efficiency 54%);

c) Residential Electric Stoves (DEMRESCKNELC, efficiency 95%).

An additional Backstop technology (BACKSTOP2) was also added to the energy system.

3.4.1.2. Tier 2 Emissions

Furthermore, Residential Biomass Stoves (DEMRESCKNBIO001) and Residential Biomass Improved Stoves (DEMRESCKNBIO002) were included in the set of polluting technologies. The rate of emissions of Residential Biomass Improved Stoves was estimated with a proportion based on the efficiencies. Knowing that the specific CO_2 emission (amount on an energy basis) for Residential solid biomass stove is of 113 kg CO_2/GJ, it was assumed that DEMRESCKNBIO002 would emit 37.7 kg CO_2/GJ, as the improved stove have an efficiency three folds higher [50].

4. Data in Brief

4.1. Main modelling assumptions

In subsection, the main assumptions that were taken and the dataset used for the Tier 2 Model on the Ugandan case study are presented.

4.1.1. Electricity supply system

The electricity demand of the country was estimated according to the United Nations Energy Balance 2017 [1], while the National Development Plan, namely “Uganda Vision 2040” [2], provided the data for estimating the demand growth rate until the end of the modelling period. Uganda has historically relied on hydropower to produce electricity, as shown in Table 2 [51]. Indeed, 73% of the installed capacity in 2018 was obtained from hydropower plants.

Oil products, mainly used in the transport sector, have been historically imported. In 2006, new deposits of oil were discovered in the area of Western Rift Valley along Uganda’s border with the Democratic Republic of Congo. Other oil deposits are under exploration. The government aims at fully establishing and appropriately manage the available oil resources for energy security and price stability.

Table 2: Installed Power Plants Capacity in Uganda[51].

Installed Capacity (GW)	**2015**	**2016**	**2017**	**2018**
Small Hydro Power Plants	0.065	0.065	0.082	0.114
Large & Medium Hydro Power Plants	0.63	0.63	0.63	0.63
Oil & Diesel Power Plants	0.137	0.137425	0.137425	0.137
Biomass & Waste Cogeneration Power Plants	0.053	0.0532	0.0962	0.096
Solar PV	0	0.0106	0.0206	0.044
Total Capacity	0.886	0.896	0.966	1.022

The National Planning Authority in 2015 signed the “Uganda Vision 2040” [52]: a development plan for Uganda to improve electricity access and energy security, lower electricity cost, and promote the adoption of the more sustainable, efficient and less polluting cooking solution.

Also, besides the introduction of the less polluting cooking solution, the government, through the national development plan, seeks to reduce the share of biomass energy used for cooking. There are plans for increasing access and consumption of clean energy [52]. In the “Uganda Vision 2040” is disclosed the intention of the government to diversify the energy mix. The following power capacity is expected to be installed in Uganda by 2040, as presented in Table 3. However, it is essential to mention that the government is currently investigating the optimal technology mix that could meet the country’s electricity demand.

Table 3: Installed generation capacity under the “Vision 2040” Development Plan [52].

Technology type (cumulative)	**Generation capacity in 2040 (GW)**	**Percentage**
Hydro	4.5	11%
Geothermal	1.5	4%
Nuclear	24	57%
Solar	5	12%
Biomass	1.7	4%
Peat	0.8	2%
Thermal	4.3	10%
Total	41.8	100%

Nuclear power is expected to play an essential role in the future of the Ugandan energy sector: by 2040, it should represent 57% of the installed capacity according to the “Vision 2040” [52]. This trend is supported by the recent government interest to cooperate with China and Russia for the deployment of uranium reserves available in the north-eastern part of the country. In 2019, an Inter-Governmental Agreement (IGA) between Russia and Uganda was signed to develop capacity building for nuclear power [53]. The country’s uranium reserves are still unknown, and no power plant is under construction at the moment. Future improvements of these data could aim at updating the values with the most recent data and development of nuclear technology in Uganda.

4.1.2. Fuel assumptions

In Uganda, biomass has the lion's share in the energy balance covering around 90% of the thermal energy need of the population [49]. This share can be further broken-up as follows: firewood (78.6%), charcoal (5.6%), and crop residues (4.7%) [54]. Being firewood the most employed type of biomass, it was assumed that the demand is wholly covered only with fuelwood, aggregating in it also charcoal and crop residues. Future improvements of this model could aim at refining this assumption and collect data for the other two biomass sub-categories. The projected fuel prices used for this research are summarized in Table 4. Where publicly available, specific data for Uganda were used; otherwise, data from international reports were preferred. Projections were estimated based on Pappis et al. [55] when no specific study was found. A 20% increase in the price of the imported commodities was assumed, compared to the respective local prices.

Table 4: Fuels prices projection until 2070

Commodity prices	***Year***								***Reference***
$/GJ	***2015***	***2020***	***2025***	***2030***	***2040***	***2050***	***2060***	***2070***	
Gasoline Production	*26.127*	*27.277*	*28.427*	*29.577*	*31.877*	*34.177*	*36.477*	*38.777*	[56][55]
Gasoline Import	*31.352*	*38.542*	*39.692*	*40.843*	*43.142*	*45.443*	*47.743*	*50.043*	[56][55]
Methane (Natural Gas) Import	*9*	*10.6*	*13.3*	*13.7*	*14.3*	*14.8*	*15.5*	*16.1*	[55]
Methane (Natural Gas) Production	*7.3*	*9*	*10.4*	*10.6*	*10.9*	*11.4*	*12*	*12.3*	[55]
Crude Oil production	*10.92*	*11.72*	*12.52*	*13.32*	*14.92*	*16.52*	*18.12*	*19.72*	[56][55]
Crude Oil Import	*13.65*	*14.45*	*15.25*	*16.05*	*17.65*	*19.25*	*20.85*	*22.45*	[56][55]

Diesel Import	*28.68852*	*29.838*	*30.988*	*32.138*	*34.438*	*36.738*	*39.038*	*41.338*	[56][55]
Diesel Production	*34.426*	*35.576*	*36.726*	*37.876*	*40.176*	*42.476*	*44.776*	*47.076*	[56][55]
Fuelwood Production	*3.113*	*3.272*	*3.438*	*3.614*	*3.992*	*4.409*	*4.871*	*5.38*	[57]
Uranium extraction	*0.8975*	*0.8975*	*0.8975*	*0.8975*	*0.8975*	*0.8975*	*0.8975*	*0.8975*	[58]

4.1.3. Emission assumptions

To conduct an environmental analysis, it was assigned to each fuel a specific CO_2 emission factor, as presented in Table 5. For the case of biomass used to meet the thermal demand of cooking applications, as explained in 3.4.1.2, knowing that the specific CO_2 emissions (amount on an energy basis) for residential biomass stoves are of 113 kg CO_2/GJ, it was assumed that the improved biomass stoves would emit 37.7 kg CO_2/GJ, as the improved stove have an efficiency three folds higher [50]. From 2040 onward, a restriction on CO_2 emissions was applied to include in the model the interest of phasing out fossil fuels starting this year.

Table 5: Fuels specific CO_2 emissions [50].

Fuel	**Specific CO_2 emission (amount of energy basis)**
	kg CO_2/GJ
Methane (natural gas)	50
Gasoline	71
Diesel	69
Heavy fuel oil	75
Fuelwood	113

4.1.4. Residual Capacity

To deal with the peaks in the electricity demand, the installed capacity was increased by 15% compared to the peak. This safety value can be introduced in OSeMOSYS using the Reserve Margin parameter. It aims at avoiding load shedding and black-outs.

4.1.5. Transmission and Distribution

The electricity grid in Uganda includes Transmission (>33 kV) and Distribution lines (<33 kV). Uganda Electricity Transmission Company Ltd (UETCL) and Umeme Ltd are responsible for the transmission and distribution services, respectively. Specific data for Uganda were used to account for the electricity grid losses. Transmission and distribution lines losses accounted respectively for 5% and 14% in 2015, as shown in Table 6. Pappis et al. [55] reported improvement in the distribution lines for Uganda: 11.6% in 2030, 9.5% in 2050 and 7.4% in 2070.

Table 6: Techno-economical parameters for transmission and distribution technologies

Technology type	***Input fuel***	***Capital Cost 2015***	***Fixed operation and maintenance cost***	***Variable operation and maintenance cost***	***Operational Life***	***Capacity To-Activity Unit***	***Efficiency***	***Capacity Factor***	***Source***
	-	$/kW	$/kW/year	$/GJ	Years	PJ/(PJ/yr), GJ/kW	%	(%)	
Transmission	Electricity from power plants	96.67	0	11.94	50	31.536	95%	100	[55]
Distribution	Electricity after transmission	1902	0	0.0001	50	31.536	86%	100	[55][59]

4.1.6. Refineries

It was assumed that local refineries would start operating from 2030 onwards. The techno-economic parameters for refineries technologies are presented in Table 7. The fixed operation and maintenance costs are included in the variable costs. Therefore, the value shown in Table 7 is zero.

Table 7: Techno-economic parameters for refineries technology

Technology type	***Input fuel***	***Capital Cost 2015***	***Fixed operation and maintenance cost***	***Variable operation and maintenance cost***	***Operational Life***	***Capacity To-Activity Unit***	***Efficiency***	***Capacity Factor***	***Source***
	Crude Oil	$/kW	$/kW/yr	$/GJ	Years	PJ/(PJ/yr), GJ/kW	%	(%)	
Refineries	Electricity from power plants	96.67	0	11.94	50	31.536	95%	100	[55]

4.2. Detailed power plant assumptions

Table 8 offers the techno-economic parameters of the power plants included in the RES of Uganda, as explained previously in section 3.4 and shown in Figure 12. The dataset here presented includes per each technology the capital cost as in 2015, the fixed operation and maintenance cost, the variable cost, the operational life, the CapacityToActivityUnit parameter and the capacity factors. To account for the technology learning process, which implies the reduction of the costs of technology over time, Table 9 was created. It offers projections of costs for some power plants until 2070.

Table 8: Techno-economic parameters of power plant

Technology type	Input fuel	***Capital Cost (2015)***	***Fixed operation and maintenance cost***	***Variable operation and maintenance cost***	***Operational Life***	***Capacity To-Activity Unit***	***Efficiency***	***Capacity Factor***	***Source***
	-	$/kW	$/kW/year	$/GJ	Years	PJ/(PJ/yr), GJ/kW	%	(%)	
Nuclear Power Plant	Uranium resource	4000	170	1.076	60	31.536	33%	85	[55][58]
Oil products power plant	Gasoline	1467	44	2.556	25	31.536	35%	80	[55][58]
Decentralized diesel generator 1kW	Diesel	752	23	0.306	10	31.536	16%	30	[55]
Combined Cycle Gas Turbine	Natural Gas	700	25	0.940	30	31.536	63%	85	[55][58]

Open Cycle Gas turbine	Natural Gas	400	11.65	1.28	25	31.536	38%	85%	[55][58]
Large and medium hydropower plant	Water resource	2100	55	0.0001	50	31.536	100%	48	[55][60]
Small hydropower plant	Water resource	2700	60	0.0001	40	31.536	100%	55	[55][60]
Solar power	Solar potential	1393	10.5	0	25	31.536	100%	varies	[55][61][60][58]
Decentralized Solar PV	Solar potential	2840	14	0	20	31.536	100%	varies	[55][58][61]
Geothermal thermal plant	Geothermal resource	3100	87.5	0.0001	25	31.536	80%	85	[55][58]
Biomass & Waste Cogeneration Power Plant	Biomass and Waste	3475	127.5	1.390	40	31.536	50%	50	[60][55]

Table 9: Projections of costs of power plants until 2070

Technology type	**Year**								**Source**
USD/kW	***2015***	***2020***	***2025***	***2030***	***2040***	***2050***	***2060***	***2070***	
Solar power	*1,393.00*	*942.6*	*701.75*	*565.6*	*418.9*	*345.6*	*297.7*	*297.7*	[55][58][60][61]
Decentralized Solar PV	*2840*	*2440*	*2040*	*1640*	*1440*	*1240*	*1040*	*840*	[55][58][61]
Geothermal power plant	*3100*	*3083.35*	*3066.7*	*2900*	*2850*	*2700*	*2650*	*2500*	[55][58]
Biomass & Waste Cogeneration Power Plant	*3475*	*3458.3*	*3441.7*	*2100*	*2050*	*2000*	*1950*	*1900*	[60][55]

4.3. Detailed cooking stoves assumptions

In Table 10, the techno-economic data concerning residential biomass and electric stoves are presented. Three types of stoves were considered: Residential Biomass Stoves, Residential Improved Biomass Stoves and Residential Electric Stoves. Those are the three competing technologies to meet the thermal needs of the population for cooking purposes. Due to time-constraints, Liquefied Petroleum Gas (LPG) Stoves were not included. Future improvements of this work could aim at widening the set of stoves considered in the analysis to obtain more detailed and relevant results.

Table 10: Techno-economic parameters for cooking stoves

Technology type	***Input fuel***	***Capital Cost 2015***	***Fixed operation and maintenance cost***	***Variable operation and maintenance cost***	***Operational Life***	***Capacity To-Activity Unit***	***Efficiency***	***Capacity Factor***	***Source***
	-	*$/kW*	*$/kW/year*	*$/GJ*	*Years*	*PJ/(PJ/yr),* *GJ/kW*	*%*	*(%)*	
Residential biomass stoves	*Biomass*	*0.6*	*0*	*3.113*	*5*	*31.536*	*18%*	*100*	[57] [62]
Residential biomass improved stove	*Biomass*	*7.4*	*0*	*3.113*	*7*	*31.536*	*54%*	*100*	[57] [62]
Residential electric stove	*Electricity*	*76.2*	*0*	*0*	*10*	*31.536*	*95%*	*100*	[57][62]

4.3.1. Limitation to the penetration of efficient stoves

The penetration of Improved stoves was limited to the percentage shown in Table 11, to better model the progressive introduction of this new appliance in society.

