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Master of Science – Energy Engineering

A Hybrid Approach for Geographical Disaggregation of High-Resolution National Electricity Load Demand

An Application to Ghana

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Sommario

A partire dal 2015, quando le Nazioni Unite hanno aggiornato quelli che erano gli 8 Millenium Development Goals (MDGs) in 17 più ampi e ambiziosi Sustainable Development Goals (SDGs), l'accesso universale all'energia in maniera economica, affidabile, sostenibile e moderna ha ottenuto una globale attenzione diventando una delle principali questioni che la nostra generazione sta cercando di risolvere, in quanto essa rappresenta un vettore fondamentale per il benessere dell'uomo, lo sviluppo economico di un paese e la riduzione della povertà.

Il Ghana, un paese a reddito medio-basso dell'Africa subsahariana, come la quasi totalità dei paesi in via di sviluppo deve affrontare enormi sfide per raggiungere il settimo obiettivo degli SDGs, con oltre 5,2 milioni di persone senza accesso all'energia, basse prestazioni infrastrutturali e una gestione imprecisa delle risorse economiche e naturali. Inoltre, una consistente scarsità di dati rigorosi sul tema energetico è diffusa tra i paesi in via di sviluppo, aumentando la difficoltà di valutare ed affrontare adeguatamente il problema energetico da parte dei responsabili politici nazionali e internazionali.

Questo lavoro di tesi cerca di colmare il divario di scarsità di dati proponendo una metodologia per disaggregare geograficamente la domanda di carico elettrico nazionale utilizzando un approccio ibrido Top-Down Bottom-Up. La metodologia si compone di tre fasi principali che seguono un'ampia revisione della letteratura e l'acquisizione di dati riguardanti il paese analizzato. La prima fase si propone di eseguire una disaggregazione quantitativa del sistema energetico al fine di identificare e caratterizzare con la maggiore risoluzione possibile gli attori più importanti che compongono il sistema, cercando di ottenere il più accurata fotografia della situazione in corso e delle quantità di energia in considerazione. La seconda fase consiste in una valutazione geografica dei fabbisogni energetici che ciascuna entità presenta utilizzando congiuntamente database geo spaziali pubblici e software open-source. La fase finale cerca di caratterizzare da un punto di vista energetico il tipo di consumo di ciascuna entità che ha individuato e localizzato nelle fasi precedenti in termini di picco di domanda giornaliero, fabbisogno energetico durante l'anno e profilo di carico nell'arco della giornata. Lo scopo di questa metodologia è quello di produrre dati della domanda di elettricità con un'elevata risoluzione temporale e spaziale al fine di fornire un punto di partenza per l'analisi energetica e il processo di elaborazione delle politiche con il fine di valutare e, si spera, raggiungere il settimo obbiettivo degli SDGs.

Infine, con l'obiettivo di convalidare i risultati di questa metodologia, la tesi crea un modello del sistema energetico del paese in analisi, il Ghana, utilizzando sia un approccio a nodo singolo accoppiato a dati reali riferiti al 2018, sia un approccio a nodo multiplo dove come dato in ingresso è presente la richiesta di carico di elettricità ad alta risoluzione prodotta.

Abstract

Starting from 2015, when the United Nations upgraded what were known as the 8 Millennium Development Goals (MDGs) into the broader and more ambitious 17 Sustainable Development Goals (SDGs), universal energy access in an affordable, reliable, sustainable and modern way achieved political and public recognition becoming one of the main issues our generation is trying to solve, as it represent a pivotal relevance for the human wellbeing, for the economic development of a country and for poverty alleviation.

Ghana, a Sub-Saharan Africa low-middle income country, like the almost totally of developing countries has to face enormous challenges in order to achieve the 7^{th} Goal of the SDGs, with over 5.2 million people without energy access, low infrastructure performances and an inaccurate economical and natural resource management. Moreover, a consistent paucity of rigorous data concerning energetic topic is spread between developing countries, raising the difficulty to properly evaluate and address the energetic problem by national and international policy makers.

This thesis work tries to fill the data paucity gap proposing a methodology to geographically disaggregate the national electricity load demand by using a hybrid Top-Down Bottom-Up approach. The methodology consists of three major phases which follow an extensive literature review as well as data acquisition concerning the analyzed country. The first phase aims to perform a quantitative disaggregation of the energy system in order to identify and characterize with the higher resolution possible the most important entities composing the system, trying to get the most accurate insight of the ongoing situation and the energy quantities in consideration. The second phase consists of a geographical assessment of the energetic requirements which each entity present by jointly using geospatial open access databases and open-source software (OSS). The final phase tries to characterize from an energetic point of view the type of consumption of each entity, which has been identified and localized in the previous phases, in terms of daily peak demand, energy requirements during the year and a general load profile along the day. This methodology's scope is to produce an electricity load demand timeseries with high time and spatial resolution in order to provide a starting point for the energetic analysis and policy making process to assess and hopefully achieve the 7^{th} Sustainable Development Goals.

In the end, in order to validate the results of this methodology, this thesis work create an energy system model of the country under analysis, Ghana, both using a Single-Node approach coupled with real-world timeseries referring to the year 2018, and a Multi-Node approach with as inputs the processed high-resolution electricity load demand.

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Introduction

This thesis focuses on the comprehensive achievement of the 7th Sustainable Development Goal which, adopted by the United Nations in 2015, aims to provide “affordable, reliable, sustainable and modern energy for all” by 2030. Reliability is one of the core concepts of this SDG and Ghana may be the proof of how even with an abundance of resources there could be difficulties in providing reliable energy access to the population. Over the last 35 years Ghana has experienced a number of power supply shortfall with adverse impacts on the economy. The most recent energy crisis in 2012 caused by an intermittent dispatchment of fuel, the Ghanaian government was obliged to undertake unfavorable deals with independent energy contractors to ensure a decent electricity dispatchment in the country. Even though the magnitude of the demand was satisfied, the electricity dispatchment was not sufficient in terms of price and reliability, and, mixed with the low post-2014 diesel fuel prices, resulted in a movement of multiple users from the grid-based electricity to more economic means of electrification.

This work, given the greater need of data in the scientific world, aims to provide a methodology to geographically disaggregate the National electricity demand and obtaining higher-resolution information about a country in order to investigate energy systems and apply it to Ghana. The purposes of the methodology are multiple, for example a better modelling, understanding and studying of the country under study in order to propose the proper policies for development. This thesis proposes a hybrid top-down and bottom-up approach in creating the indispensable data through an extensive study of the literature, the collaboration with some major stakeholders, the use of freely available datasets and finally the use of open-source stochastic software and geographic information system (GIS) frameworks. Finally tries to validate the results by creating energy system models both with a Single-Node and Multi-Node approach. The modelling approaches have been developed by using Calliope, an energy modelling tool, and the input data comes from institutional stakeholders for the Single-Node approach while are the results of the applied methodology for the Multi-Node approach.

Chapter 1 consists of an overview of the energy access issue in the Developing Country, focusing on the Ghanaian power sector, reviewing the major historical challenges that the country had to face since the present time.

Chapter 2 focuses on the review of the literature in terms of energy modelling and the major efforts that had been made for the creation of consistent dataset related to the developing countries, analyzing the gaps that still exist and proposing the newly approach studied in this work.

Chapter 3 is dedicated to the methodology adopted for this work, from the analysis of the power sector's generation and transmission sides to an extensive analysis of the electricity consumption in the country and its division in the 4 most representing macro regions that the model needed through the use of proper dataset from IEA and the Social Accounting Matrix (SAM), showing the effects of both a top-down and a bottom-up analysis in the creation of the multi-node demand by means of open access databases, open-source geospatial software the stochastic modelling tool RAMP.

Chapter 4 proposes a presentation of the results obtained by the application of the methodology to the country Ghana, describing all the phases of the process and the actual results coming from the software. The final part consists in the creation of a single-node and a multi-nodes model of the country's energy system, showing and analyzing the major differences as well as the benefits that both models present.

Finally, *Chapter 5* proposes a discussion on the output given by the methodology and an analysis of the potential benefit, if any, of the hybrid geographical disaggregation approach.

Chapter 1
Developing Countries and Energy Access

1.1 7th SDG and Energy Access in Sub-Saharan Africa

Energy has a pivotal relevance for the human wellbeing, for the economic development of a country and for poverty alleviation [1], [2].

Over the last years this concept has taken anywhere more and more importance, evolving the idea that all around the world actions must be taken with the common purpose of ensuring access to energy to the world population.

Even if in September 2000 it acquired political recognition and all the member of the United Nations adopted a 15-year development agenda called Millennium Development Goals (MDGs), the problem of guarantee energy access for all was non-sufficiently handled, lacking of a clear and well defined target [3]. For this reason, in September 2015 a new agenda consisting of 17 new targets was pledged by all the 193 UN member states: The Sustainable Development Goals. This new agenda, comprising of broader and more ambitious targets than the MDGs, clearly states a shared interest of the members in the problem of energy accessibility, with its 7th SDG which establishes to *"Ensure access to affordable, reliable, sustainable and modern energy for all"* by 2030 [4].