Table 11: Projections of the maximum share of efficient stoves in percentage (%)

Technology type	**Year**								**Source**
Upper Activity Limit	***2015***	***2020***	***2025***	***2030***	***2040***	***2050***	***2060***	***2070***	
Residential Improved Biomass Stoves	*5%*	*8.5%*	*8.5%*	*12.8%*	*17.1%*	*22%*	*26%*	*26%*	[57]

5. Application to Uganda

This chapter is structured as follows. In Section 5.1, the context is introduced, in terms of general information on Uganda, energy balance, existing infrastructure, challenges and policies. Section 5.2 briefly recalls the methodology (extensively described in 1.6). Section 5.3. presents the assumptions made for the construction of the model. Section 5.4 describes the scenarios and their assumptions, while Section 5.5 presents the graphical results. Section 5.6 is dedicated to the cost-benefit and environmental analysis and final recommendation for policymaking from the analysis.

5.1. Introduction

This section describes the case study of Uganda, its energy mix, policies in place and resources available. This information is used later to define the assumptions of the long-term energy model created to test the functionalities of CCG-SAND Interface and provide insights to policymakers.

5.1.1. Background

Uganda is a landlocked Eastern African country with large areas of inland waters (18%) endowed with natural resources and ample fertile land (34% of arable land) [63] [64]. Figure 13 shows the geographical location on the African continent.

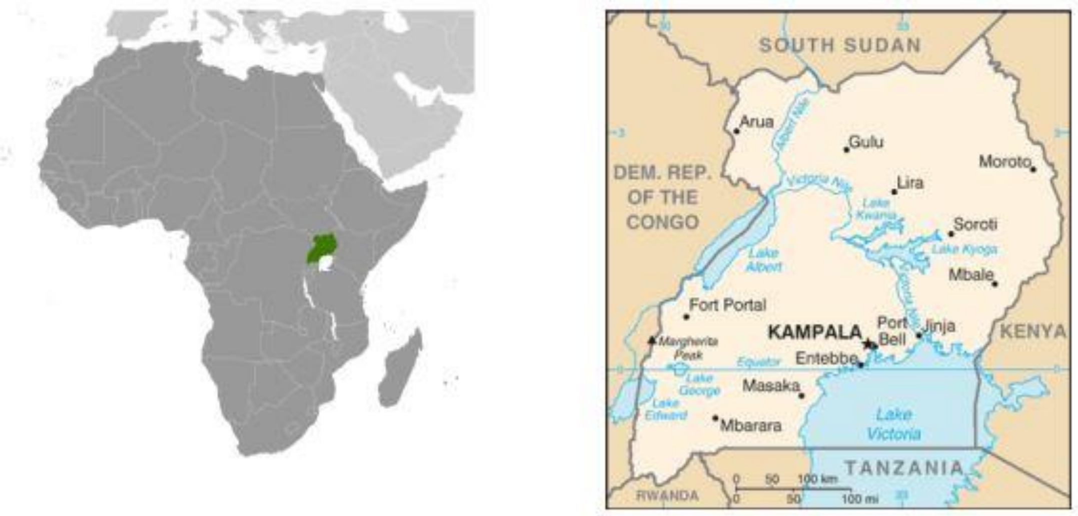


Figure 13: Position of Uganda in the African continent [65]

It inhabits over 40 million people, where the majority (75%) live in rural areas of the country [66]. The electricity access of the population reached 41% in 2018, growing at an average rate of 2.8% in the last ten years [67]. The electrified population can be further classified in urban and rural inhabitants: respectively 54.8% and 7% in 2015 [68]. The annual average electricity consumption, 215 kWh per capita in 2015 [69], is the lowest value in the world (Sub-Saharan average of 552 kWh; World average of 2,975 kWh) in the same range of other developing countries (Ghana at 246 kWh and Zambia at 551 kWh per capita [70]). As shown in the left pie-chart of Figure 14, the total primary energy supply consists mainly of biofuels (90%), then oil products (8%) - mostly used for transport and thermal power plants – and the remaining 2% is electricity [49]. It stands out how biomass is a crucial energy asset in Uganda. In the right pie-chart of Figure 14, it is shown how Uganda relies on hydropower plants for 79% of its electricity generation (with an installed capacity of 0.69 GW in 2015 and 0.74 GW in 2018), oil products power plants account for 15% (0.14 GW in 2018), and Biomass Combined Heat and Power plants (CHP) for the remaining 6% (0.0962 GW) [51]. In search of reducing import dependencies, the country recently explored the possibilities for exploiting reserves within its national borders and successfully discovered reserves of oil and gas as well as uranium.

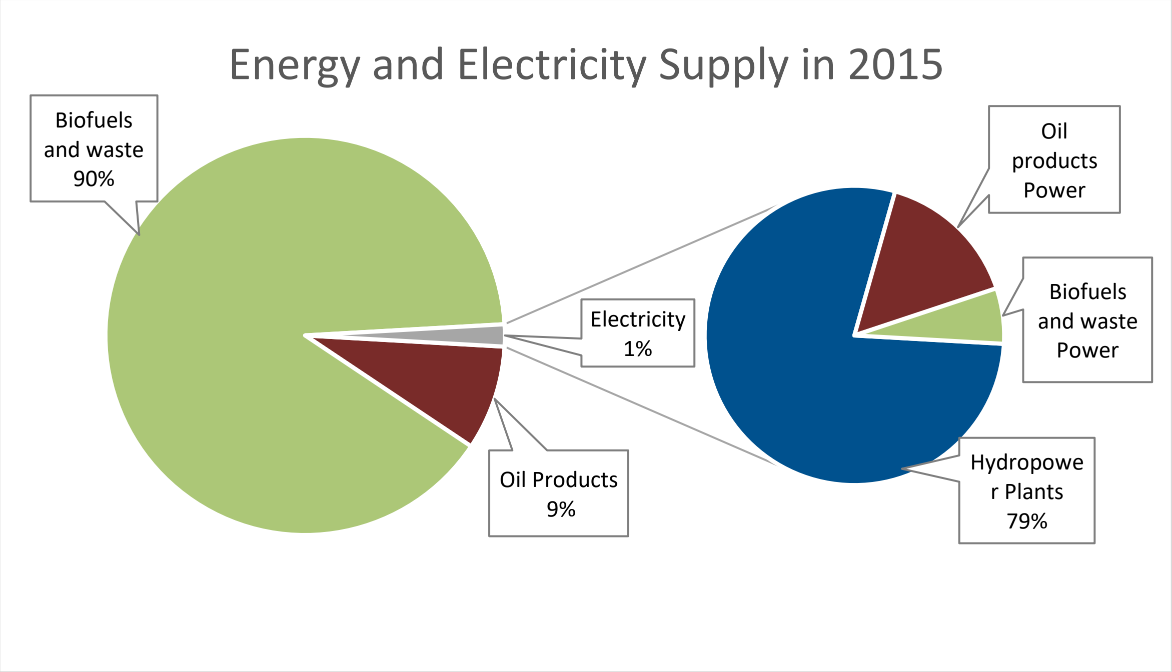


Figure 14: Energy and Electricity supply mix of Uganda in 2015 [51] [49]

5.1.2. Clean Cooking Challenge

Close to 100% of rural households and 98% of urban households use biomass for cooking [62]. The most common cooking technology is the three-stone fire, later in this chapter called Residential Biomass Stoves, with 18% efficiency. This method of cooking is inefficient because much of the heat from the fuel is dispersed before it gets to the cooking pot. Where cooking is done indoors, as is usually the case, it exposes the user to indoor air pollution, which is a significant health issue [62]. In Uganda, according to the World Bank, only 1% of the population has access to clean fuels or technologies for cooking [71]. The trend has not seen any improvements in Uganda in the last 16 years, as can be seen in Figure 15, causing a tremendous impact on the health of the population. To have a more comprehensive overview of the challenges that Uganda is facing, this data was benchmarked with the neighbouring countries: Kenya, Tanzania, South Sudan, Rwanda and the Democratic Republic of Congo. Only Kenya experienced a considerable increase in the percentage of the population with access to clean cooking solutions.

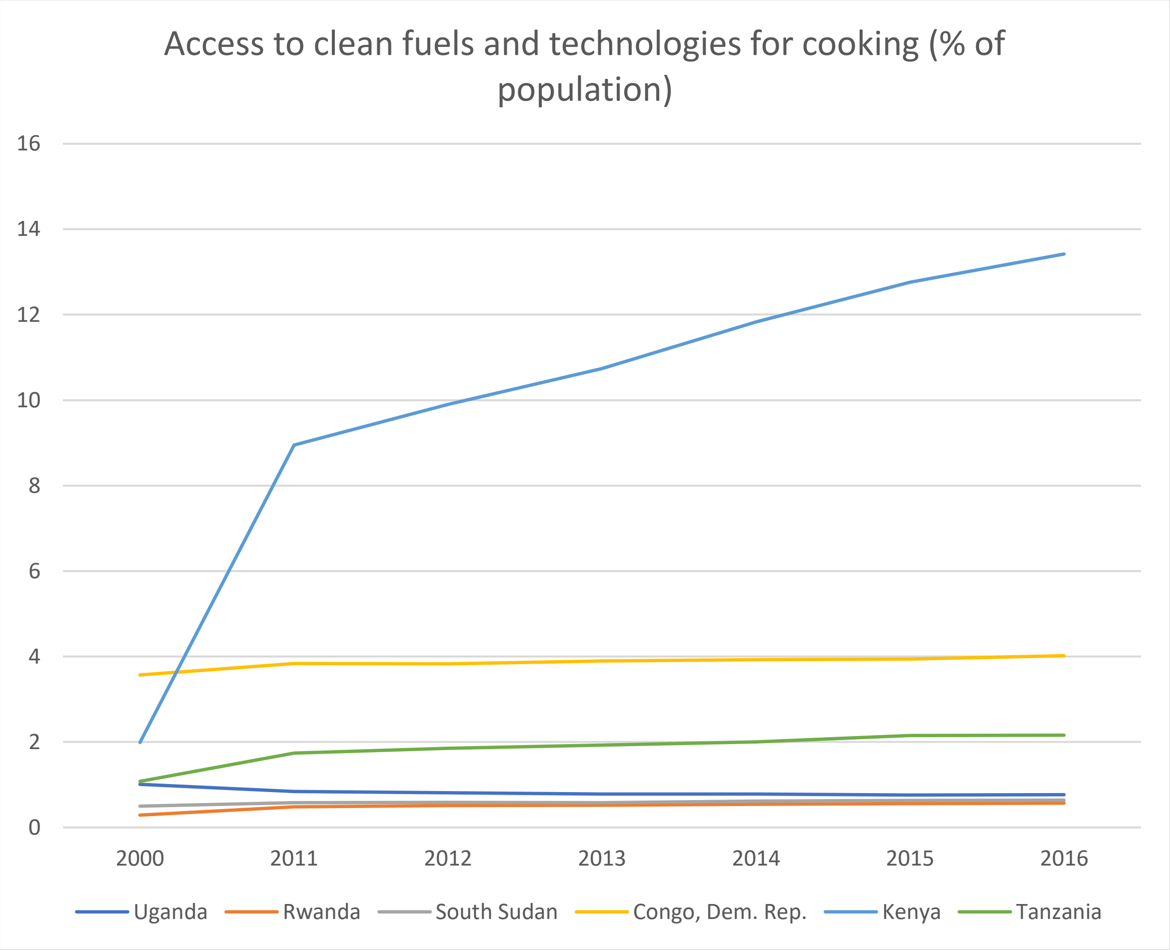


Figure 15: Benchmarking access to clean fuels of technologies in seven countries [54]

Lower Respiratory Infections are one of the primary death causes in Uganda, arising from the use of solid fuels indoors without proper ventilation using inefficient and polluting stoves [72]. The mortality rate attributed to household and indoor air pollution was of 155.7 per 100.000 people in 2016, a doubling of the number in 2012. Compared with neighbouring, the mortality rate is in the same range (Figure 16) as one of the other countries, being Kenya the one with the lowest rate. This trend is in line with the higher access to clean options in Kenya compared to the other countries: a decreased mortality rate due to air pollution is one of the positive effects of clean cooking policy in Kenya.

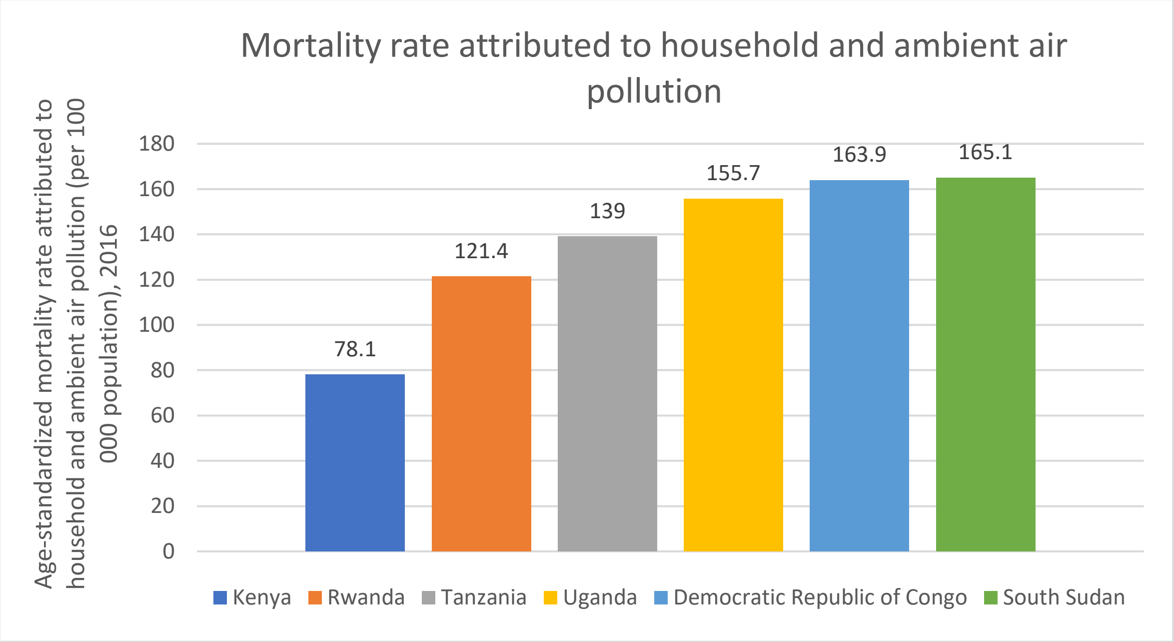


Figure 16: Benchmarking the mortality rate due to air pollution [73]

Also, outside of people's homes, air pollution is a significant problem. The average exposure to air pollution is five times higher than the guideline value recommended by the World Health Organization (WHO) to adverse health effects [74]. Air quality levels are defined considering the quantity of particulate matter (PM) and exposure time. Depending on their size, the particulate is categorized in $PM_{2.5}$ and PM_{10}. Uganda's annual mean levels of $PM_{2.5}$ by far exceed the WHO guidelines by up to five times, being 10 μg/m^3 the recommended annual value for $PM_{2.5}$. These pollutants are more dangerous than PM_{10} because being smaller in size can reach the cardiopulmonary system more efficiently and more in-depth. Kampala, the capital of Uganda, is the second most polluted city in the African continent, mostly due to the inefficient and polluting transportation system, burning waste and manufacturing [74].