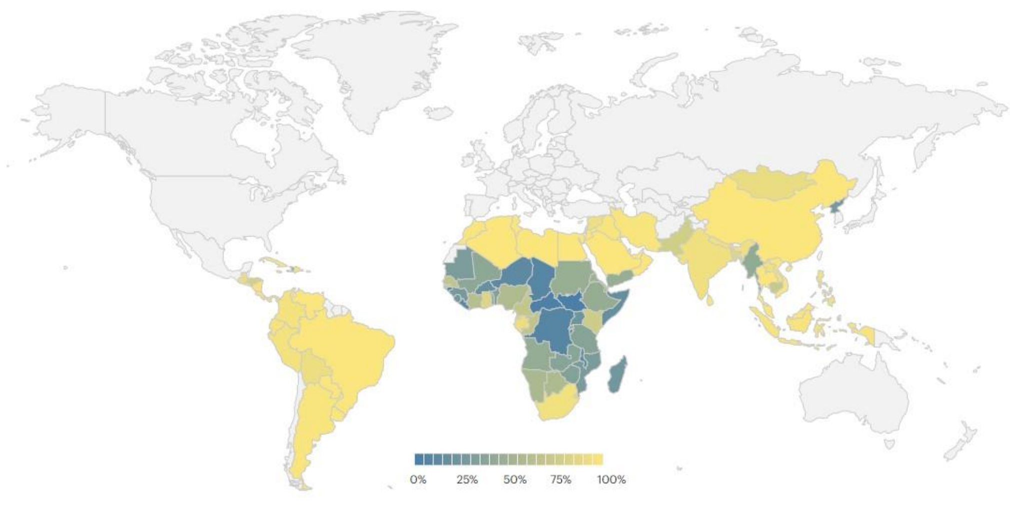


Figure 1.1 Proportion of population with access to electricity, 2019 (Source: IEA)

Even if in 2019 the number dropped to a record low, with "only" 770 million people without electricity access, the size of the problem of energy access are anyway of remarkable proportions, with the risk of an uneven progress and, even more alarming, the threat of the Covid-19 pandemic outcome to reverse the positive trend of electrification [5]. Of these numbers, as we can see from Figure1.1, the most alarming fact is that more than two-thirds of people without electricity access live in sub-Saharan Africa.

Even though North Africa almost reached universal access to electricity, the electrification rates of sub-Saharan Africa remain very low compared to other developing parts of the world. Lack of electricity obliges households and other users to rely, if they can afford it, to inefficient, polluting, and expensive alternative solutions for essential services.

Sub-Saharan Africa has made progress in the electrification rate over the past five years, doubling the number of people gaining access to electricity from 9 million a year between 2000 and 2013 to more than 20 million between 2014 and 2018. As a result the number of people without access to electricity in sub-Saharan Africa slowly declined to around 595 million in 2018 [6].

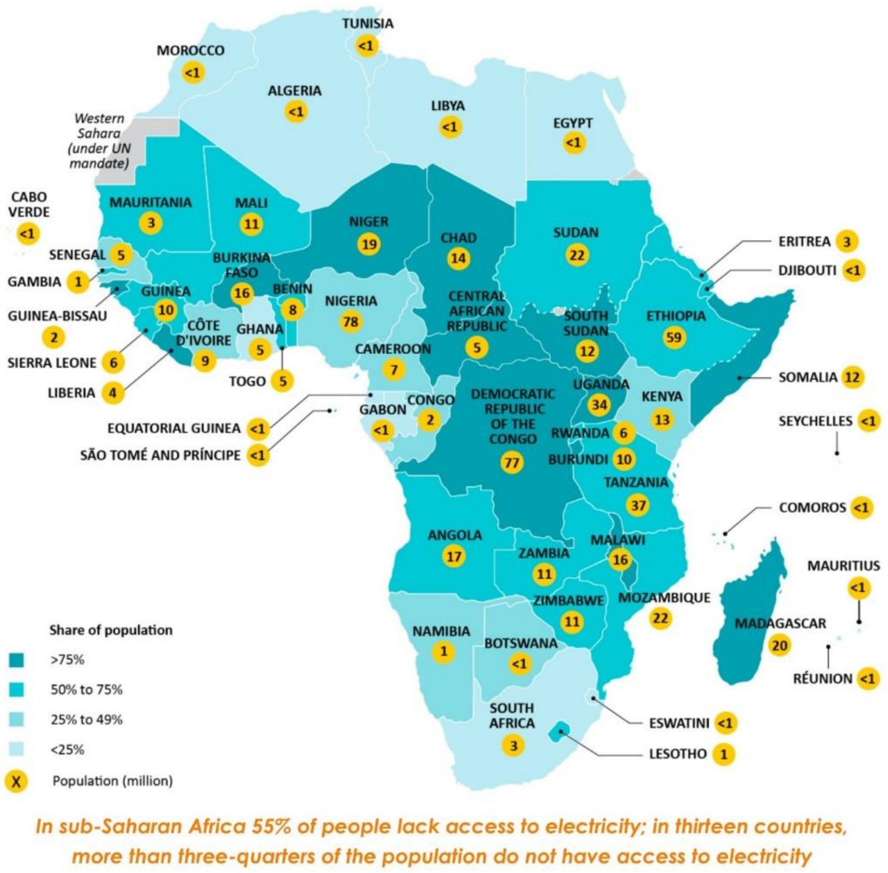


Figure 1.2 Population without access to electricity by country in Africa, 2018 (Source: Africa Energy Outlook 2019)

In the goal of universal electricity access the infrastructures play a fundamental role, but Africa, and especially sub-Saharan Africa, lags behind in virtually all aspects of infrastructure quality.

For the last three decades, the per capita generation capacity has remained flat, highlighting the need of massive ramp-up in investments to make up the deficit in energy infrastructures.

It is widely recognized that a deficient power infrastructure dampens economic growth, constrained by inadequate power generation, unreliable transmission and distribution networks, limiting the social benefits of electricity use with significant economic costs [7].

These gaps weigh on the economy both on the commercial and the industrial sector which are hampered by unreliable electricity supply and high energy costs underscoring the importance of solving the power crisis [8].

Despite this, in 2018 the overall sub-Saharan economy reached the $4.3 trillion in 2018, with a forecasted GDP growth for the continent of 4% in 2019, with some countries growing faster than the average [6], as for example, the International Monetary Fund estimated that Ghana’s GDP was expected to grow up to 9% in 2019 [9].

However, as discovered during the 2014 price shock, recent growth in developing country has been significantly influenced by their great dependence on commodities, which expose them to a severe impact in case of commodity price decline, which could be the case for Ghana and the new discoveries of huge gas reservoir [6].

For this reason, the power infrastructure must represent a solid pillar to promote the economic growth, by a constant and reliable supply of power as well as efficient mean of transportation and distribution.

1.2 Energy modelling for a Sustainable Future

Once formulated the complex and ambitious correlation between energy access and socio-economic development, it is important to analyze which tool can be useful for the achievement of such target.

Energy has been at the center of political and scientific debate for many centuries. The energy system directly and indirectly interacts with economic, social and environmental systems. Through these interactions the systems influence the (sustainable) development of each other [10].

Research has produced a variety of indicators of sustainable development so that it is possible to gain some insight into whether or not an area, a region or a nation is on trajectory of sustainable development [11], [12] but understanding and address policy-makers on the long-term remains a huge challenge yet [13].

One key element which has proven to be fundamental in the energy planning process as well as capable of exploring the complex long-term changes is energy system modelling.

Energy modelling has a long history, it often supports decision-making in energy system planning and its development can be linked to the rising importance of scenario planning throughout the twentieth century [14].

While energy systems models were initially focused more on energy security and costs, climate change policy has since emerged as a powerful factor driving many studies, with a focus on pathways to achieve the significant reductions in greenhouse gas emissions called for by climate science [15].

A major challenge to adopting a long-term, integrated planning approach in the past has been the lack of methodologies that enable a comprehensive, multi-dimensional and dynamic perspective, as well as tools that can evaluate the interactions and trade-offs among the economic, social and environmental dimensions of development [16], [17], but right now, with the increasing expansion and development of both proprietary and open source software, the most important shortcoming stands in the lack of proper database and reliable timeseries on which perform a modelling study and base long-term decisions.

1.3 Ghanaian Context

The Republic of Ghana, formerly known as the Gold Coast, was one of the first African country to obtain independence back in 1957 and nowadays is classified as a unitary republic with an executive presidency and a multiparty political system.

The country is located in the center of the West African coast, it shares boundaries with Burkina Faso to the north, Cote d'Ivoire to the west, Togo to the east and the Atlantic Ocean to the south. Ghana has a total surface of 238533 km^2 (which make it about the size of Britain) and is divided in 16 administrative regions, with the capital, Accra, that lies in the south of the country [18]. It has a warm, humid climate, with annual mean temperature between 26°C and 29°C. The climatic conditions across the country are hardly uniform, with the north characterized by higher temperatures and the south by generally humid conditions [18].

As of 2020, the population reached 29,34 million people with an average population growth rate of 2,15%. It has a young age structure, with approximately 57% of the population under the age of 25 but the increased life expectancy, due to better health care, nutrition, and hygiene, and reduced have increased the country's share of elderly persons. The urban population accounts for 56,7% of the total, with an annual rate of urbanization of 3,34% (2015-2020 est.). The major urban areas per population are Kumasi, Accra and Sekondi-Takoradi [18].

From an economical point of view, Ghana has a market-based economy with relatively few policy barriers to trade and investment in comparison with other countries in the region, and it is endowed with natural resources. Its economy in recent years suffered the consequences of loose fiscal policy, high budget, and a depreciating currency [18]. Industry sector accounts for almost 25% of GDP, employs 14,4% of the workforce and is composed mainly of food, timber textiles, cement, oil refineries, aluminum, and pharmaceuticals, among others. Gold, oil, and cocoa exports are major sources of foreign exchange. Expansion of Ghana's nascent oil industry has boosted economic growth, but the fall in oil prices since 2015 reduced by half Ghana's oil revenue. Production at Jubilee, Ghana's first commercial offshore oilfield, began in mid-December 2010. Production from two more fields, TEN and Sankofa, started in 2016 and 2017, respectively. The country's first gas processing plant at Atuabo is also producing natural gas from the Jubilee field, providing power to several of Ghana's thermal power plants [18], [19]. As of 2018, key economic concerns facing the government include the lack of affordable electricity, lack of a solid domestic revenue base, and the high debt burden.

The Gross Domestic Product of the country was $ 125.4 billion (2011 PPP $) ranking 73 of 196 countries, with a per capita value of $ 4212 (2011 PPP $), a real annual GDP growth rate of 8.4%, and a total GDP growth over the 2008-2018 period of 130%, ranking 18 of 196 [18], [20], [21]. This figures let Ghana achieve a Human Development Index (HDI) of 0,596 in 2018, placing the country 142 in the world, above the Sub-Saharan average [20].

1.3.1 Energy Review

Over the last years Ghana experienced an increase of energy demand propelled by both population and urbanization growth, and a quite steady economic development.

As of 2018 the TPES of the countries amounts to 9.92 Mtoe, with Crude Oil and Biofuels and waste representing the 82% of the total.

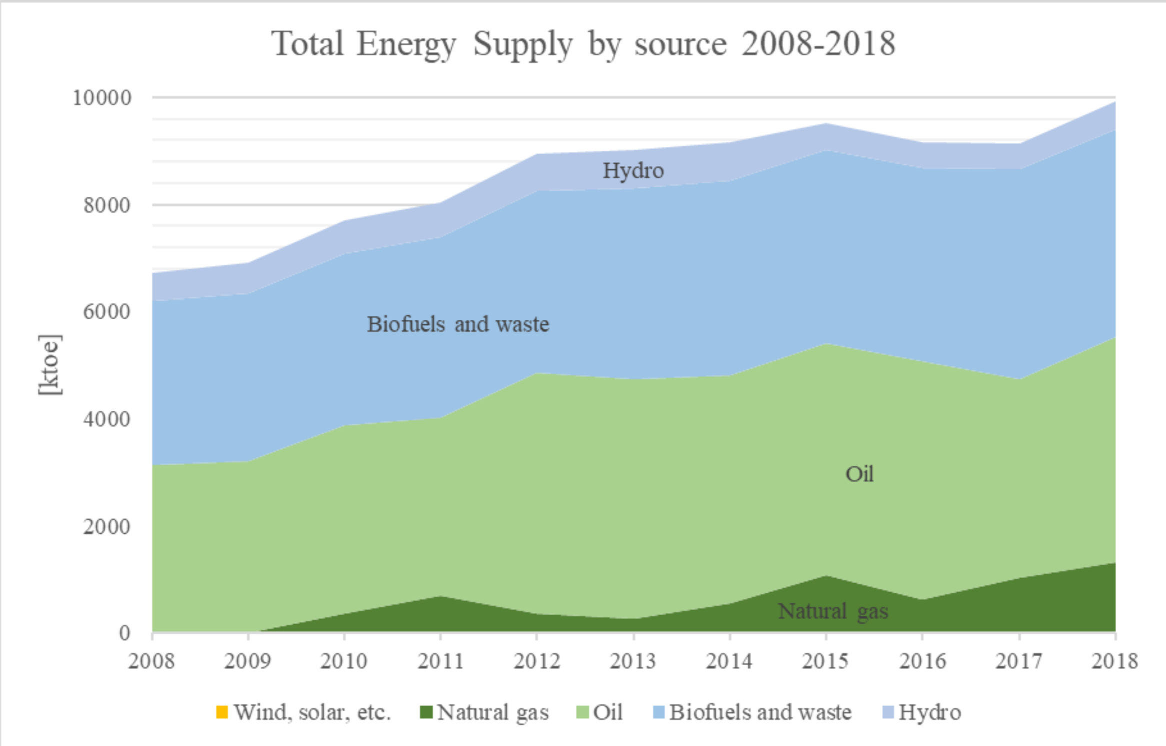


Figure 1.3 Total Energy Supply by source, Ghana (Source: IEA)

Figure 1.3 shows the evolution of sources of the Total Primary Energy Supply over the last 10 years, noticing an increase in the share of natural gas over the period [22].

In line with most of the Sub-Saharan countries, Ghana present energetic characteristics below the world average in terms of Total Primary Energy Supply (TPES) and Total Final Consumption (TFC). Electricity represents only little above 14% of the Total Final Consumption (TFC) in Ghana, while more than 80% derives from Crude Oil and Biofuels and waste.

However, Ghana has always been one of the leaders in region of Sub-Saharan Africa in terms of expanding the access to electricity within the country, reaching more than 82% of electricity access in 2018 [23], higher in respect to the region or the low income group and more in line with the lower middle income countries group, as can be seen from Figure 1.4.

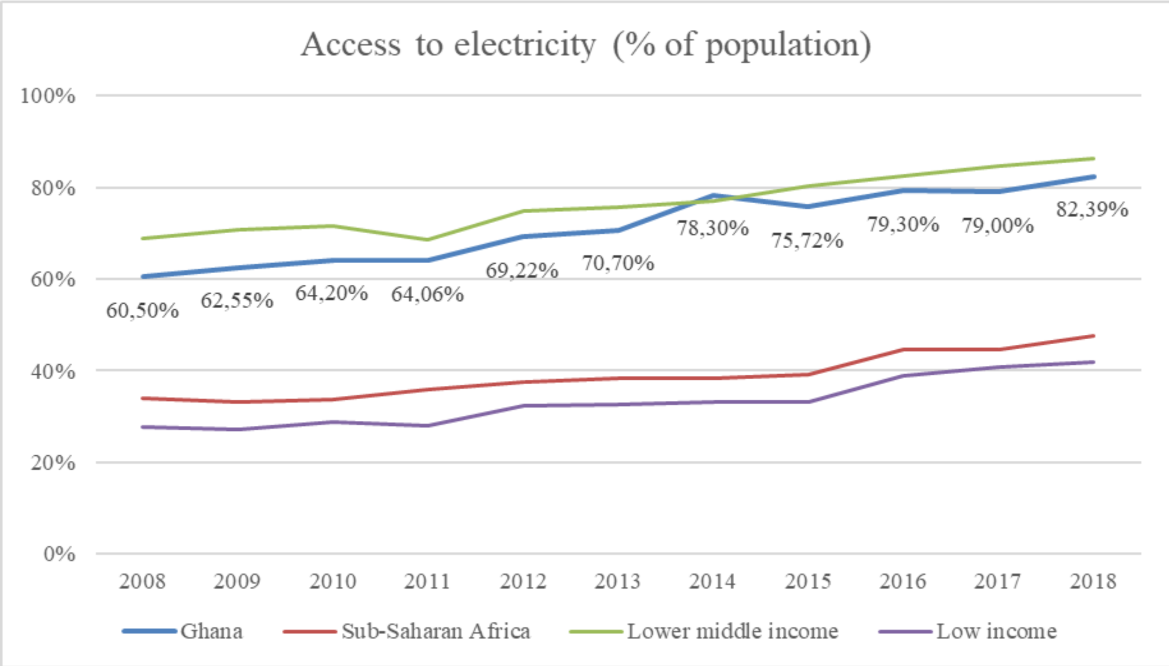


Figure 1.4 Access to electricity 2008-2018 (Source: IEA)

1.3.2 History of Ghana Power Sector

Ghana has travelled quite a journey in developing its power sector from the days of 1914, when the electricity was produced in the formerly Gold Coast by diesel-powered generator plants scattered across the country, starting from Sekondi to supply railways operations and then extended by the Electricity Department of the Public Works Department (PWD) to Takoradi and other major cities as Tema, Accra, Kumasi, etc., to about 82% of electricity coverage across the entire country in recent days [23], [24].

After Ghana secured independence in 1957, the impetus to embark on the massive industrialization of building roads, schools, hospitals, and factories called for a reliable supply of power. The need to build a dam to provide the country with hydropower was born. The government sourced loans to execute the project, and as a result, the Volta River Authority (VRA) was established in 1961 and charged under the Volta River Development Act, Act 46, with the duties of electricity generation via the water power of the Volta River, the construction of the Akosombo dam and a power station near Akosombo, and the resettlement of residents. Formal construction of the dam commenced in 1962, with the project consisting of four units of total capacity of 588 MW, and was completed in 1965 at an estimated cost of $200 million [25].

The second and third of hydropower development consisted of the construction of two additional hydropower units with a total capacity of 324 MW in 1972, and in 1977 with the construction of four turbine units with a capacity of 160 MW at Kpong, downstream of the Akosombo Dam on the Volta River.

Finally, the Akosombo hydro power plant was retrofitted in 2005, upgrading its capacity to 1020 MW, and in 2007 three units, with a total capacity of 400 MW, were constructed on the Black Volta at Bui.

With these projects completed in 2013, the total installed hydropower capacity of the country was up to 1580 MW [26], [27].

Rapid import industrialization followed the construction of the dam in Ghana’s major cities, thus increasing the demand for power, which increased nearly sixfold from 1968 to 1976 reaching 3971 GWh with an annual growth rate of about 10 % [25].

The first power crisis happened in 1984, as shown in Figure 1.5, as a result of the deteriorating economy in the late 1970s and compounded by a major drought from 1983, disrupting the generating capability of the Akosombo dam mainly because the total inflow of the dam in the previous years was less than 15% of the expected total, triggering major power rationing and a reduction of supply to neighboring countries Togo and Benin.

A second power crisis hit in 1998, caused by low rainfalls and inflows to the Volta Lake in the previous years, resulting in another round of power rationing and dropping electricity supply to consumers [28].