Furthermore, the massive demand for solid biomass is causing deforestation in the country. The loss of forest area in the neighbouring countries is depicted in Figure 17. Uganda lost the highest share of forest area as a percentage of the land area since 1990. This rate went from 24% in 1990 to 8% in 2016. Therefore, being the total land area of Uganda 241,037 km² [75], only 19,282 km² of forest remain at present. Every year, around 1300 km² of the forest, equivalent to 217,764 football pitches, are lost due to deforestation.

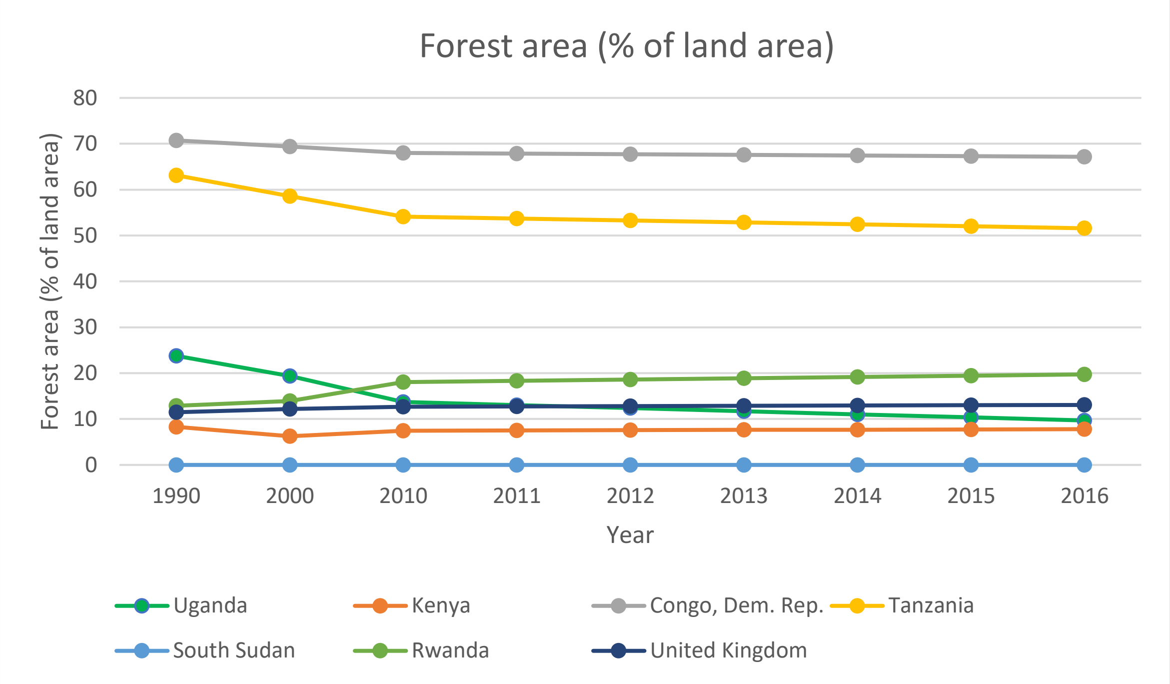


Figure 17: Forest area (% of land area) comparison [75]

Due to the environmental and health problems described above, it, therefore, appears of compelling importance to reduce the dependence from solid biomass for energy (mainly cooking and boiling) purposes in Uganda. This interest is evident in the Ugandan Government Biomass Energy Strategy (BEST), which is further described in 5.1.4.

5.1.3. Climate Change and Electricity Access

As has been described in subsection 5.1.1, in Uganda, 79% of the total electricity is generated using hydropower plants. Although hydropower is considered a renewable and clean technology for electricity production, there are two main challenges related to the dependence of hydropower as a primary source of electricity supply: water allocation and climate change. The integrated System Analysis reported by Sridharan et al. [76] described how vulnerable is the Ugandan energy systems to severe climate events and how difficult it could become in the future to allocate the water resource to electricity generation, rather than to other sectors of the society such as the domestic and agriculture use. On the other hand, temperatures and precipitation forecasts are becoming more uncertain than ever due to climate change. Maslin et al. [77] pointed out that the range of uncertainty in energy and climate models will grow as climate change is every day more evident. This unpredictability does not mean that energy models are not reliable and useful for governments long-term planning.

On the contrary, governments should not wait until the perfect model is created, but rather based their policies on the available evidence. In normal conditions, there are two annual rainy seasons in Uganda, going from March to June and from October to December. However, Uganda regularly experiences weather anomalies called El Niño (prolonged periods of rain) and La Niña (extended periods of droughts). In the recent years, there was a more robust, disruptive and more frequent occurrence of these type of events, sparking the attention of several scientists who have hypothesised and are currently researching if this projected change could be related to climate change and global warming [75].

Therefore, the unpredictability of projections due to climate change poses a higher risk on the security of electricity supply for the Ugandan population, that relies on hydropower, which depends on the water potential. Besides, as documented by Cook [78], it is vital to improve electricity access, in particular in rural areas, to reduce poverty and foster development in the country. These are some of the drivers of the government interest to diversify the energy mix and invest in new technologies such as nuclear, solar, geothermal.

5.1.4. Policy Analysis

The government is investigating more efficient energy solutions. In particular, the following policies were analysed in this study:

- *"Uganda Vision 2040"* [52]: the development plan of Uganda established in 2015 to reduce the use of biomass for cooking and installing new electricity generation capacities (ambitious targets);
- *Biomass Energy Strategy* (BEST) [62]: a document of the Ministry of Energy and Mineral Development of the Government of Uganda published in 2014 and produced in collaboration with the United Nations Departments for Development (UNDP). This document is in line with the "Uganda Vision 2040" plan, and it aims at analysing the biomass sector in Uganda, delineate the need for more efficient cooking solutions and set strategic targets for the coming years;
- *Uganda's Intended Nationally Determined Contribution (INDC)* of 2015 [79]*:* the plan to reduce greenhouse gas emissions under the United Nations Framework Convention on Climate Change (UNFCCC). Among the targets set, there is a commitment to restore forest cover to 21% by 2030.

5.1.5. Available resources

Uganda is endowed with abundant natural resources legally distributed around the country, such as solar, geothermal, biomass, hydropower, uranium and biomass-based cogeneration, which are not fully exploited yet [80].

The country has recently discovered a reserve of 6.5 billion barrels of oil, and it aims at exploiting it as well as building a refinery facility in the coming years [81].

However, in the context of sustainable development, the abundantly available renewable resources form a more promising solution to fossil fuel exploitation for meeting the electrification targets and energy security in Uganda.

5.1.6. Limitations to the implementation

A significant challenge to the deployment of diversified renewable energy generation is the high cost of investments. The government is trying to increase the country's attractiveness for foreign investments in the country. These investments trends are encouragingly supported by the projected decreased cost of energy technologies, i.e. PV panels installations.

5.2. Materials and Methods

This section describes the materials used to perform the energy modelling exercise. The Ugandan case-study was used to test the functional Excel-based interface developed for this Master thesis (CCG-SAND Interface). As extensively described in chapter 2, CCG-SAND Interface is an energy modelling functional mock-up tool, based on the widely used OSeMOSYS for bottom-up long-term energy planning and policy formulation [26]. Furthermore, the supplementary materials, namely the "Data Preparation Template" and the "Results Viewer", were used respectively for a standardized manipulation of the data and to visualize results in the form of graphs. As mentioned in 2.3 and 2.5, they are available for download on Google Drive folder [47]. The following section recalls the primary assumptions made and the constraints applied for the development of the Ugandan Tier 2 model.

5.3. Uganda Model Development

CCG-SAND interface was tested and validated with the Ugandan case-study, for which Tier 2 Model was used. As described in section 3.4, Tier 2 is an extension of Tier 1 Model, and it attempts to represent the Uganda energy sector. The higher level of detail of this model is therefore linked to assumptions related to the Ugandan energy sector, its challenges and constraints. Figure 18 shows the structure of the energy system that Tier 2 represents. As stressed in section 1.2.1, the energy system “comprises all components related to the production, conversion, delivery, and use of energy” as for the IPCC Fifth Assessment Report [19]. Tier 2 models shown in Figure 18 is built in the following way:

a) the blocks on the left side show production of primary resources such as biomass, gasoline, diesel, natural gas, solar potential, uranium potential, wind potential, geothermal resource and water resource;

b) in the middle conversion technologies for the production of electricity were included: biomass and waste cogeneration power plants (PP), small hydro PP, large and medium hydro PP, centralized solar PV, geothermal PP, wind PP, oil-fired gas turbine, natural gas PP, nuclear PP, rooftop solar PV, stand-alone diesel generator;

c) in green are highlighted those boxed representing a conversion technology to address the thermal demand of the cooking sector: Residential Biomass Stoves, Residential Biomass Improved Stoves, and Residential Electric stoves;

d) the delivery of the electricity is assigned to Transmission and Distribution technologies;

e) the end-user, therefore the final demands, are represented as lines in the right side of the figure: electricity demand and thermal demand of the cooking sector. As mentioned before, the final electricity demands of the different sectors of the society, namely transport, industry and households have been aggregated in a single stream called Total Electricity Demand.

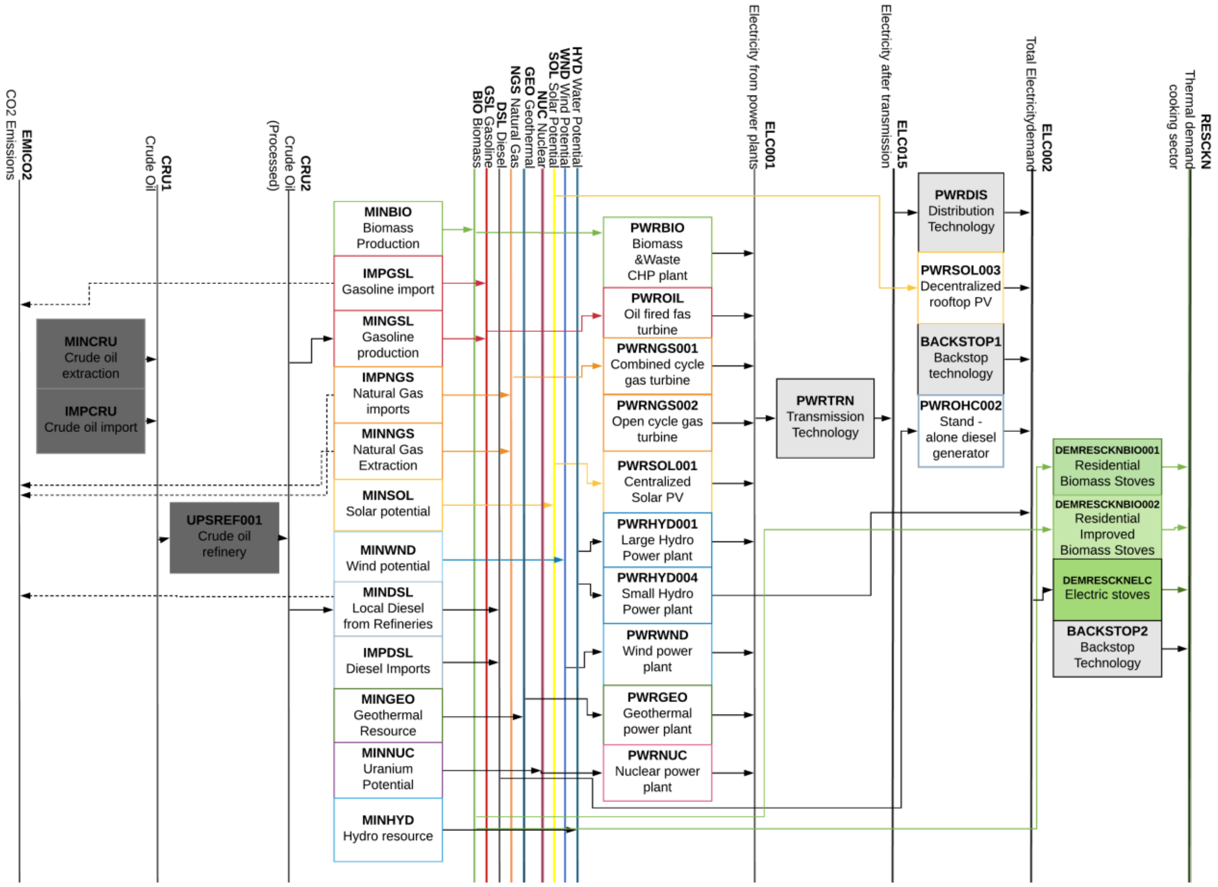


Figure 18: Tier 2 Model for Uganda

Although the transport sector is one of the most polluting in the country, as mentioned above, it was out of the scope of this thesis; however, it represents a good foundation for future expansion of the model.

5.4. Scenarios description

The five scenarios modelled are developed to compare alternative growth pathways for Uganda energy mix with the Business-as-Usual (BaU) Scenario. Therefore, the scenarios of this analysis are six in total, as depicted in Figure 19. The research focused on two main points: first, the interest was to model a lower dependency on hydropower, according to the expected instability in generation due to adverse climate events such as droughts or floods. To address this challenge, it was analysed what would be cost and the emissions associated with the implementation of the "Uganda Vision 2040", which aims at installing a more diverse capacity for electricity generation. Therefore, there are two main scenarios related to electricity generation, BaU and "Vision 2040".