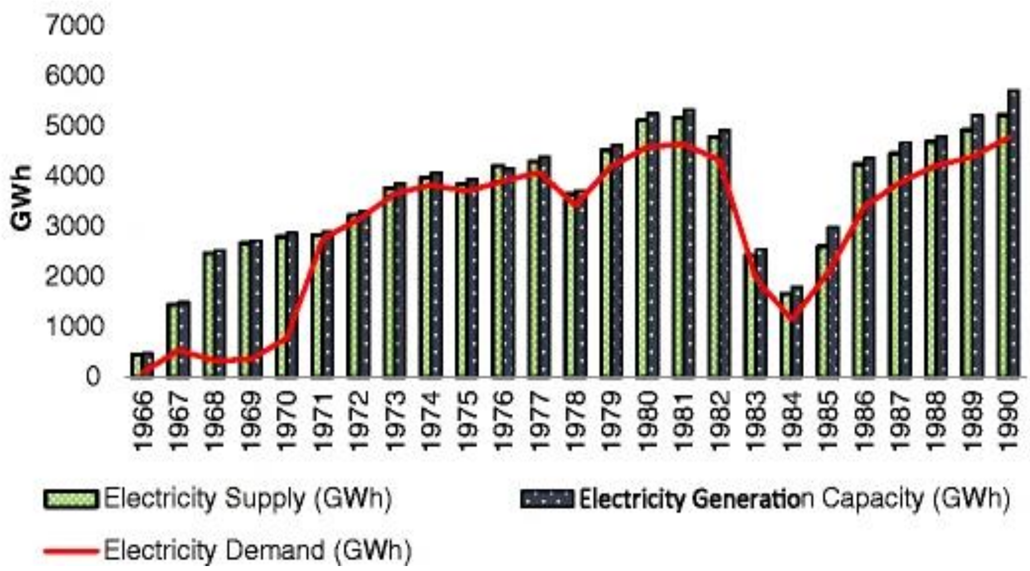


Figure 1.5 Trends in electricity demand, supply, and generation potential from 1966 to 1990
(Source: Data from VRA Annual Reports (1966–1990))

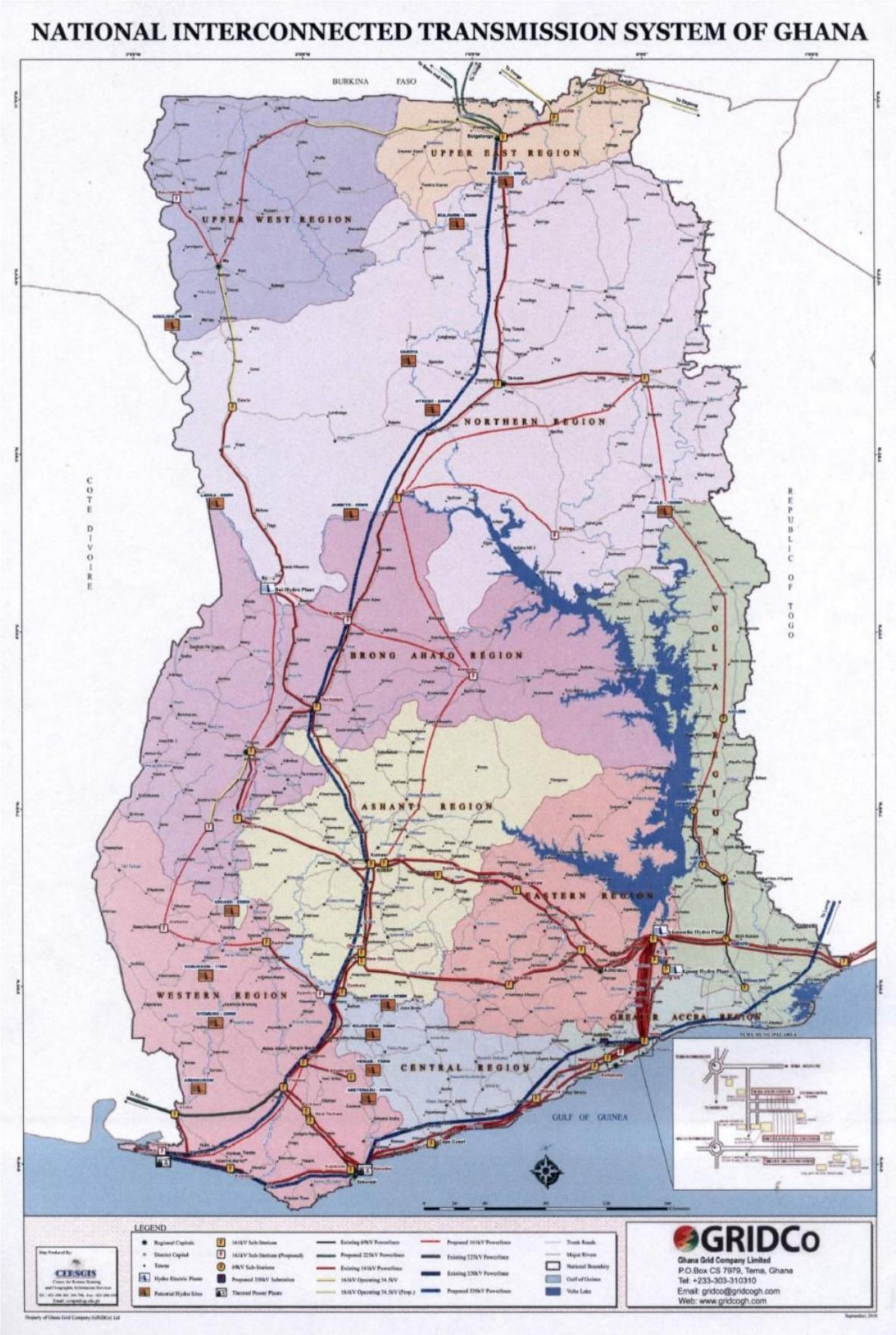


Figure 1.6 Transmission System of Ghana (Source: GRIDCo)

The power crisis that accompanied the droughts sent a clear signal to VRA and the government of Ghana that the nation’s almost exclusive dependence on hydroelectric power was flawed and that hydropower cannot be solely relied upon to meet the energy requirements of Ghana.

Therefore, Power Sector Reforms was initiated by the Government of Ghana in 1994 to, among other purposes, reduce the increasing pressure on the GOG and to transform the vertically integrated structure of the power sector into one that allowed for the entry of independent power producers (IPPs). These IPPs were expected to bring private sector investment into the energy sector, increasing the generation capacity to ensure the availability of reliable power supply.

Hence, the way was paved and IPPs started investing in the energy sector, starting from CMS Generation of Michigan, an American company, followed by Sunon Asogli, a Chinese company, and so on. By the end of 2018, the Ghana power system consisted of a number of hydropower and thermal plants owned by the VRA, Bui Power Authority (BPA) and several IPPs with a total installed capacity of 4470 MW and a number of ongoing projects on the way to completion [27].

These generating capacity are evacuated through a transmission network with a total length of approximately 5200 km and with a voltage levels spanning 69 kV, 161 kV, 225 kV and 330 kV, as showed in Figure 1.6, managed by Ghana Grid Company (GRIDCo), a state-owned entity, and distributed by other two state-owned utilities, the Electricity Company of Ghana (ECG) and the Northern Electricity Distribution Company (NEDCo), and a private company, the Enclave Power Company.

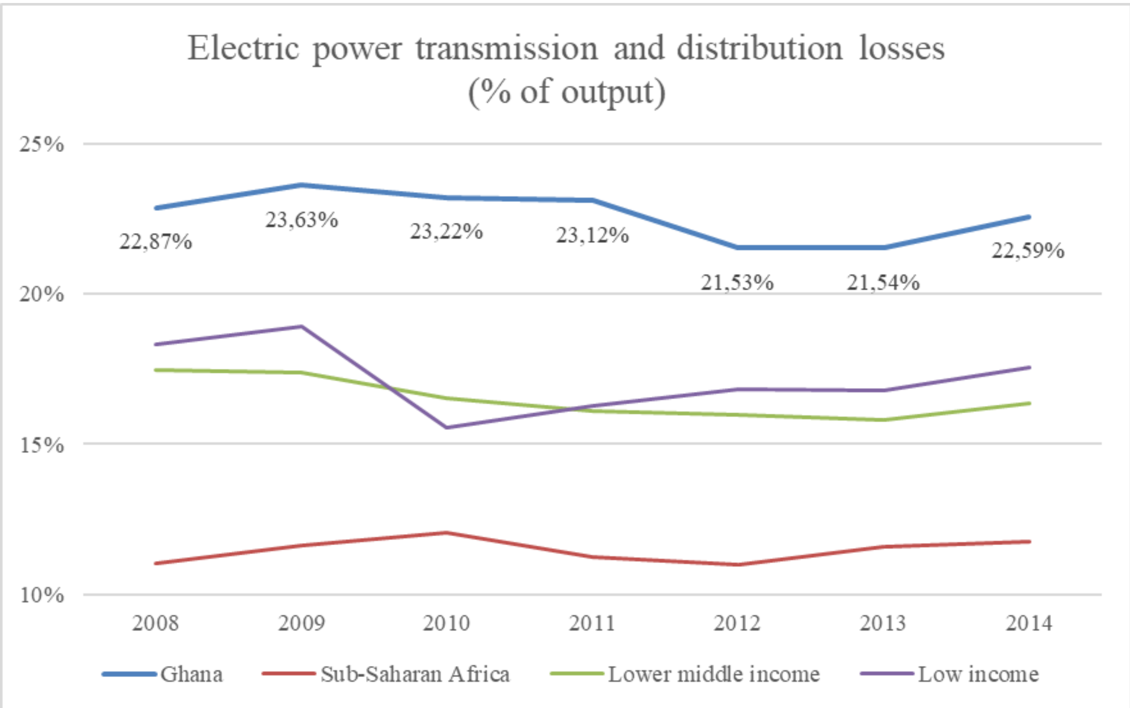


Figure 1.7 Electricity Power Transmission and Distribution Losses (Source: World Bank)

We have to notice that in Ghana, electric power transmission and distribution losses are a big constrain for the development of the countries, accounting almost 23% of the total power transferred, showing a negative record in respect with the Sub-Saharan countries and low and lower middle income countries, as shown in Figure 1.7 [23].

Even after this remarkable expansion and evolution of the power sector, the country faced another deep crisis of generation shortfall, christened as Dumsor, meaning “on and off” in the local Akan language, spanned continually from 2012 to 2015, where power outages and rationing negatively impacted the Ghanaian economy.

The three major factors, which among others, contributed to the 2012-2015 power supply crisis were:

- The accidental rupture of the West Africa Gas Pipeline (WAGP) along the underwater gas pipeline segment between Togo and Benin by the anchor of a vessel, which completely shut-off gas supply from Nigeria to Ghana, Togo and Benin which resulted in major power supply problems. Even after the reparation and the returning to service the expected contractual gas volume was never delivered.
- The over-drafting of the Akosombo Dam reservoir, which forced by the loss of thermal generation of the gas-only-fired power plants in Tema and some plants in Takoradi, due to technical challenges, required an excessive exploitation of the reservoir, keeping the generation above the recommended level from this source.
- The confused and not reactive economic side of the power sector, which was penalized by the cash flow constraints connected with the higher prices of thermal generation in comparison with hydropower generation which was not fully passed to the consumers as it arose, and by the lack of adequate and timely investment in the sector, where as for example of funding challenges is the development of the Bui hydropower plant, which took place in 2007 after a number of feasibility studies undertaken between 1966 and 2006 [27].