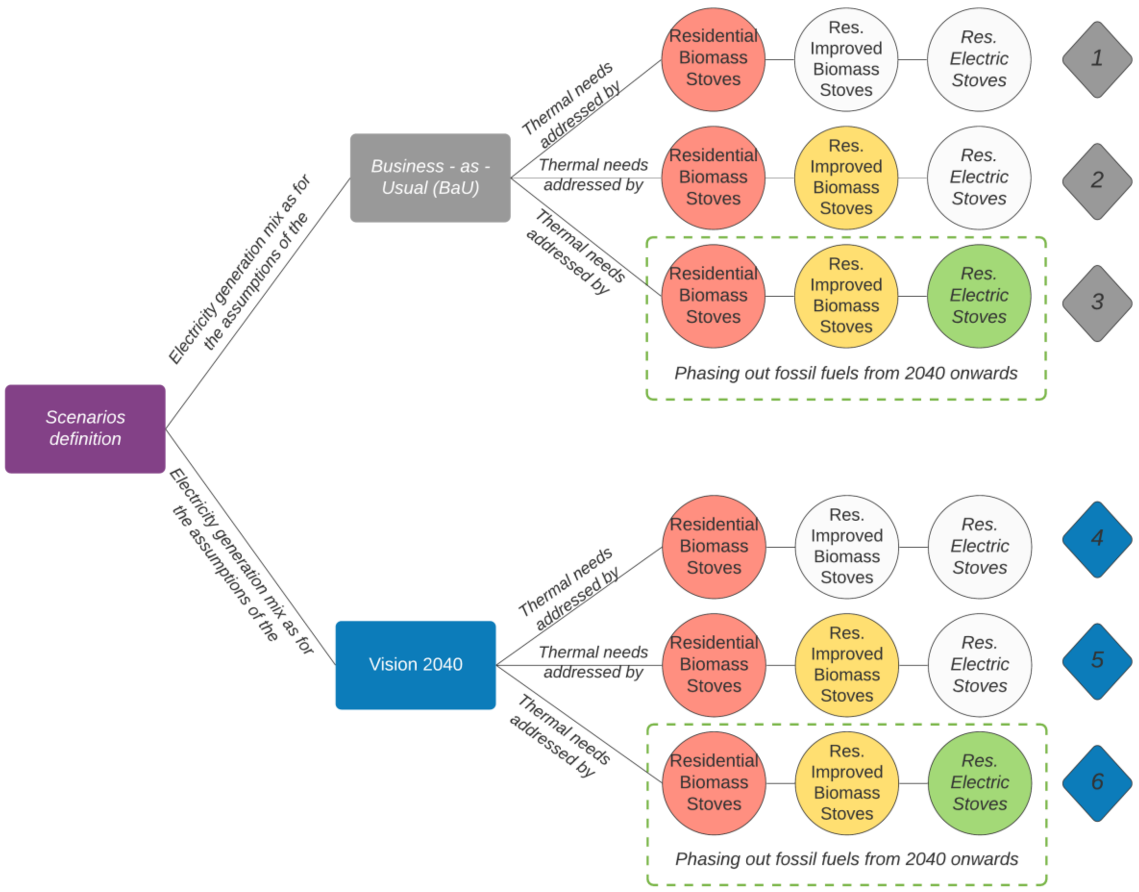


Figure 19: Visual description of the six scenarios analyzed in this thesis

The second focus point was how to reduce indoor pollution from the use of inefficient wood stoves in the cooking sector. For this purpose, three alternative cooking solutions were tested on top of the two main scenarios for the electricity generation, resulting in six scenarios in total.

In each of the scenarios, the thermal demand for cooking purposes is addressed with:

1) using only Residential Biomass Stoves (18% efficiency);

2) with increased penetration of (Residential Biomass) Improved Stoves (54% efficiency) and,

3) using only Residential Electric Stoves from 2040 onwards.

A detailed description of each scenario and assumptions is summarized in Table 12.

Table 12: Description of Scenarios

Scenarios	**Electricity Generation Mix Description**	**Cooking solution**	**Emission Constraints**
1	Business-as-Usual (BaU)	Residential Biomass Stoves	N.A.
2		Residential Improved Biomass Stoves	N.A.
3		Residential Electric Stoves	Phasing out fossil fuels from 2040 onwards
4	Vision 2040	Residential Biomass Stoves	N.A.
5		Residential Improved Biomass Stoves	N.A.
6		Residential Electric Stoves	Phasing out fossil fuels from 2040 onwards

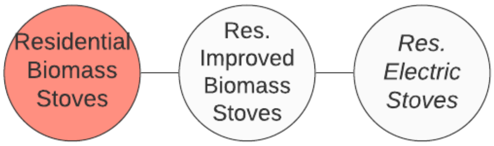
Business - as - Usual (BaU)

5.4.1. Business-as-Usual (BaU)

This scenario aims at reflecting the cost and the emissions of doing nothing. With this aim, no energy policies are applied but instead the historical trends and investments are represented. Capacities are estimated from Climatescope [51]. The share of activity of each technology is assumed to remain constant from 2015 to 2070, following electricity demand growth. Table 13 lists the historical capacity installed in Uganda. Although in 2018, the installed capacity of solar power plants was of 0.032 GW, it was disregarded in the BaU Scenario for the sake of this specific exercise. Future improvement of the model could attempt to add solar power in BaU energy mix. To represent the historical capacities (Table 13), upper constraints, proportional to the installed capacities, were set on the technologies' activity in CCG-SAND Interface.

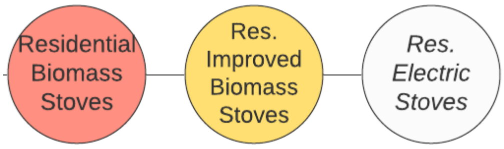
Table 13: Historical Installed Capacity in Uganda [51]**.**

Installed Capacity (GW)	**2015**	**2016**	**2017**	**2018**
Small Hydro Power Plants	0.0654	0.0654	0.0824	0.1141
Large&Medium Power Plants	0.63	0.63	0.63	0.63
Oil&Diesel Power Plants	0.1374	0.137425	0.137425	0.137425
Biomass&Waste Power Plants	0.0532	0.0532	0.0962	0.0962
Solar Power	0	0.0106	0.0206	0.0446
Total	0.886625	0.896625	0.966625	1.022325



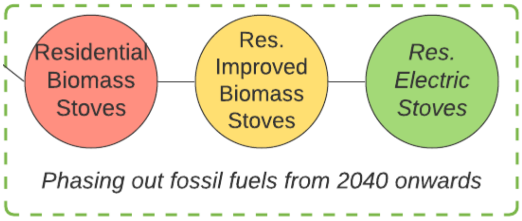
5.4.1.1. Electricity generation BaU with Residential Biomass Stoves

This scenario analyses the effects of electricity generation with BaU assumptions. The biomass demand for cooking is, in this case, addressed only using low-cost Residential Biomass Stoves (efficiency 18% [57], emissions from wood combustion 113 kg CO_2/GJ [82]). These assumptions are in line with what written in the Biomass Energy Strategy of the government [83].



5.4.1.2. Electricity Generation BaU with Improved Stoves

In this second scenario, the BaU assumptions were maintained, but a competing technology to address the thermal demand of the cooking sector was added. Residential Biomass Improved Stoves (efficiency 54% [57], emissions from wood combustion assumed 37 kg CO_2/GJ [82]) were introduced in this scenario. It was assumed that in 2015 the share of Improved Stoves covered only 5% of the total demand, while the rest of the production was left to inefficient stoves (Residential Biomass Stoves). Instead in 2020, the share is assumed to be 8.5%, growing linearly till 2030 when it accounts for 12.5%. These assumptions are based on the study conducted in Nigeria by Okolo et al. [57]. From 2030 until 2070, the share of Improved Stoves was calculated with an estimation of the previous growth trends.



5.4.1.3. Electricity Generation BaU, emission constraint from 2040 and Electric Stoves

The third scenario recalls the assumptions presented in the BaU, but it adds a new constraint, the annual emissions were limited to zero from 2040 until the end of the modelling period. This assumption reflects the interest of Uganda’s government to reduce the emissions related to the electricity sector as included in the INDC of 2015 [79]. The year 2040 was assumed to be the starting time for phasing out fossil fuel in the country as it coincides with the “Uganda Vision 2040” timeline that the government has for the country. Furthermore, this assumption is in line with the WWF target of “100% Renewable Energy Future by 2050” [84] in Uganda, anticipating it of 10 years. Although the commitment to climate neutrality by 2040 was not explicitly mentioned, this model attempts to go a step further than just an emission reduction. It shows what would be the cost and the reduction of emissions that could be achieved if the country’s interest in moving toward a low-carbon future is successfully done. Electric Stoves (efficiency of 95%) were added to address the thermal demand for cooking applications, being the third competing technology for this demand. As for the INDC, this addition reflects the interest of the government to promote the use of more efficient stoves to reduce the country's deforestation and the unhealthy indoor pollution related to burning wood for cooking needs.

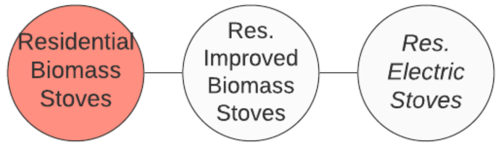
Vision 2040

5.4.2. Vision 2040 Scenario

Vision 2040 is the alternative scenario to the BaU, analysed for electricity generation in Uganda. It reflects the Development Plan for the country, which is called "Uganda Vision 2040". The energy section of this document [52], shows the specific interest of the government to foster the implementation of alternative renewable energy technologies and, in doing so, diversifying the energy mix. In Table 14, the required capacities for electricity generation under study by the government are presented.

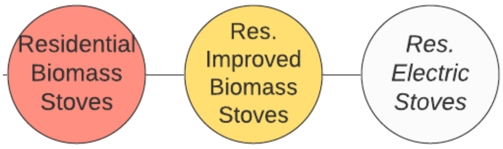
Table 14: Projected generation capacity in 2040 under the "Vision 2040" development plan [52]

	Generation capacity in 2040 (GW)	**Share of generation capacity [%]**
Hydro	4.5	11%
Geothermal	1.5	4%
Nuclear	24	57%
Solar	5	12%
Biomass	1.7	4%
Peat	0.8	2%
Thermal	4.3	10%
Total	41.8	100%



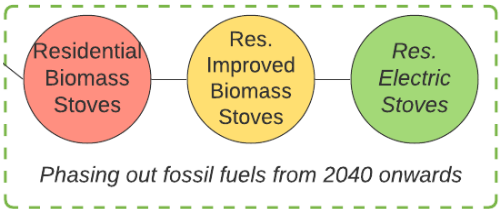
5.4.2.1. Electricity Generation "Vision 2040" and Residential Biomass Stoves

In the 4th scenario, the electricity mix assumptions follows the "Vision 2040" guidelines, while the demand for biomass is addressed, relying only on the most inefficient stoves option. The assumptions and the data concerning the Residential Biomass Stoves are the same presented in subchapter 5.4.2.1.



5.4.2.2. Electricity Generation "Vision 2040" and Improved Stoves

In the 5th scenario, it was analyzed the effect of generating electricity with the newly installed power plants as for the "Uganda Vision 2040" but adding a competing technology to the model to address the cooking sector's thermal demand, Improved Stoves. The assumptions and the data used are the same as explained in subchapter 5.4.1.2.



5.4.2.3. "Vision 2040" electricity generation, emissions constraints from 2040 and Electric Stoves

In the 6th and last scenario, the focus was on modeling a green future, in which from 2040 onwards, there is a diversified, renewable, and reliable electricity generation system as envisioned by "Uganda Vision 2040". Furthermore, in parallel, the cooking sector has three alternative solutions to address its thermal demand: Residential Biomass Stoves, Improved Biomass Stoves, and Electric Stoves. Again, the assumptions for the Electric Stoves are the same as were presented in subchapter 5.4.1.3.

5.5. Results and discussion

In this section, the results obtained by testing the CCG-SAND Interface on the Ugandan case-study are presented.

Business - as - Usual (BaU)

5.5.1. Technical results of Business-as-Usual Scenario

5.5.1.1. Demands

The electricity demand was estimated from the United Nations Energy Balance 2017 [49]. As shown in Figure 20, the total electricity demand in Uganda is expected to see a 38-fold increase between 2015 and 2070, under the BaU scenario assumptions, growing at a 10% rate each year. This growth is in line with the government commitment to increase electricity consumption per capita [52].

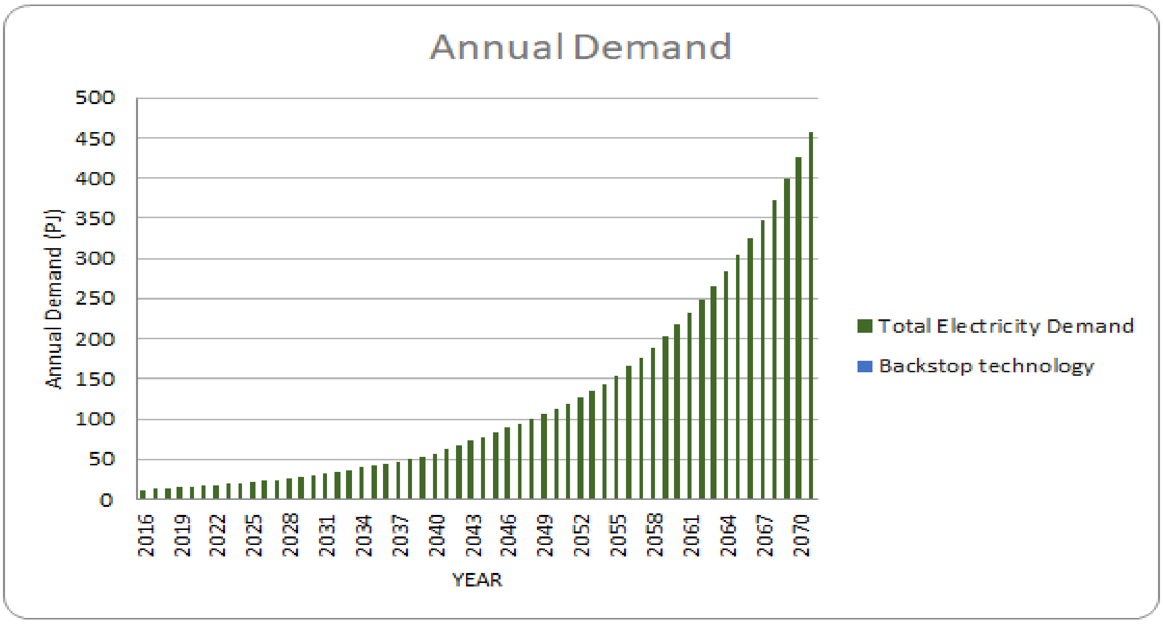


Figure 20: Electricity demand forecast 2015-2070

In the BaU scenario, the thermal demand of the cooking sector increased threefold in the modelling period (Figure 21). The assumptions made here for the growth rate of demand were based on the United Nations Energy Balance 2017 [49].