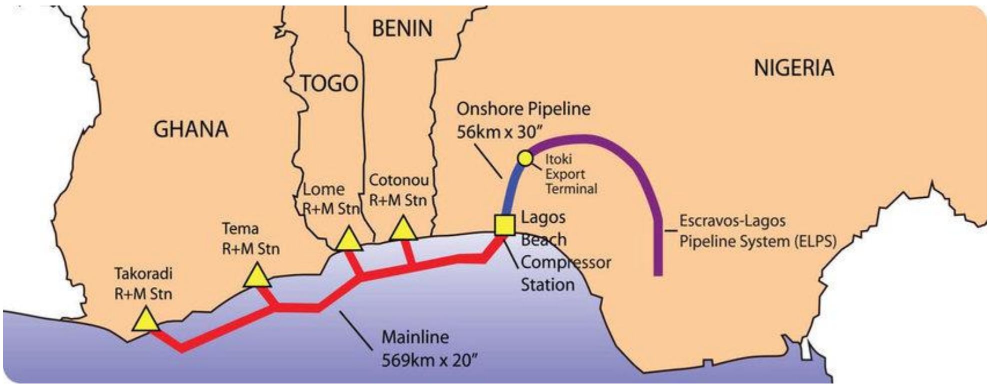


Figure 1.8 West Africa Gas Pipeline (WAGP) schematic (Source: West African Gas Pipeline Company, www.wagpco.com)

The most recent crisis exposed again the fragility of the power sector caused by a lack of diversification in the generation mix and forced the Government of Ghana to classify as “emergency periods” the ongoing situation and in an effort to supply the much-needed power the Government started to respond to a number of unsolicited proposals and procured short-term emergency power plants. This uncoordinated emergency procurement of power plants led to an over procurement of power projects and once the capacity shortage was eliminated through the procurement, the tariffs were raised to reflect both the depreciated value of the local currency and the increased generation costs (partly due to the expensive emergency power purchase contracts that had been entered into) and, mixed with the relative low post-2014 diesel fuel prices, resulted in a reduction in the consumption of grid-based electricity.

To date, the financial impact of the 2012 gas supply disruption and the limited supply of gas volumes to Ghana from Nigeria are still being felt in the power sector [27].

1.3.3 Ghana Power Sector Institutions

The institutional roles of various entities in the power planning process are described in this section, introducing their contribution to the thesis work.

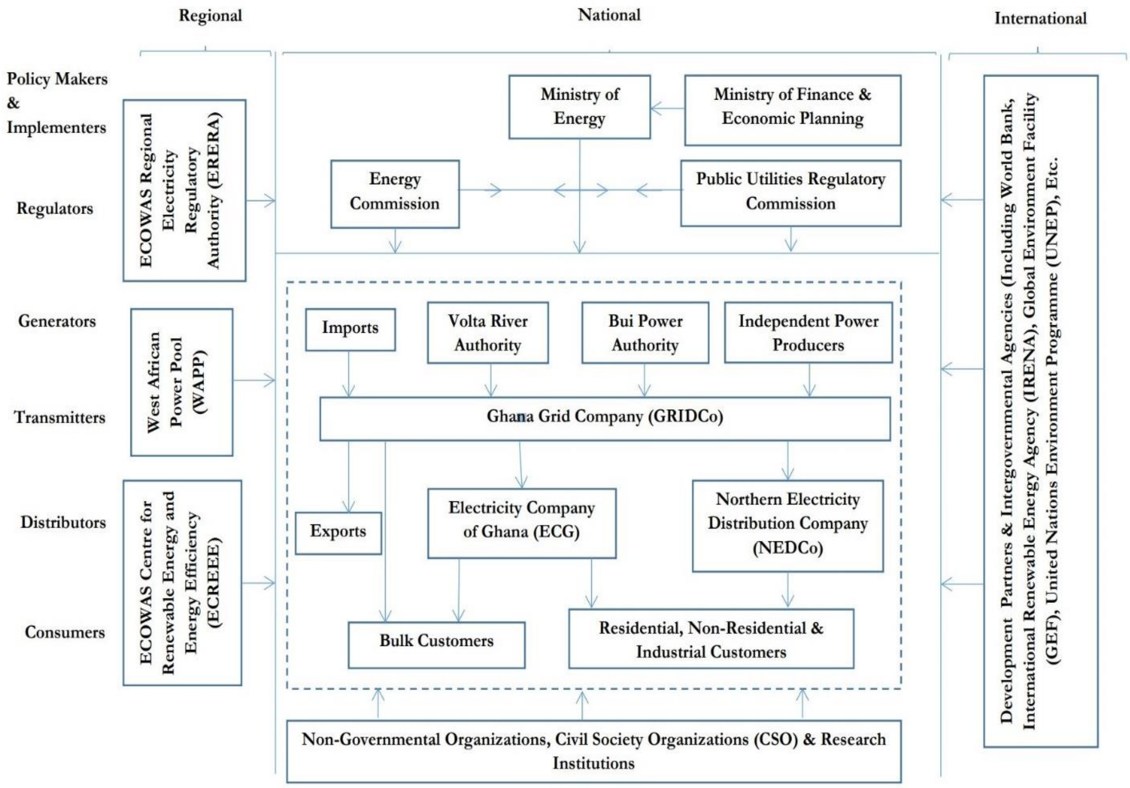


Figure 1.9 Schematic of the stakeholders in the Ghana's Power Sector (Source: Center for Global Development, www.cgdev.org)

The type of planning work performed by these agencies is conducted in "silos", denying the synergy that a joint or a more collaborative planning team could achieve.

- Ministry of Energy (MoEn): is a policy-making institution which formulates, monitors, and evaluates energy sectors policies to ensure that reliable and high-quality energy services are provided at the minimum costs to all the sectors of the economy. MoEn is often the primary point of contact for development partners who are seeking to provide technical, financial, or any other type of support to the power sector agencies in Ghana and in fact it was one of the first contacted stakeholders in this thesis work.
- Energy Commission (EC): based on its mandate, stipulated by the Energy Commission Act, 1997 (Act 541), its functions include the licensing of the operators in the generation, transmission and distribution electricity and natural gas, the service of energy policy adviser to the Government of Ghana, the preparation of indicative national plans to ensure that all reasonable demands for energy are met, and finally, the creation and assurance a comprehensive database for national-decision-making for the efficient utilization of energy resources. In the effort to fulfill its planning mandate, the EC produced the SNEP, which was updated in 2019, which contains the Integrated Power System Master Plan (IPSMP), the fundamental document on which are based most of the assumption in this work.
- Ghana Grid Company (GRIDCo): the transmission utility which, as stipulated in the Electricity Regulations, 2008 (LI 1937), plan and operate in a safe, reliable and transparent manner the National Interconnected Transmission System (NITS), which provided to the author an extensive database containing all the information about the transmission network needed for the thesis.
- Individual Distribution Companies (DISCos): composed by two state-owned and one private company, they carry out their own load demand forecast to determine the levels of electricity demand in their areas of operation. Additionally, they carry out various studies with the purpose of loss reduction, the determination of suitable locations and capacity for grid implementations and also, if needed, the support of their network expansion based on anticipated load growth. These entities provide to FEEM and the author the regional load demand, fundamental for the validation or the confutation of the theory expressed in the thesis work.
- Volta River Authority (VRA) and Independent Power Producers (IPPs): provide information to the Annual Supply Plans on the availability of their various generating resources to meet the projected demand. The document containing the information provided by these entities have been of fundamental importance during the study of the supply side in the work [27].

Other entities exist in the power sector of Ghana, such as PURC, GNPC and GNGC but the information provided were not indispensable or can be used in an advanced continuation of the thesis work.

1.3.4 Current Challenges and Opportunities in the Power Sector

It has to be noticed that several weakness can be found in the Ghana's Power Sector, as for example the poor grid system, which faces with lot of problems as an enormous amount of power losses caused mainly because of the obsolete nature of the facilities [29].

Other weaknesses are the poor maintenance culture, which is a problem not only associated with Ghana, but research indicates that it is a general problem in developing countries [30] and the lack of investments and adequate financing, which can be noted in the case of the Bui hydropower plant, where 40 years passed between the first feasibility study and the actual start of the development of the dam [27].

Ghana has been committed to providing universal access to electricity by the year 2020 as an establishment of the National Electrification Scheme [31], and even if the goal was not achieved, the rate and the percentage of electricity access are promising.

Moreover, there is an increasing energy demand in the country in recent years, as result of the country's increasing population (average growth rate of 2% per year), industrialization and urban growth (average growth rate of 4% between 1980–2018) [23]. The consumption of electricity has been increasing in the residential, industrial, and commercial sectors with an annual growth rate of over 10% in the last decade. Quite a large number of Ghanaians are still without access to clean and affordable sources of energy and the improvement of the power sector is imperative to deliver electricity to such home and businesses.

Despite challenges in the electricity sector as well as the short fall in supply, the country still exports power to its neighboring countries like Togo, Cote d'Ivoire, Burkina Faso, and Benin. According to the Energy Commission's 2018 report, the country exported a total of 284 GWh of electrical power to Benin and Togo. Approximately 57.5 GWh of electricity was also exported to Burkina Faso in 2017 (Energy Commission of Ghana Report, 2018). Countries in West Africa signed the West African Power Pool (WAPP) agreement in October 2008 which is aimed at developing facilities for the generation of energy for the various countries as well as interconnection of the various individual national grids to enhance power supply [32].