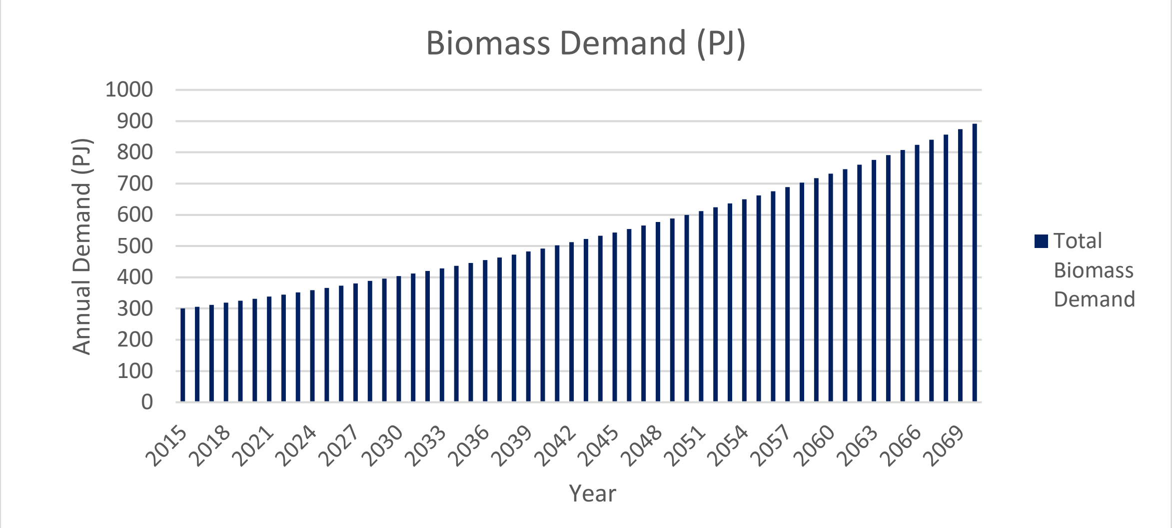


Figure 21: Biomass Demand used to satisfy the thermal needs of the cooking sector

5.5.1.2. Electricity generation mix under BaU

The electricity generation by plant type in the BaU scenario is shown in Figure 22. An upper limit was added to the activity of Oil products power plants (15%), Biomass and Waste cogeneration Power Plants (6%) and small hydropower plant (10%). The percentages were calculated from the historical capacity installed in the country [51]. As a first case study, it was of interest to hypothesise that there is no policy deviation and the Uganda government continues to invest in the same power technologies as done in the past. As expected, large and medium hydropower plant would then have to supply most of the electricity demand.

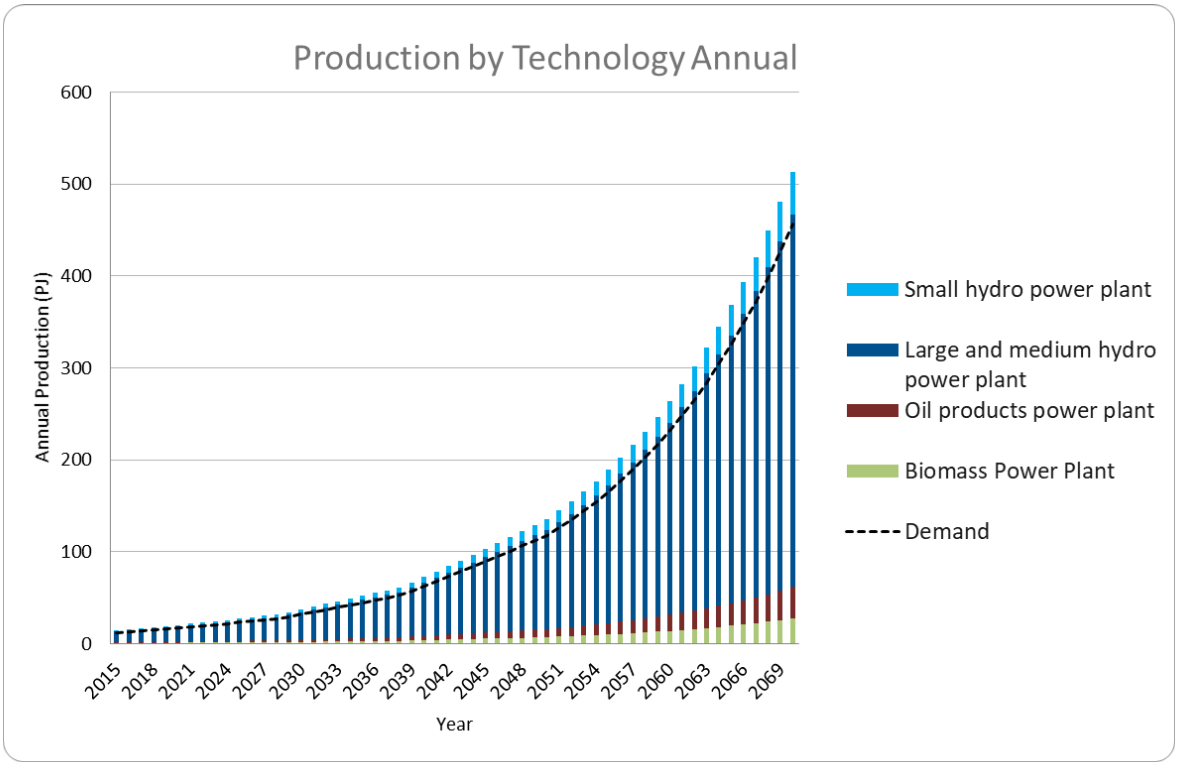


Figure 22: Electricity production by power plant type in the BaU Scenario

Vision 2040

5.5.2. Electricity generation mix under “Uganda Vision 2040.”

The electricity generation mix under “Uganda Vision 2040” was modelled. It is the government plan to install a variety of different power technology in the country by 2040. The detailed capacity presented in the official document is reported in 5.4.2. Therefore, lower constraints were included from 2040 to 2070 to ensure that those capacities were installed. In this way, the policy was replicated, but the model could still freely optimize to find the cheapest technology to address the remaining demand, as no upper limit was added. From 2015 until 2040, the assumptions made for the BaU scenario were applied, adding a small penetration of Solar Power (10%) increasing during these 35 years. As Figure 23 shows, from 2040, new technologies are producing electricity, whether in the BaU scenario results represented in Figure 22: Electricity production by power plant type in the BaU ScenarioFigure 22, mainly hydro is generating electricity. The lion’s share is now of the Nuclear Power plants which provide up to 57% of the electricity needed.

Nevertheless, also, geothermal thermal plants, centralized and decentralized solar power solutions, biomass, small, large and medium hydro play their part. When choosing between Oil, Coal or Gas turbine, the model found in the Combined Cycle gas turbines the optimal solution to address the demand. No constraints on the total annual emission were applied in this scenario.

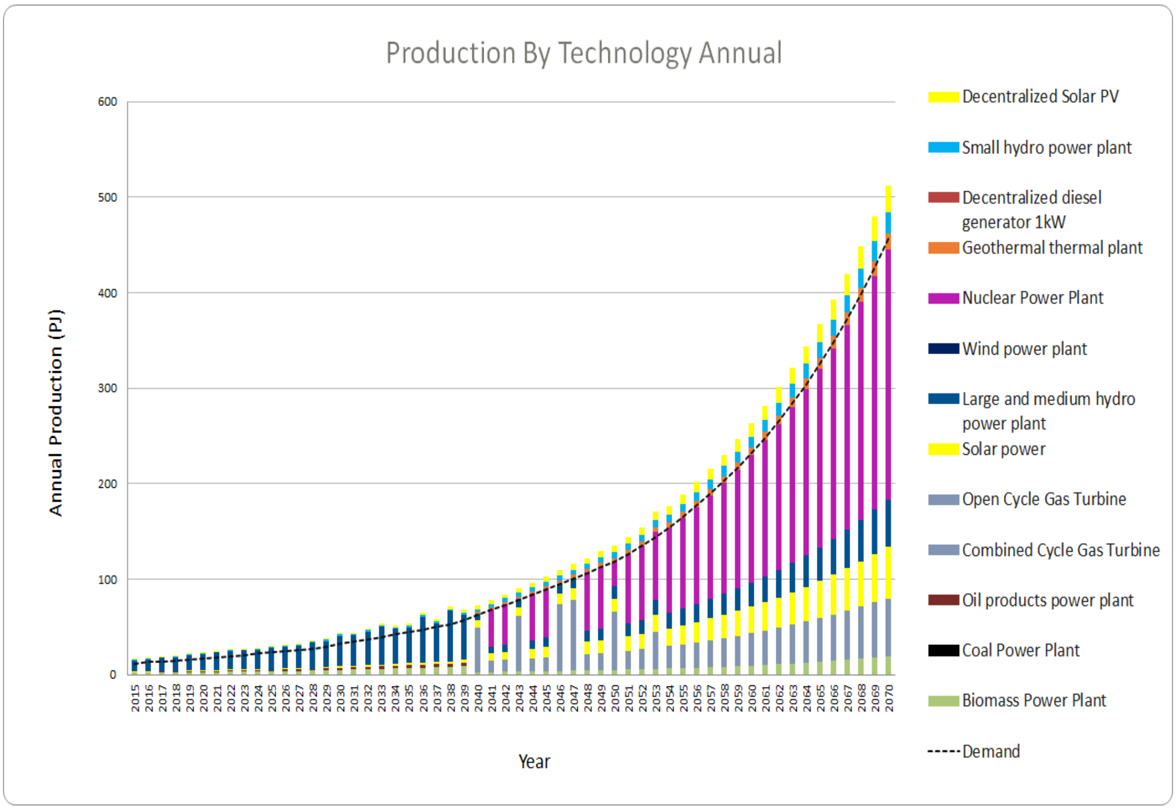
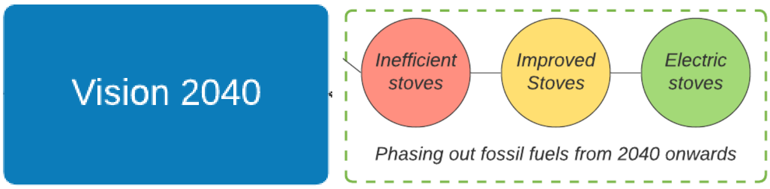


Figure 23: Electricity generation by power plant type under the “Vision 2040” Scenario



5.5.2.1. Electricity generation mix under “Uganda Vision 2040” policy and emissions constraint

This subsection presents the specific results obtained under the “Vision 2040” Scenario for electricity generation with the applied constraint on the emissions from 2040 onwards. It aimed at replicating what would happen in economic and environmental terms if fossil fuels are phased out.

Figure 24 shows how the electricity demand increased when the constraint on the total annual emissions was applied. The increased demand for electricity can be justified by the fact that from 2040 onwards the only technologies operating to supply the thermal demand for cooking news are the Electric Stoves. Using electricity as an input fuel, rather than fossil fuel, the introduction of Electric Stoves clarifies why electricity demand would grow accordingly. What was before fuelled by biomass (with inefficient and efficient stoves), is now fuelled with electricity. The electricity demand would then reach more than 1400 PJ in 2070.

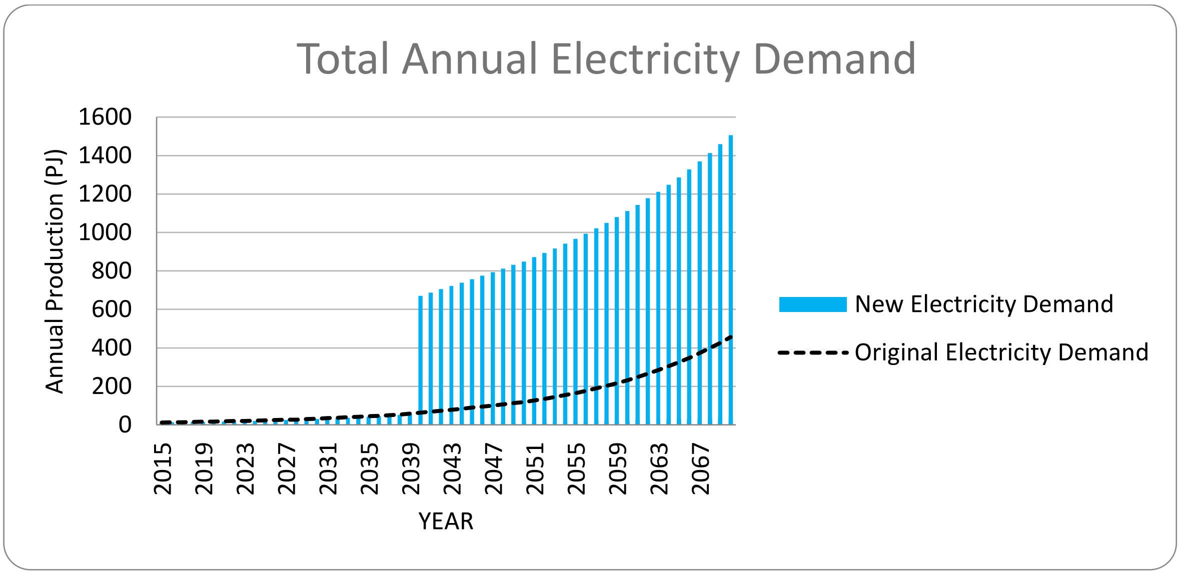


Figure 24: Increase of the total annual energy demand in the Phasing out fossil fuels scenario

As Figure 25 shows and as expected, the electricity production is assigned to technologies that do not use fossil fuels as an input, therefore: nuclear, solar, hydro, geothermal and biomass power plants. The high variance of production during the modelled years is explained by the variability of renewable sources which make up the energy generation mix. The activities of Biomass Cogeneration PP and Hydro PP were upper limited to reflect the interest of the government to reduce the dependency from hydropower for the electricity generation and from biomass for addressing the thermal cooking needs.

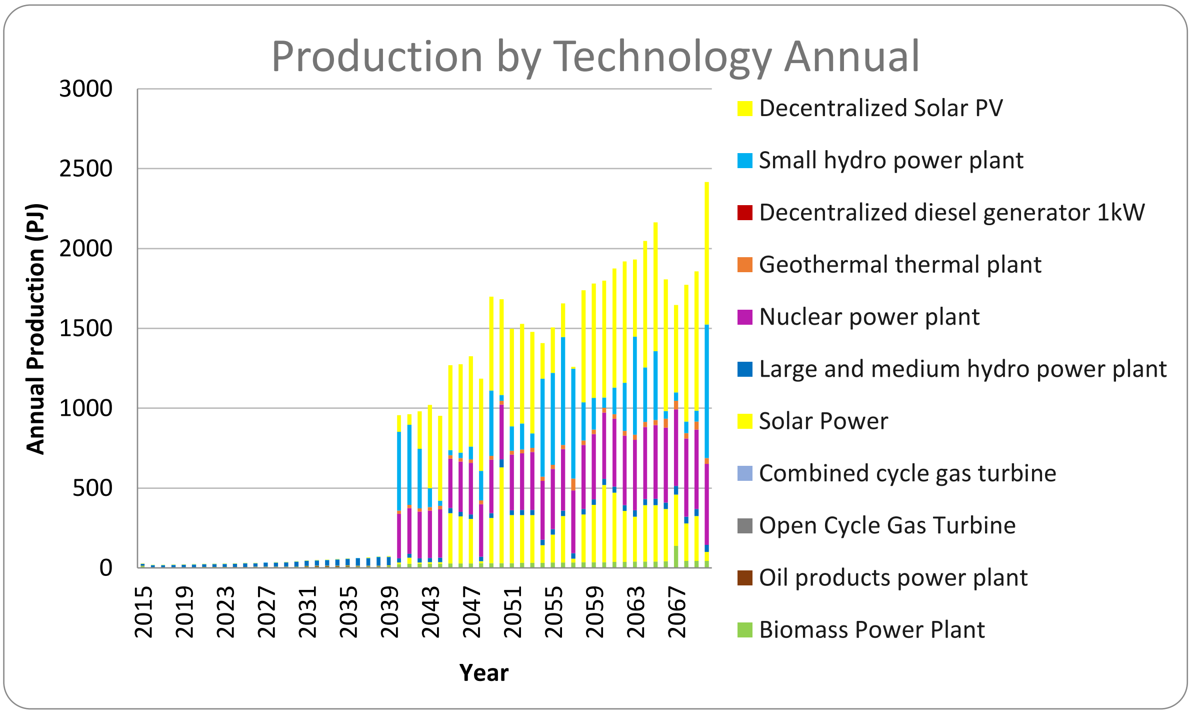


Figure 25: Electricity generation by plant type phasing out fossil fuels under the “Vision 2040.”

5.5.3. Cooking stoves analysis

Figure 26 presents the results obtained after modelling the three different combinations of Residential Stoves to address the thermal demand for cooking purposes. These three configurations were replicated with both the BaU and “Vision 2040” assumptions of electricity generation, as explained in 5.4. The upper graph of Figure 26 shows trends in line with what expected: only Residential Biomass Stoves (with an 18% efficiency) operate. The graph in the middle depicts the increased penetration of (Residential Biomass) Improved Stoves in the energy mix. An upper, but not a lower, limit on the activity of the Improved Stoves was set to reflect the actual situation in the country and the assumptions taken from Okolo et al. [57]. Lastly, as shown in the bottom graph, when the constraints on the activity of the Residential Electric Stoves (which have higher efficiency and cost) were released, the model would choose to operate them only from 2040 onwards when a constraint on the emissions is applied.

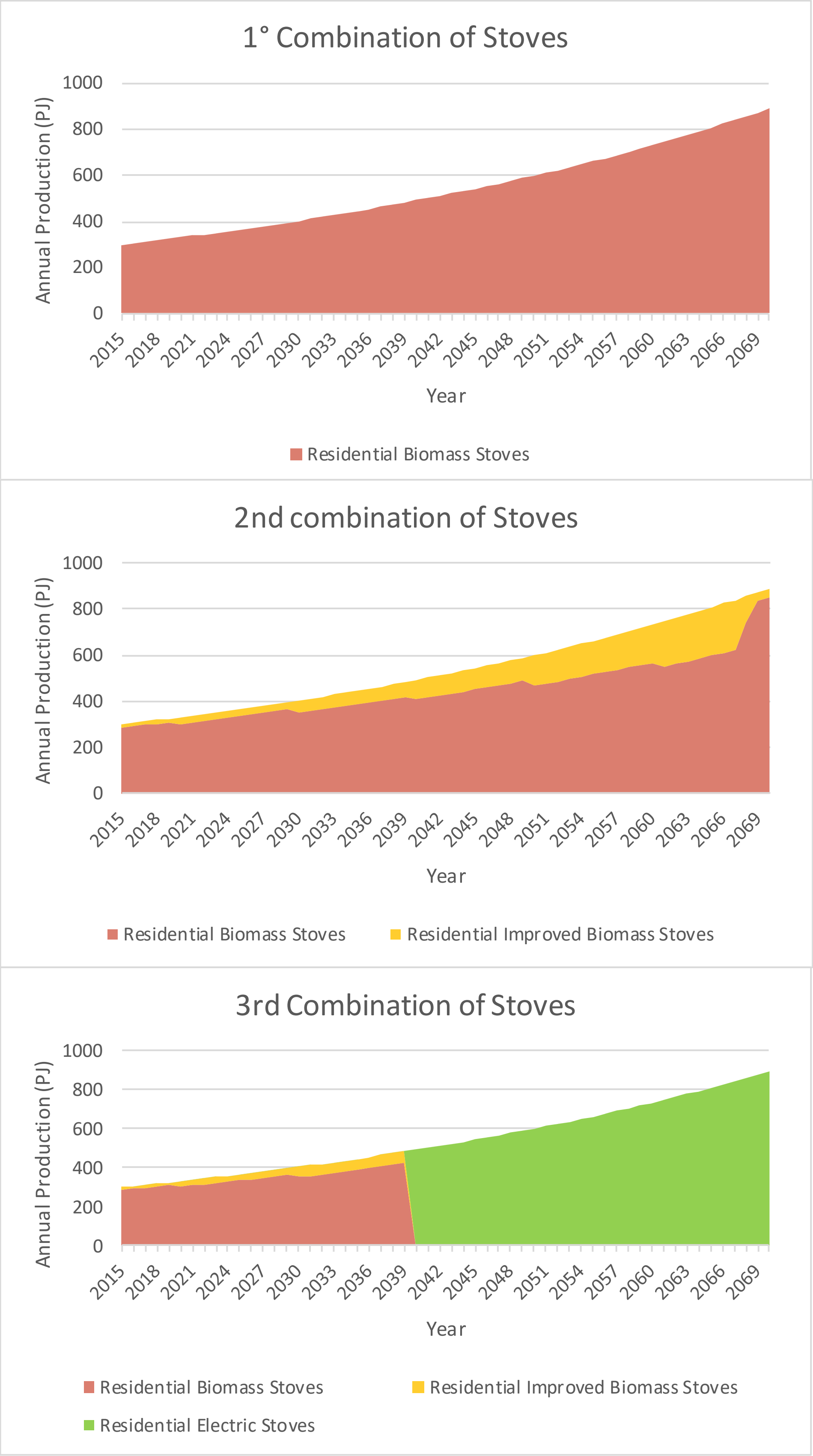


Figure 26: Annual Production (PJ) by Stove type under three alternative combinations

5.6. Cost-Benefit and Environmental Analysis

In this section, a cost-benefit analysis of the six scenarios is presented. Figure 27 summarized the results obtained the six scenarios modelled in this Master thesis. A comparison between the cumulative Total Discounted Cost and the Total Emissions in the period 2015-2070 is presented. Table 15 presents the detailed break-down of economic and environmental, respectively, results obtained for each scenario and a comparison with the BaU Scenario.

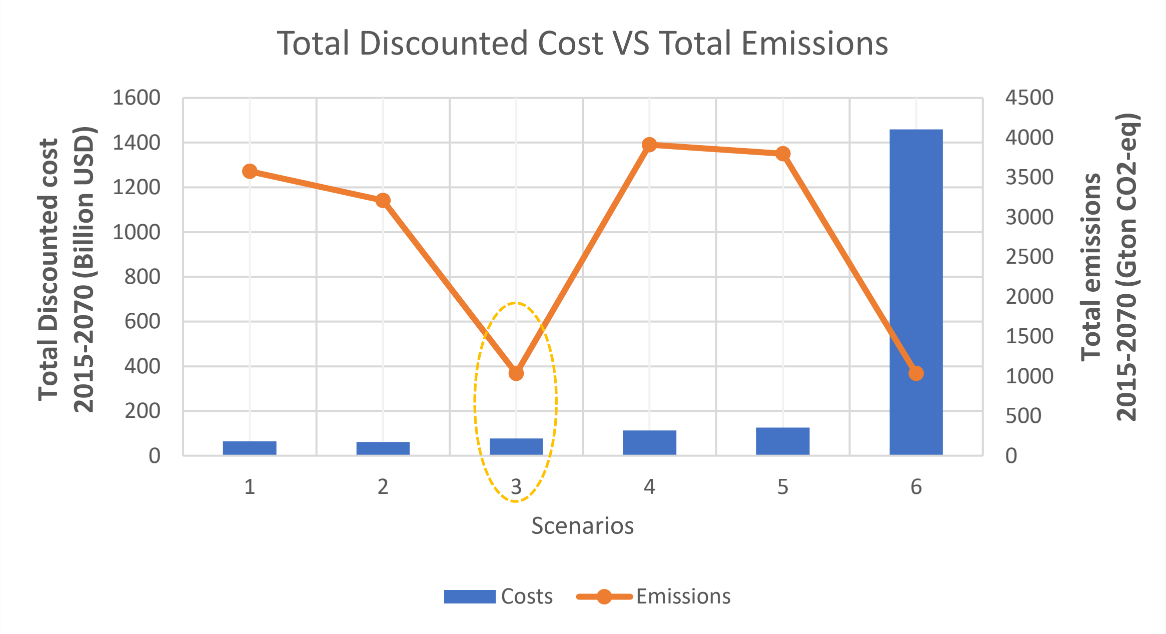


Figure 27: Total Discounted Costs comparison with Total Emissions under the six scenarios

As expected, the implementation of the “Vision 2040” Policy (Scenario 4) increases the total discounted cost of +76 % compared to the BaU scenario (Scenario 1) assumptions for electricity generation (see Table 15). The other expected result was an increase in the total discounted cost when phasing out fossil fuels from 2040 onwards (Scenario 3 and 5). However, what is worth to mention is that when phasing out fossil fuels and applying the “Vision 2040” policy, the cost increases of +2178% (Scenario 5). This high number is explained by the fact that probably this policy should be revised as it relies mainly on nuclear power plants, which are the most expensive technology available. From these results, it is possible to conduct a preliminary sensitivity analysis of the model. The introduction of Improved and Electric stoves does not have the same economic impact as the implementation of the policy “Vision 2040” (Scenario 3,4,5). This effect can be noticed by the deviation of the Total discounted cost from the BaU Scenario, adding improved (Scenario 2) or electric stoves (Scenario 3) in the Bau Scenario the cost is reduced of 4.6 % or increase of 19%, respectively.

On the other hand, replicating the same assumptions for the cooking stoves, with the "Vision 2040" scenarios, an increase of 97% (Scenario 5) and 2178 % (Scenario 6) in cost, respectively, were obtained. In parallel with the economic analysis, it is interesting to observe how the total emissions of CO_2 vary depending on the scenario analysed. As expected, the introduction of Improved (Scenario 2) and Electric stoves (Scenario 3) resulted in a reduction of CO_2 emissions off 10% and 71%, respectively compared to the BaU Scenario. The value stays in the same range in the case of the "Vision 2040" assumptions for electricity generation, accounting for a reduction of 6% (Scenario 5) and 71% (Scenario 6), respectively, in this case. Therefore, to find a trade-off between economic feasibility and emissions reduction, it can be concluded that the optimal pathway of growth for the country follows a Business-as-Usual scenario, which aims at phasing out fossil fuels from 2040, using Improved and Electric stoves (Scenario 3). From this analysis, it can be concluded that the "Vision 2040" policy (Scenario 3,4,5) could benefit from a revision of its ambitions as this strong dependency from nuclear energy and solar has a way too high cost associated with a reduction of emissions which is not comparable to the price paid for it. The government could aim at investigating what would, for example, happen if the dependency from hydro is reduced but has still a role in the generation of the electricity of the country, and the nuclear power plants do not represent the 57% of the capacity installed.

Table 15: Cost-benefit and environmental results of the six scenarios

Scenario	Electricity Generation Mix	Constraints on Emissions	Cooking Solution	Total Discounted Cost 2015-2070 (Billion USD)	% Cost Variation from BaU	Total Emissions 2015-2070 (Gton CO_2 eq)	% Emissions Variation from BaU
1	Business-as-Usual (BaU)	N.A.	Residential Biomass Stoves	64.0	-	3576	-
2		N.A.	Residential Improved Biomass Stoves	61.7	-5%	3210	-10%
3		No CO_2 from 2040	Electric Stoves	77.0	19%	1035	-71%
4	Uganda Vision 2040	N.A.	Residential Biomass Stoves	112.7	76%	3911	9%
5		N.A.	Residential Improved Biomass Stoves	126.4	97%	3797	6%
6		No CO_2 from 2040	Electric Stoves	1459.7	2178%	1032	-71%

6. The potential use of CCG-SAND Interface in a Master Course

CCG-SAND Interface was tested on an introductory teaching example provided by the UN Department of Economic and Social Affairs (UNDESA) before using it to support modelling of a real case study [85] [86]. This preliminary test aimed to check that all the functionalities of the Interface were working as expected and improve the material itself. Furthermore, four Master Students from Imperial College London used this Exercise to get started with CCG-SAND Interface before embarking on analysing the model for a specific country as part of their MSc theses. Their country-model included climate-energy planning for Laos, Kenya, Nigeria, and Vietnam. With their work, they aimed at performing energy modelling calculations for a detailed and informative evidence-based policy and long-term investment planning that directly influence government decisions in those countries.