The country's energy policies favor the use of fossil fuel which tends to impede the penetration of other possible alternative energies. For example, the Ghanaian government subsidizes fossil fuel for its people. However, in order to limit the negative effect of greenhouse gases (GHG) on the environment as a result of the continual use of fossil fuel, there is the need for countries to depart from the use of fossil fuel onto the path of clean energy. According to the IEA, phasing out the subsidies on fossil fuel by 2020 could lead to a 5% reduction in emission of GHG. Fuel subsidies distort markets and hinders the development of competitive alternative energy, which leads to a reduction in the possibility of the needed capital investment. Furthermore, policy and decision makers tend to give more attention to short-term growth of the economy rather than the long-term sustainable development, this discourages investors and business leaders from exploring new path [33], [34].

However, in 2019, Ghana published a Renewable Energy Master Plan with several and remarkable goals as:

- Increase the proportion of renewable energy in the national energy generation mix from 42.5 MW in 2015 to 1,363.63 MW (with grid-connected systems totaling 1,094.63 MW).
- Reduce dependence on biomass as the main fuel for thermal energy applications.
- Provide renewable energy-based decentralized electrification options in 1,000 off-grid communities.
- Promote local content and local participation in the renewable energy industry [35].

Even though several African countries have formulated a series of policies for the development of their respective energy sector, the effective and consistent implementation of these policies encounter potential risks as a result of influences from both home and abroad [36]. Policy implementation uncertainties as a result of political regime changes are a threat to such investments and a huge problem in Ghana as several projects initiated by past governments across the country are left to rot when there is a change in political power. This does not promote development particularly in a country that is cash trapped and therefore requires that the country's resources be put to good use. It also increases the level of risks in the financing of investments which scares investors.

Hence, the country should differentiate its energy mix, introducing a number of renewables projects, for which the country would be plenty of resources, and switching to more secure means of fuel procurement, given the new discoveries of oil and gas reservoirs and their development into commercial production.

Other than this, it should implement some efficiency-orientated policies in order to reduce the enormous losses which the power sector has to face.

1.4 Data Paucity in Development Countries

The quality, availability, timeliness and use of basic economic and demographic data to inform policy makers remain a significant challenge across Africa, especially for the last in development countries [37].

Data are essential for governments and institutions in order to plan, execute and evaluate the right policies for the right country but Africa has to face several challenges in terms of know-how and for qualified human resources.

Lack of accuracy and missing data are significant obstacles to making and measuring progress on development. Between 1990 and 2009, only one Sub- Saharan country had data on all 12 MDG indicators [38].

One remarkable example of data inaccuracy is the 2104 Nigeria rebasing, which is the change in the method of calculating the Gross Domestic Product (GDP). The process is usually carried out every three or five years and it is needed to capture the most up-to-date picture of the economy, but in the case of Nigeria it was not done since 1990 [39].

Efforts have been made after the 2015 UN development agenda, calling for “data revolution” and promoting open data and open access tools in order to promote the public access to information that can be used to inform on global development efforts, donor decisions, and policies [40].

Entering the energy engineering field, data paucity affects the generation of proper models and simulations which help the institutions in the policies addressing.

Usually energy-related data are nation-wide, limiting the analysis of potential differences within the country and hence limiting the most efficient use of the resources that each region offers.

In fact, the purpose of having regional data of a country is to create more accurate model which can spatially describe the country in a comprehensive way.

The advantage of these multi-node models is the possibility to reproduce the distribution of spatially dependent particularities in the supply and demand profiles: weather dependent electricity generations, for instance from wind and solar, differ in the potentials for each node, which is a precious data in order to achieve the most effective placement of such technologies, which different policies adopted push to increase their use.

Moreover, multi-node models enhance the description of transmission technologies which were not considered in single-node models but often present big issues for the country, and hence have to be taken into consideration in the analysis.

For these reasons in this thesis is proposed a method to generate accountable data about energy topic using different open access software and open access data, overstepping the problem of data paucity and enhancing the creation of a more precise multi-node model in order to analyze the electricity situation of Ghana.

Chapter 2
Literature Review

2.1 Energy system modelling

As already stated, energy has a pivotal role to improve human wellbeing, economic development, and poverty alleviation of a country.

Hence, in a period of strong changes and challenges related to energy and sustainable development, an accurate analysis of the energy systems is crucial to better understand these linkages.

Energy modelling has the scope to recreate and analyze energy systems and support multi-criteria assessments of the impact of energy policies on the economy and environment [41].

While most of energy systems models were initially focused more on energy security and costs, climate change policy has since emerged as a powerful factor driving many studies, with a focus on pathways to achieve the significant reductions in greenhouse gas emissions called for by climate science [15].

Many approaches have been tried, but energy models can be mainly divided into two main categories: bottom-up and top-down models.

- Engineering bottom-up models describe current and prospective technologies in detail, usually cast as mathematical programming problems. They are therefore well suited to the analysis of specific changes in technology or command-and-control policies such as efficiency standards. A common shortcoming of the bottom-up analysis is that it fails to account for price distortions, economy-wide interactions and income effects [42].

These models can be further divided into four categories:

1. Energy systems optimization models: covering the entire energy system, primarily using optimization methods, with the primary aim of providing scenarios of how the system could evolve.

2. Energy systems simulation models: covering the entire energy system, primarily using simulation techniques, with the primary purpose of providing forecasts of how the system may evolve.
3. Power systems and electricity market models: focused exclusively on the electricity system, ranging in methods and intentions from optimization/scenarios to simulation/prediction.
4. Qualitative and mixed methods scenarios: relying on more qualitative or mixed methods rather than detailed mathematical description [14].

- Macro-economic top-down models instead examine the broader economy and incorporate feedback effects between different markets triggered by policy-induced changes in relative prices and incomes. They typically do not feature technological details of energy production or conversion. Energy sectors, like other non-energy sectors, are mostly represented in an aggregate way by means of smooth production functions which capture substitution (transformation) possibilities via substitution (transformation) elasticities. As a consequence, conventional top-down models cannot readily incorporate different assumptions about how discrete energy technologies and costs will evolve in the future; top-down models may also violate fundamental physical restrictions such as the conservation of matter and energy [42].

We can subdivide top-down models into:

1. Input-Output models (I/O models): generally used for energy-economy analysis with long-term time horizon, requiring extensive data but not always able to account for major characteristics as rural-urban division.
2. Econometrics models: based on regression or time-series model and requiring extensive data and time-series.
3. General Equilibrium models: simulate the behaviors of consumers and producers subjected to policies, income levels, energy prices change and other factors. The functions of Demand and Supply describe the conditions of the market.
4. System Dynamic models: they take advantage of complex non-linear simulations to build the model and the policies implications [43].

Typically, as the complexity of the description increases, computational efforts arise. This brings to many energy models focusing on particular aspects or to a specific location [44].

A general comparison of energy system models considers that bottom-up accounting type of framework seems to be more efficient and reliable for a developing country context because of its flexibility [43] but traditionally these models, given a detailed technical description, tend to aggregate time and space variables, aggregating technologies at national level and considering a small number of time slice per year to reduce computational effort.

Examples of established models are MARKAL [45], MESSAGE [46], TIMES [47] and LEAP [48] but these methods to model energy systems are no more compatible with the new challenges that energy systems are facing nowadays, such as the rise of flexible demand driven by new technologies and distributed generation, the importance of electrification and intermittent supply with the resulting need for more temporal detail, and the new paradigm of distributed energy and varying renewable resource potential with the resulting need for more spatial detail [14].

Another issue these energy models have to face is the rising availability of Open-Source Software (OSS) and the related advantage it adds to the energy system modelling environment. It has been shown that Open Source Software can generally meet high standards with little or no difference in quality relative to proprietary software [49] having the huge advantage of free accessibility, which makes them particularly attractive for academic and developing countries application. Dealing with OSS, we must cite the energy model OSeMOSYS designed to extend the availability of energy modelling to the communities of students, business analysts, government specialists and developing country energy researchers [50].

Further insights are shown in Table 2.1, where strengths and weaknesses of different categories are shown.

In this thesis work we will use Calliope, an open-source energy modelling framework developed by the Department of Environmental System Science of ETH, Zurich. Calliope is a framework to build energy system models, designed to analyses ranging from single urban districts to countries and continents. Its formulation of energy system components was influenced by the power nodes modelling framework by Heussen et al. but generalized to consider energy carriers other than electricity. Calliope's key features include the ability to handle high spatial and temporal resolution and to easily run on high-performance computing systems. Its design cleanly separates the general framework (code) from the problem-specific model (data). It provides both a command-line interface and an API for programmatic use, to be useful both for users experienced with Python and those with no Python knowledge.

A Calliope model consists of a collection of YAML and CSV files that define technologies, locations, links between locations, resource potentials, and other constraints. Calliope takes these files, constructs an optimization problem, solves it, and reports results in the form of xarray datasets, which can easily be saved to NetCDF files for further processing. It uses Pyomo as a backend to interface with both open and commercial solvers, currently handling linear and mixed-integer problems, although nonlinear components could be implemented if necessary for new kinds of problems. Finally, Calliope's built-in tools allow interactive exploration of results using Plotly (Plotly, 2018) [51].

The major shortcoming of Open-Source Software is the relative access to open data. Data is both an input and output of the modelling process. Raw data in the energy field is spread widely and of varying quality, coming from academic sources, non-governmental bodies, markets, individuals, and commercial entities but an impediment to openness is the widespread use of non-disclosure agreements under which commercially sensitive data may be shared. A less obvious impediment is that in many cases, no explicit license is attached to input data. Contrary to common practice, this does not imply the legal permission to use and share data. This is of crucial importance since the degree of openness and the licensing conditions of input data influence the degree to which a model based on them can be created [52].

In the developing country context, data limitations arise an additional limitation. Both bottom-up and top-down approaches require different sets of information and often such detailed data is not available or where available, the quality may not be of high standard. The data gap poses hurdles to build scenarios, evaluate technologies and analyze policy impacts [43] and the effort made in this thesis work try to create an alternative method to estimate fundamental data for the modelling process.