This chapter aims to analyse the potential employment of CCG-SAND Interface in an energy Master program. It provides a guide to academia to set up an Energy System Analysis course in universities using CCG-SAND combined with the UNDESA Exercise, namely Climate, Land, Energy and Water Systems (CLEWS-O) - OSeMOSYS, for hands-on labs and capacity building activities [86].

6.1. Course Structure of Reference

The structure, syllabus, and Intended Learning Outcomes (ILOs) of the course “Introduction to Energy Systems Analysis” [40] were used as a reference for the potential introduction of CCG-SAND with CLEWS-O in a Master Course [86]. Therefore, the current course structure was analysed to identify best in which of the Course modules could be introduced CCG-SAND and its applications. This course is currently offered at the Royal Institute of Technology (KTH) in Stockholm, and it was developed at the Department of Energy System Analysis of the same university. Moreover, other universities around the world recently showed interest in introducing a course in Energy System Analysis following the same teaching modules as KTH. The potential dissemination of CCG-SAND with CLEWS-O could be therefore even broader than the particular case at KTH. An overview of its original structure is shown in Figure 28. The five main Lectures and individual assignments are described as follows:

1) Introduction: general notions of energy modelling and linear programming are given. The structure of the Reference Energy System (RES) and the temporal representation are also introduced in this module;

2) Model Development: in this set of Lectures, the students get to know the main optimization

models and get an in-depth presentation of OSeMOSYS. In the practical activities, called Lab, of this block, the students develop a simple individual model for long-term energy planning using one of the available Interfaces.

3) Beyond the energy system: after analysing the energy system of their model, the students understand the links between water, land use and energy and replicate them extending their case-study.

4) Scenario Analysis: in this module, all the concepts related to the need for creating and comparing different Scenarios are presented;

5) Applications: finally, in the last part of the course, the students are expected to carry out a detailed analysis of a selected national energy system, including independent data gathering, problem definition, model choice, generation of solutions and interpretation.

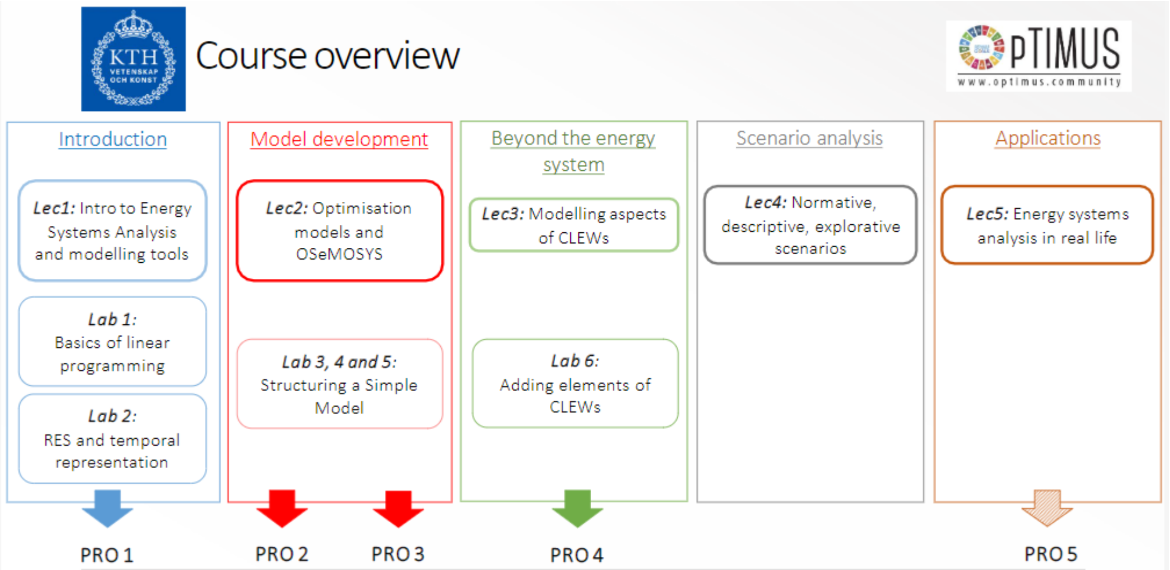


Figure 28: Structure of the course "Energy System Analysis" used for reference for the potential application of CCG-SAND Interface in a Master Course [40]

6.1.1. From MoManI to CCG-SAND Interface

To carry out the Laboratories Activities, students are trained to use the MoManI first to develop a simple model through a guided exercise. From the analysis of the main drawbacks and limitations of MoManI, and these gaps, it was created CCG-SAND Interface as detailed described in chapter 2 of this Master thesis.

6.1.2. From SIMPLICITY to CLEWS-O Exercise

The introductory exercise that students are expected to carry out is called SIMPLICITY, which requires them to develop a model for this fictitious region called SIMPLICITY. The combination of theoretical concepts with hand-on exercises makes it suitable for teaching activities. It has been used so far in many university courses and for capacity building activities around the world. Thanks to this exercise, students learn the parameters used in OSeMOSYS and how to employ them better to replicate the specific needs and interests of the energy modelling exercise. The individual assignments at the end of each module allow the student to analyse the results and made them aware of the meaning of the data. The idea is, therefore, to replace SIMPLICITY with CLEWS-O Exercise [86].

6.2. Potential Improvements to the Course

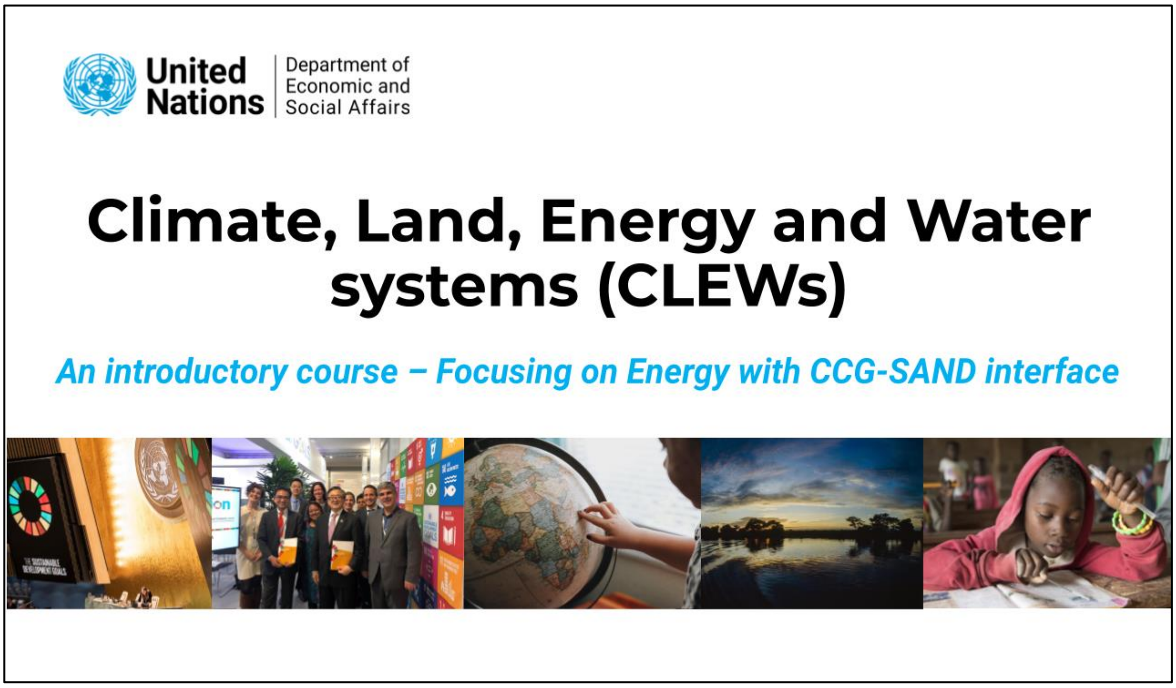
At the end of the semester, the students are invited to give feedback on the course through an anonymous online survey. From the analysis of the comments gathered during the years, some drawbacks and challenges experienced during the course emerged. In particular, as already anticipated in Section 6.1.1., the users experienced difficulties in using MoManI, from the input data process until the results analysis and visualization phases. Therefore, to improve the students' experiences and thanks to a close collaboration with the reference teacher at KTH (who is part of the Optimus Community of Practice [44]), it was analysed in which way CCG-SAND Interface could be employed in course. The teacher has identified CCG-SAND Interface as a promising interface, which could potentially substitute the previous one (MoManI) for the teaching activities of the course in Introduction to Energy System Analysis at KTH. Indeed, CCG-SAND Interface keeps the same functionalities of MoManI, offering the user a more user-friendly experience in all its phases from data input until results visualization.

Furthermore, the employment of CCG-SAND Interface would be combined with the CLEWS-O (UNDESA Exercise [86]), instead of previous simple exercise, SIMPLICITY. This choice comes from the interest of teachers at KTH to align with other capacity-building efforts around the world and set a new standard and structure to what is being harsh to users in their first approach to energy modelling. The following section 6.3. gives an overview of CLEWS-O exercise [86], together with detailed step-by-step instructions on how to employ CCG-SAND Interface to complete the Exercise and visualize results.

6.3. Overview of CLEWS-O Exercise

CLEWS-O is an introductory teaching example originally developed by UNDESA for their capacity-building activities [86]. It includes six exercises. However, only the first five exercises, related to the energy part of the modelling exercise, were tested and improved using CCG-SAND Interface. The last section exercise, which focused on the integration of Land and Water in the Energy System, was not included in this preliminary test, as it falls out the scope of this

Master thesis. The cover slide of the CLEWS-O PowerPoint presentation is shown in Figure 29 [86]. The complete presentation is available on the Google Drive folder [86].



United Nations | Department of Economic and Social Affairs

Climate, Land, Energy and Water systems (CLEWs)

An introductory course – Focusing on Energy with CCG-SAND interface

Figure 29: Preview of the PowerPoint presentation of CLEWS-O Exercise using CCG-SAND Interface [86].

6.4. Main modelling assumptions

6.4.1. Division of the Year

The original data provided by UNDESA [85] for the YearSplit and the SpecifiedDemandProfile included four Timeslices called: SummerDay (SD), Summer Night (SN), Winter Day (WD) and Winter Night (WN). As explained in [87], the "number of time slices must be large enough to take into account all important variations in the system (energy demand variations, supply-side variations, availability of resources)" and "should not be too high to minimize problem size, data handling and computational efforts". Therefore, periods of the year with similar characteristics were aggregated in only two seasons (Summer and Winter) to simplify the problem. A detailed description of the procedure followed to exploit the potential of CCG-SAND Interface fully was introduced in chapter 2 and 9.3. In the latter case, all the 96 available time-slices in CCG-SAND Interface were used. However, thanks to the flexibility of CCG-SAND Interface, the teacher can decide to modify the number of time-slices (i.e. six). The only requirement is that the sum of all the values added for the parameter YearSplit is 1.

6.4.2. Demand, technologies and commodities

CLEWS-O Model has only one demand for electricity (ELC002), which is satisfied by a different combination of technologies in each of the Exercises. The user builds the full RES only in the last part. The complete system is shown in Figure 30, whereas the most relevant parameters are presented later in this section. On the left side of the RES, there are the technologies that convert the primary energy resource into useful fuels (import or production of primary commodities). Then in the middle, there are Power plants that transform the primary resource in Electricity (ELC001). An aggregated technology for Transmission and Distribution finally satisfies the final demand for electricity (ELC002).

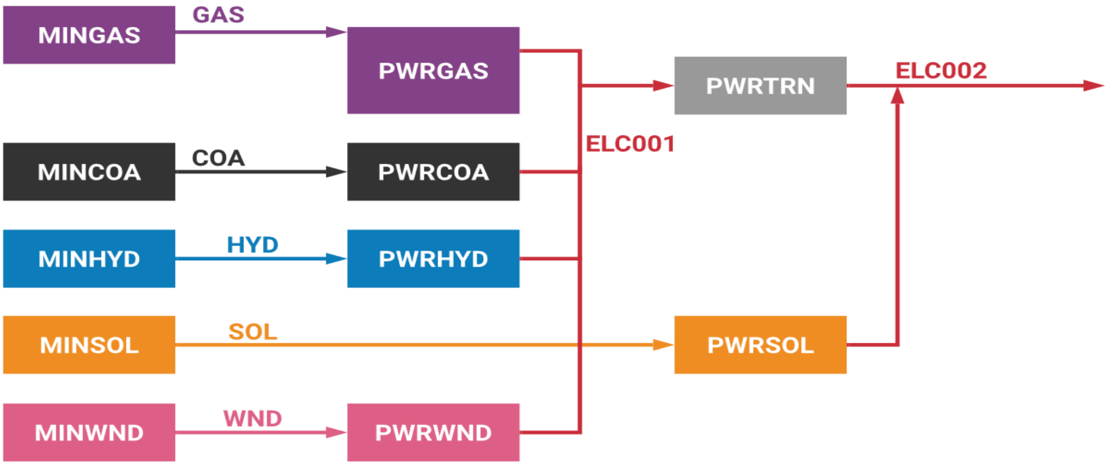


Figure 30: Reference Energy System of CLEWS-O Exercise tested with CCG-SAND Interface [86]

6.4.3. Backstop technology

The Backstop is a fictitious technology added for ‘emergency’ reasons. It has high Capital, Fixed and Variable Cost (999999). If this technology is satisfying the demand (totally or partially), it means that there is something not correct in the data added for the other technologies. The solver always finds the optimal solution, and so it would always prefer another technology with lower costs rather than the Backstop. In case the backstop appears as a generating technology in the results, it is advisable to check the input data and find the bug.

6.4.4. Naming convention

In CLEWS-O, it was employed the naming convention provided by UNDESA and available on the Google Drive folder [88]. Table 16 and Table 17 lists the codes used for each technology and commodity, respectively, of the CLEWS-O Exercises.

Table 16: Naming convention and description of the technologies in CLEWS-O Exercise

Technology Code	Description
MINCOA	Coal Production
MINGAS	Natural Gas Production
PWRCOA	Coal Power Plant
PWRGAS	Natural Gas Power Plant
PWRTRN	Transmission & Distribution Technology
BACKSTOP	Backstop Technology
PWRHYD	Hydropower Plant
PWRSOL	Solar Power Plant
PWRWND	Wind Power Plant
MINHYD	Water potential
MINSOL	Solar potential
MINWND	Wind potential

Table 17: The naming convention of the Commodities in CLEWS-O

Commodity Code	Description
COA	Coal
GAS	Natural Gas
ELC001	Electricity from power plants
ELC002	Electricity after transmission - Final demand
SOL	Solar potential
HYD	Hydro potential
WND	Wind potential

6.5. Expected outcomes

An overview of each CLEWS-O Exercise is presented in Table 18. Additionally, it is specified which technologies and commodities should be added, if there are any additional requirements and the outcomes expected.

Table 18: Expected outcomes of the different parts of CLEWS-O Exercise

Exercise	**Technology**	**Commodity**	**Additional Requirements**	**Outcomes**
1a	MINCOA MINGAS PWRCOA PWRGAS PWRTRN BACKSTOP	COA GAS ELC001 ELC002	AccumulatedAnnualDemand set to 100 PJ; No SpecifiedDemandProfile; Default Values for the Fixed, Capital and Variable Cost of Technologies, Add Efficiency values using InputActivityRatio and OutputActivityRatio	Under the same cost assumptions for PWRCOA and PWRGAS, the model chooses the most efficient one to satisfy all the demand.
1b	Same as for 1a	Same as for 1a	Same as for 1a, but add values for costs as for Table 19.	The solver finds the cheapest (optimal) solution: PWRCOA is the only technology satisfying the ELC002 demand.
1c	Same as for 1a	Same as for 1a	Same for 1b but move demand from AccumulatedAnnualDemand to SpecifiedAnnualDemand. Add values for SpecifiedDemandProfile	When adding the SpecifiedDemandProfile, the energy mix that addresses the demand at the cheapest cost is made of a combination of PWRCOA and PWRGAS.

2a	To 1c) Add PWRHYD PWRSOL PWRWND	To 1c) Add SOL HYD WND	CapacityFactor for PWRHYD, PWRSOL and PWRWND set to 1	The solver finds the cheapest (optimal) solution: PWRSOL is the only technology satisfying the ELC002 demand.
2b	Same as for 2a	Same as for 2a	Add CapacityFactor values for PWRHYD PWRSOL PWRWND as for Table 20.	When adding the Capacity Factors for renewables, PWRHYD is the only technology satisfying the demand.

6.6. Techno-economic assumptions

The techno-economics parameters needed for CLEWS-O Exercise are reported in Table 19. The CapacityFactor values for the renewable technologies: PWRHYD, PWRSOL and PWRWND, are collected in Table 20. The capacity factor is critical to account for the variability of renewable production, i.e. solar power plants (PWRSOL) produces only when the sun is shining; therefore the CapacityFactor at night is equal to zero, meaning that these technologies are not contributing to supply the demand for electricity (ELC002).

Table 19: Techno-economic assumptions for the CLEWS-O Technologies

Parameter	**Units**	**MIN COA**	**MIN GAS**	**PWR COA**	**PWR GAS**	**PWR TRN**	**PWR HYD**	**PWR SOL**	**PWR WND**
AvailabilityFactor	Fraction	1 (100 %)	1 (100 %)	1 (100%)	1 (100%)	1 (100%)	1 (100%)	1 (100 %)	1 (100%)
CapitalC	$/kW	0	0	1250	2200	8000	2500	1200	1600

ost									
FixedCost	$/kW/yr	0	0	30	75	0	60	20	40
Variable Cost	$/GJ	5	35	0	0	0	0	0	0
OperationalLife	Yrs	30	30	30	30	50	80	20	20
Capacity To-ActivityUnit	PJ/(PJ/yr),	1	1	31.536	31.536	31.536	31.536	31.536	31.536
Efficiency	GJ/kW	100%	100%	33%	55%	100%	100%	100%	100%

Table 20: Capacity Factors used for Renewable Energy Technology

TimeSlice	**PWRHYD**	**PWRSOL**	**PWRWND**
SD	0.3	0.35	0.3
SN	0.3	0	0.2
WD	0.5	0.25	0.25
WN	0.5	0	0.3

6.7. Solving CLEWS-O Model

The energy-related exercises of CLEWS-O Model were testes using CCG-SAND Interface. An overview of the total discounted cost per each of the exercises is presented in Figure 31. It is interesting to notice that the cost increased from 142527 (Million $) in 1b) to 320387 (Million $) in 1c). This increased cost reflects the fact that during peaks of electricity demand, both PWRCOA and PWRGAS should be generating to satisfy the demand; therefore, the cost is higher.

From 1c) to 2a) the cost experienced a sharp drop of almost 22 folds. As expected, the introduction of renewables technologies such as wind, solar and hydro (PWRWND, PWRSOL and PWRHYD) reduces the overall cost of the energy system. Finally, it is interesting to notice how in 2b the price increased again up to 130198 (Million $). This trend reflects the intermittency of renewables technologies. In 2b, it was required to specify the value of the CapacityFactor for renewable technologies, which then reduces the overall production of renewables (i.e. PWRSOL does not produce when the sun is not shining). The total discounted cost for Exercise 1a was not taken into account in this analysis as no costs were added in Exercise 1a, but only from Exercise 1b onward.

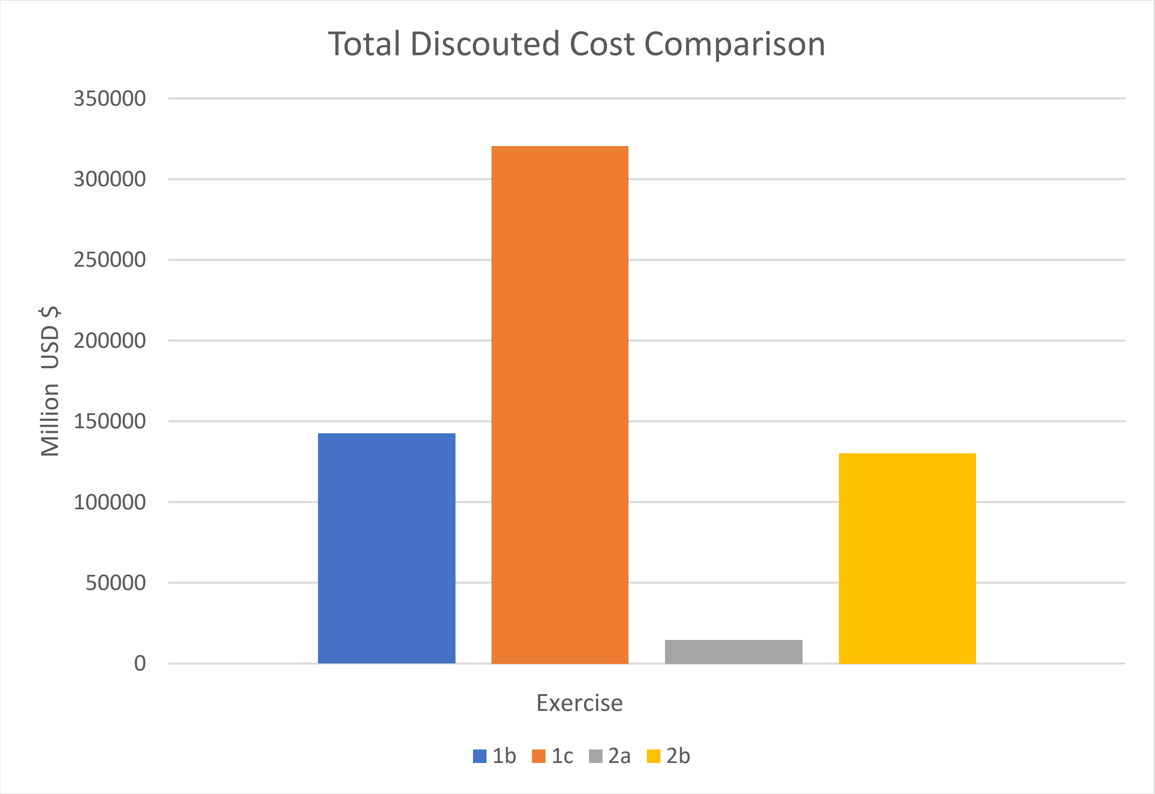


Figure 31: Total Discounted Cost comparison for the different parts of CLEWS-O Exercise

6.8. Conclusion and future improvements of CLEWS-O Exercise

This chapter provides an introductory teaching example to get familiar with CCG-SAND Interface. As for this first version, only the energy-related Exercises of CLEWS-O Model were tested and improved. Future revisions could aim at integrating Land and Water links in the system. Moreover, potential future work might include a survey comparison between the user experience with MoManI and with CCG-SAND Interface. Finally, it could be analysed the impact of replacing MoManI interface for the didactic purposes and the achievement of the Intended Learning Outcomes (ILOs) in the context of the Course in Introduction to Energy System Analysis [40].

7. Conclusions

This Master thesis aimed at making energy modelling for policymaking a more accessible practice by developing a straightforward and functional tool for long term energy planning. The functional Excel-based CCG-SAND Interface was created, by identifying gaps and potential suggestions for improvements of the OSeMOSYS users which employed MoManI as an interface. To test, validate and improve the functionalities of CCG-SAND Interface, the CLEWS-O teaching exercise and the Ugandan case study were used. CLEWS-O introductory modelling exercise, provided by UNDESA, was tested using CCG-SAND Interface by four Master Students of the course "Environmental Technology" of the Imperial College London, who later employed the Interface for their Master theses country-models. These first successful tests clearly showed that the learning curve of CCG-SAND Interface was shorter compared to the previous OSeMOSYS Interface (MoManI). However, it raised the question of ensuring a standard collection and accessibility of data.

Therefore, the general but standardized structure of Tier 1 and Tier 2 Model strengthened the response to the transparency, traceability and repeatability of the work across users. In this Master thesis, the country-specific Tier 2 Model focused on modelling the leading energy and societal challenges of Uganda. On one side, it was analysed the need for a reduced dependency from hydropower for electricity generation due to climate change unpredictability and complexity of water allocation in the future. Therefore, the government development plan, called "Uganda Vision 2040", which includes the interest of diversifying the energy mix, was tested using CCG-SAND Interface. The financial and environmental results obtained by modelling the "Uganda Vision 2040" policy with CCG-SAND Interface highlighted the need for a future revision of the national development strategy, which should aim at diversifying the energy mix without mostly depending on nuclear energy for electricity generation. In parallel, under the BEST Strategy, the Ugandan case-study focused on addressing the severe health and living conditions impacts of inefficient stoves used for cooking by more than 90% of the population. The environmental analysis conducted depicted a massive reduction of CO_2 emissions when using Improved Residential Biomass and Electric Stoves. The quality of life of Ugandan people could be improved if a transition to a cleaner energy system is undertaken. The results depicted a disproportionately high cost compared to the associated reduction of CO_2 emissions. From these results, it can be seen that CCG-SAND Interface constitutes a valid instrument for long-term national energy modelling for policymaking. Finally, the familiarity that most users have with Excel workbook makes it accessible to a broader audience of actors who want to influence energy policies based on energy modelling evidence.

7.1. Contributions and Dissemination

CCG-SAND was presented to the members of the Optimus Community of Practice [44], which involves Individuals from academia, research, and the development community engaged in supporting, directly or indirectly, sustainable development policies with evidence derived from modelling. The Interface was also presented to the coordinator of the Energy System Analysis course of KTH, Francesco Gardumi, who showed great interest in the tool. A discussion for the potential use of CCG-SAND in next term course in Introduction to Energy System Analysis at KTH is currently open. Moreover, CCG-SAND Interface was recently presented to a senior software developer who is currently testing it using another solver and added functionalities aiming at automatizing some processes and reduce the computational time.

The complete dataset used for the Ugandan case-study, the ratio behind each scenario, the assumptions and the results obtained were shared and peer-reviewed by an Associate professor at the Makerere University in Kampala City of Uganda. The final goal of the case study, which aimed to support local energy modelling activities and inform local institutes about the results obtained, was reached.

As said, CLEWS-O was improved and test using CCG-SAND Interface by different users. The potential usability ranges from capacity-building activities of the United Nations and potential future application in a Master Programs. As previously mentioned, there is an open discussion to use CCG-SAND Interface with CLEWS-O Exercise at KTH Stockholm. Chapter 6 of this thesis is the foundation for potential future collaborations for the write-up of a joint paper which compares academic outcomes after the replacement of MoMani with CCG-SAND Interface in a university course.

7.2. Potential improvements and future work

Future improvements of CCG-SAND Interface could aim at completing the linking process between Sheets to offer a completely flexible tool to the user. Besides, the validation of CCG-SAND Interface with another solver is advisable to i) reduce the computational time and ii) automatize the process of exporting the data file from the Excel Workbook. Future work includes also finding an optimal solution to represent storage technologies in CCG-SAND Interface.

The standardized format and structure of the Tier 1 Model could be scaled up by developing country-specific models for target countries. Collaborations with different institutions for the collection and population of these toolkits is advisable. These toolkits, which should at least include a reference energy system (RES), a dataset and pre-defined scripts, have the potential to be a valid instrument to foster capacity building activities in the target countries and create an evidence-based community of policymakers quickly. They should be as agnostic as possible to be used with different modelling tools.

The dataset for the Ugandan case-study should be revised in the future with updated data on the development of nuclear energy and refineries technologies in the country. The Tier 2 Model for Uganda could be expanded including i) the transport sector, ii) more cooking appliances (i.e. LPG Stoves); iii) different input fuels for the stoves (i.e. charcoal and crop residues) and iv) a division of the electricity demand for residential, commercial and industrial sectors. Future revisions of the government policies are advisable. The modelling results break-down could be compared to neighbouring countries and analyse the trends and best practices.

The validation of CLEWS-O Exercise with CCG-SAND Interface could aim at including the Water and Land use links with Energy (the sixth part of CLEWS-O). Future work includes the potential replacement of MoManI with CCG-SAND Interface in the Energy System Analysis course at KTH. It could be carried out an analysis of the impact that this introduction would cause on the achievement of the Intended Learning Outcomes (ILOs) of the Master course.

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