Table 2.1 Strengths and weaknesses of different energy modelling approach [53]

Model Type	Strengths	Weakness
Bottom-up	- detailed and technology-rich structure allows to incorporate various resource constraints, cost implications of different technological developments and resulting emissions - national/regional modelling approach allows to assess interconnectedness between energy systems on country/regional/global level	- socio-economic aspects are addressed to a limited extent and the assumptions about socio-economic system are often simplified
Top-down	- broader scope makes it possible to examine feedbacks between the energy sector and other sectors of the economy - holistic approach for modelling economic system allows for climate change policies' analysis - socio-economic dynamics is modelled in relatively detailed manner	- simplified representation of the energy system makes it difficult to understand the implications of the different energy technologies' development
Hybrid models	- flexibility of the modelling approach allows to combine different models with different orientations in accordance with the research questions asked - it is possible to use models for different questions without changing model itself/developing new model - by combining bottom-up and top-down models the methodological limitations of both approaches can be reduced - the approach is suitable for modelling different nexuses related to energy system (i.e.: water-energy, water-land-energy) - by combining bottom-up structures with macroeconomic structures models allow to examine policymaking in the short- and especially in the long-term	- the models' structures can be very complex, which may make interpretation of the modelling output difficult - connection of models of different scales and using different modelling techniques can be a time-consuming and high-technical-skills-demanding process

2.2 Proxied estimation of electricity demand division

Different research tried to fill the gap in the data shortcoming, trying to estimate sensitive and important data to the energy modelling process in a number of ways, and here we cite the most consistent to the method applied in this thesis.

2.2.1 M-LED: multi-sectoral latent electricity demand assessment for energy access planning

The Multi-sectoral Latent Electricity Demand, or M-LED in short, is an open sources geospatial data processing and assessment platform. It enables an estimation of electricity demand in communities that live in energy poverty. The key novelty of the platform is its multi-sectoral, bottom-up, high spatiotemporal resolution evaluation, which altogether advances the state- of-the-art on latent electricity demand characterization. Here, by latent demand, we refer to demand which would exist if the infrastructure and techno-economic conditions to supply it would be met. Secondly, besides modelling different non-residential sectors including the agriculture, service, and productive activities, the platform includes a more detailed assessment of residential demand – representing heterogeneous appliances ownership and usage patterns and allowing for stochastic variability in the demand. Thirdly, the M-LED platform enables a characterization of the seasonal and hourly variation in the demand from different sectors is of crucial importance for properly planning the energy system and assessing the complementarity of variable renewable energy sources supply curves with the demand. Finally, the multi-sectoral approach includes an assessment on the water- energy needs and the nexus implications for agriculture-related activities. This encompasses an analysis of the potential revenues and costs from the potential agricultural productivity growth thanks to artificial irrigation as a result of the provision of electricity [54].

M-LED is an open source, bottom-up platform which purpose is to characterize the power requirements across different sectors, combining openly available geospatial information, modelling instruments, and scenario analysis to support a sectoral-inclusive electrification planning. A key passage is the exploitation of the Remote-Areas Multi-energy load Profiles (RAMP) model to create a stochastic, seasonal-heterogeneous energy demand profile of each player in the electrification process [54], [55].

Once RAMP estimates the energy demand, using a set of appliances that can be used from the population, geospatial information is used to evaluate the distribution of the population with electricity access and the type of settlements (urban or rural prevalence) and finally, based on the regression coefficients there is an allocation of each household without access to electricity enclosed in each cluster to each of the RAMP-generated demand profile archetypes [54].

The results achieved by this work are remarkable, from the introduction of the demand estimation methodology with the purpose of a detailed latent electricity demand to the highlight of the necessity in including more players in respect to the electrification based on residential demand only, and the methodology applied is a great starting point to consider in the development of this thesis work, given the great necessity, in an open data proxied estimation of the electricity demand, of tiers on which to base the process.

GHSL based assessment of rural and urban settlement seems a really interesting and flexible tool, as well as the use of the RAMP model to estimate the electricity load profiles, and for this reason they have been implemented in the thesis work.

2.2.2 High-resolution gridded nighttime lights dataset to assess electrification in Sub-Saharan Africa

Another notable work which introduced the use of geospatial information is the creation of a fully reproducible high-resolution dataset of electricity access built on regularly updated gridded nighttime light (NTL), population, and land cover data [56].

This work is also boosted by the growing demand for reliable data to support decision-makers with the major limitations found in context of developing countries, where data availability is affected by a number of issues, including financial, technical, and infrastructure constraints to collect and maintain up-to-date data as well as data quality lack [57].

The authors employ VIIRS-DNB (Visible Infrared Imaging Radiometer Suite, Day-Night Band) stray-light corrected product for NTL radiance and LandScan and WorldPop gridded population distribution datasets.

Nighttime lights (NTL) have already been used as a proxy for electricity access, residential consumption, outage detection, population fluctuation and migration, regional GDP, and income inequality, but this is, however, the first time a fully reproducible and updated dataset at this high level of resolution has been constructed and validated for Sub-Saharan Africa. [56]. The remotely sensed NTL data is derived from Suomi National Polar-orbiting Partnership (NPP)-VIIRS monthly composites [58] and after a partial pre-processing at the source, mixed with electricity access rate data by ESMAP/World Bank database and the 2017 MCD12Q1 V6 MODIS Land Cover Type26 from the Annual University of Maryland classification [59] are processed on the Google Earth Engine platform in order to produce satellite imagery and extract data, which is subsequently used to produce the datasets and generate plots in the R scientific computing environment [56].

The remarkable results obtained is the capacity to reproduce a high-resolution dataset with the use of completely open-source software and open access data. Also, the approach used for the geospatial data management and population clustering and classification is reusable in this thesis as it represents a fundamental step in the proxied electricity demand estimation.

2.3 Objective, Gaps and Challenges

Finally, we can identify the gaps that this work will try to fill. The growing demand for data in developing country marks an essential prerequisite for this thesis. We found from the literature a variety of effective way to extrapolate important and sensitive information from open access data, consolidating the option of filling the lack of on the field interviews and research through remote analysis.

This thesis work tries to fill the data paucity gap proposing a methodology to geographically disaggregate the national electricity load demand by using a hybrid Top-Down Bottom-Up approach. The methodology consists of three major phases which follow an extensive literature review as well as data acquisition concerning the analyzed country. The first phase aims to perform a quantitative disaggregation of the energy system in order to identify and characterize with the higher resolution possible the most important players composing the system, trying to get the most accurate insight of ongoing situation and the energy quantities in consideration. The second phase consists of a geographical assessment of the energetic requirements which each entity present by jointly using geospatial open access databases and open-source software (OSS). The final phase tries to characterize from an energetic point of view the type of consumption of each entity identified and localized in the previous phases in terms of daily peak demand, energy requirements during the year and a general load profile along the day. This methodology's scope is to produce an electricity load demand timeseries with high time and spatial resolution in order to provide a starting point for the energetic analysis and policy making process to assess and hopefully achieve the 7th Sustainable Development Goals.

In the end, in order to validate the results of this methodology, this thesis work create and energy model of the country under analysis, Ghana, both using a Single-Node approach coupled with real-world timeseries referring to the year 2018, and a Multi-Node approach with as inputs the processed high-resolution electricity load demand.

Chapter 3
Methodology

In this chapter we review the methodology of the thesis work, starting from the data acquisition to the estimation of the multi-nodal electricity demand through the use of the open-source software and open access data, and finally the generation of both single- and multi-node energy model of Ghana.

The most challenging part of the thesis, the electricity demand estimation at regional level, has been performed through the use of multiple open access dataset as well as open source software like Quantum-GIS, a free and open source Geographic Information System, and RAMP, a bottom-up stochastic model for the generation of high-resolution multi-energy load profiles for energy systems located in remote areas, while for the modelling process we used Calliope, an open source optimization linear programming energy model, characterized by its flexibility with high spatial and temporal resolution.

The chapter is divided into a Data Collection section, in which all the data gathering process has been completed, a Load Demand Estimation section, in which is presented the entire process of estimation and division at regional level, and finally a Energy Modelling section in which we introduce both the single- as well as the multi-node energy system model for the country Ghana.

3.1 Data Collection

Data collection process can be divided into two parts mainly, the first is the one dedicated to gathering and validating information about the existing structures of the power sector, starting from the various plants which generate power, to the transmission network that operate in the country and the electricity demand, both in technical and in administrative terms. The second part of data gathering is relative to the estimation of the electricity demand and aimed to collection of socio-economic data about Ghana as well as geospatial information with the highest resolution and accountability possible.

3.1.1 Multi-node energy system model

Several institutions took part in the process and here there is a list of each contributor and a description of the collected data:

- Fondazione Eni Enrico Mattei provided:

    - Hourly electricity demand in kW over the year (365 days) for the period spanning from 2010 to 2018 at national level. The electricity load demand is the starting point for the estimation of the regional consumption.
    - Hourly production profiles of all the hydropower plants operating in the area for the year 2018, more precisely the Akosombo Hydroelectric Power Station, the Kpong Hydroelectric Power Station and Bui Generation Station. The production profiles are expressed as percentage of the total installed capacity.
    - Several report on gas related project and don documents assessing the gas potential of the country.

- Ghana Grid Company Ltd., or GRIDCo, and the Energy Commission provided:

    - Annual report about the analysis of performances of the power sector in Ghana over a number of aspects as transmission losses, to monthly peak demand and total consumption, as well as forecasts for the year next to the report. Every year a report is submitted by the Electricity Supply Plan Committee as requirement of the Ghana Electricity Grid Code.
    - Extensive and high-resolution information about the transmission network. Specifically, it is included the Name, Identifier, type of station (Generation or substation), coordinates of starting and arriving points, length of the line, year of construction, operating voltage in kV and thermal limit in MVA.

After the analysis of the literature obtained online or provided directly, a number of interviews have been performed over a period of several months in order to finalize the review process of the power sector of Ghana.

These interviews consist of a first contact with the designed stakeholders through a questionary, attached in Appendix A, which contained a number of preliminary questions in order to understand the type of information which can be asked to the interviewed as well as the level of knowledge in terms of Power Sector.

Several institutional stakeholders have been contacted, which we list here:

- Professor Chris Gordon, associate professor and researcher at the University of Ghana, representative of the international network Climate and Development Knowledge Network (CDKN) and board member of the Non-Profit Organization Kite and activist of sustainability and energy topics.

  He gave us a relative clarification of the institutional characters playing in the power sector of Ghana, advising the most coherent figures to contact. Moreover, as board member of Kite, an organization very interested in renewable energies, he talked about solar power installed and private installation which are not represented in the official reports.
- Mr. Cletus Alengah, a researcher and policy associate of the SDGs Advisory Unit at the office of the President of Ghana.

  He gave us explanation about the transmission and distribution network, clarifying all the main players as well as introducing the problem caused by the 2013-2016 power crisis and the overestimated number of Purchase Power Agreements (PPAs) stipulated by the government that consequently led to the overpayment of the exceeding installed capacity or the interruption and put them in stand-by, with major consequences on the electricity market in terms of prices and market strength. Finally, he agreed to help us with the pre-interviews, which he could send to a larger number of well-positioned stakeholders.
- Mr. Hanson Monney, Erough ngineer at the Ministry of Energy of Ghana.

  During his interview we focused on the technical parameters of all the power plants in Ghana, from the installed and dependable capacity to the location and the type of generation plant, as well as on the licenses issued by the regulatory institutions for the main power production plants, a number of ongoing renewable projects and the forecast development of the power sector in the future years. He also provided some technical information about the installed solar power plants, specifically the installed capacity as well as the prices of the electricity of those power plants.

  With his help we reviewed the entire dataset about power plants in Ghana, validating all the research conducted by literature review and previous interviews. This passage was fundamental since it gave us a solid dataset to describe and localize precisely all the power plants and the possibility to construct the generation side in the energy model.
- Mr. Ishmael Edjekumhene, executive director of Kite Association.

> During his interview we focused on renewable energy, talking about some solar power plants project and their progresses. We also validated the information obtained with Mr. Hanson Monney and clarified the latest details about some power plants.

Once finalized the data collection through interviews and a review of the literature, the problem could be observed: the lack of electricity load demand data at regional level was the main limitation for the creation of a multi-node energy model.

3.1.2 Electricity load data collection

The problem of data paucity, as already stated in the first chapter, is a huge shortcoming for the study of developing country, their modelling and all the production of correct policies and investments aimed for their economic and social growth.

In order to overturn the shortcoming of data, the idea to estimate the information at regional level thanks to open access data seems promising.

For this reason, the first step is to collect and evaluate which type of data could be useful for the objective.

The project, as it will be show below, will consider the categories of the Table 3.1, for which we had to collect geospatial and technical information for the load demand estimation.

Table 3.1 Sectors and sub-sector identification

Sector	Costumers	Identifier
Residential	Urban	hhd-uX
	Rural	hhd-rX
Industry	Metal Industry	metl
	Mining Industry	omin
	General Industry	*Other*
Commercial & Public	Miscellaneous	*Other*

The first, fundamental dataset is the Global Human Settlement Layer, created and supported by the Joint Research Centre (JRC) and the Directorate General for Regional and Urban Policy of the European Commission. JRC is the European Commission’s science and knowledge service which employs scientists to carry out research in order to provide independent scientific advice and support to EU policy.

The GHSL image analytics framework produces new global spatial information, evidence-based analytics and knowledge describing the human presence on the planet Earth. The GHSL operates in a fully open and free data and methods access policy, building the knowledge supporting the definition, the public discussion and the implementation of European policies and international frameworks such as the 2030 Development Agenda and the related thematic agreements [60].

The framework uses heterogeneous data including global archives of fine-scale satellite imagery, census data, and volunteered geographic information. The data is processed fully systematically and generates analytics and knowledge reporting objectively and systematically about the presence of population and built-up infrastructures. The dataset consists of three main information components hierarchically placed at three different levels of abstraction: Global Human Settlement built-up areas (GHS-BU), the GHS population grids (GHS-POP) and the GHS urban/rural classification model (GHS-SMOD) [61]. For this study we focused on the intermediate and top abstraction information layer of the GHSL, referred to the population grids and to urban/rural classification model. The methodology behind this work consists, in short, in several steps: from a regular acquisition of images of the Earth surface by Earth observation satellites and their manipulation through ortho-rectification, georeferencing, spectral calibration and radiometric corrections, to analysis of the human settlements characterized by constructed, man-made objects, which building footprints are modelled into built-up areas. This information combined with population censuses, create the intermediate layer: a grid of 1 km of resolution representing the presence and density of population, expressed in absolute number of inhabitants. Finally, the information about population density and built-up areas are used to classify, under determined conditions and parameters, the type of settlement creating the top layer representing the different spatial entities [60]–[62].

Hence the information we are referring to are the following, both openly available online:

- GHS population grid (GHS-POP), derived from GPW4.10, multi-temporal (1975-1990-2000-2015), R2019A [GHS_POP_MT_GLOBE_R2019A] [63]

This spatial raster product depicts the distribution and density of population, expressed as absolute number of people per cell. Residential population estimates for target years 1975, 1990, 2000 and 2015 provided by CIESIN Gridded Population of the World, version 4.10 (GPWv4.10) at polygon level, were disaggregated from census or administrative units to grid cells, informed by the distribution and density of built-up as mapped in the Global Human Settlement Layer (GHSL) global layer per corresponding epoch.

- GHS Settlement Model layers (GHS-SMOD), derived from GHS-POP and GHS-BUILT, multi-temporal (1975-1990-2000-2015), R2019A [GHS_SMOD_POPMT_GLOBE_R2019A] [64]

The GHS Settlement Model layers (GHS-SMOD) GHS_SMOD_POPMT_GLOBE_R2019A delineate and classify settlement typologies via a logic of cell clusters population size, population and built-up area densities as a refinement of the "degree of urbanization" method as described by EUROSTAT [65]. It is composed by two datasets: the GHS-SMOD raster grid, representing the settlement classification per grid, and the urban center entities vector, delineating the urban center boundaries, with main attributes, in a vector file.

The assumptions under which the dataset is produced are multiple and here we shortly cite them from the dedicated technical report [60]:

- Basic criteria: criteria for shaping the GHSL Settlement model as grid population density, grid cluster population size, and connectivity rule to form grid cell clusters.
    - Urban Centers: Population density of 1500 inhabitants per km^2, cluster population size of 50k inhabitants.
    - Urban Clusters: Population density of 300 inhabitants per km^2, cluster population size of 5k inhabitants.
    - Rural Clusters use population density of 300 inhabitants per km^2, cluster population size of 500 inhabitants.
    - Low density Rural grid cells use population density of 50 inhabitants per km^2.
- Permanent water surface excluded: all cells with at least 0.5 share of permanent water surface not populated nor built, are classified as "Water grid cells".
- Density on permanent land: densities values used in the GHSL SMOD are calculated using the permanent land surface portion inside the unitary surface of the spatial unit (grid cell).
- Xbu_share 50%: the Urban Centers are set by adding to the basic criteria (see point above) also those cells with at least 50% of built-up surface. This assumption is useful for accommodating the presence in the city of large areas with low resident inhabitants but strongly functionally linked with the city, as for example large productive or commercial areas.

- Generalization of HDC (smooth and gap filling): the “holes” within the Urban Centre perimeter after the smoothing are filled if they are smaller than 15 km^2 in surface. The effect of this assumption is that Urban Centers are more compact and simpler in shape, then easier to translate to GIS POLYGON entities. Ideal typical case is the inclusion of large parks or low-density population areas within the “Urban Center” perimeter.
- Xbu_share 3%: candidate samples for the “Urban Cluster” domain are accepted only if they exhibit a built-up surface share greater than 0.03.

With the described set of assumptions, at the first hierarchical level, the GHSL SMOD classifies the 1 km^2 grid cells by identifying the following spatial entities: a) “Urban Centre”, b) “Urban Cluster” and classifying all the other cells as “Rural Grid Cells”.

The second hierarchical level of the GHSL SMOD follows the same approach based on population density, population size and contiguity with a nested classification into the first hierarchical level. At the second hierarchical level, the GHSL SMOD classifies the 1 km^2 grid cells by identifying the following spatial entities: a) “Urban Centers” as at the first level; b) “Dense Urban Cluster” and c) “Semi-dense Urban Cluster” as parts of the “Urban Cluster”, classifying all the other cells of “Urban Clusters” as “Suburban or peri-urban grid cells”; and identifying d) ”Rural Cluster” within the “Rural grid cells”. All the other cells belonging to the “Rural grid cells” are classified as “Low Density grid cells” or “Very Low-Density grid cells” according to their cell population.

The settlement grid at level 2 represents these definitions on a single layer grid. Each pixel is classified using the following set of codes (classes) and rules:

- **Class 30**: “Urban Centre grid cell” if the cell belongs to an Urban Centre spatial entity.
- **Class 23**: “Dense Urban Cluster grid cell” if the cell belongs to a Dense Urban Cluster spatial entity.
- **Class 22**: “Semi-dense Urban Cluster grid cell” if the cell belongs to a Semi-dense Urban Cluster spatial entity.
- **Class 21**: “Suburban or per-urban grid cell” if the cell belongs to an Urban Cluster cells at first hierarchical level but is not part of a Dense or Semi-dense Urban Cluster.
- **Class 13**: “Rural cluster grid cell” if the cell belongs to a Rural Cluster spatial entity.
- **Class 12**: “Low Density Rural grid cell”, if the cell is classified as Rural grid cells at first hierarchical level, has more than 50 inhabitant and is not part of a Rural Cluster.

- **Class 11**: “Very low-density rural grid cell”, if the cell is classified as Rural grid cells at first hierarchical level, has less than 50 inhabitant and is not part of a Rural Cluster.
- **Class 10**: “Water grid cell”, if the cell has 0.5 share covered by permanent surface water and is not populated nor built.

In our work we use the level 2 of the GHSL-SMOD to identify and localize the urban and rural settlement and to attribute the amount of energy consumption of each sector to each region as described in the section below.

Another important dataset used in the electricity load demand estimation is obtained from the work on electrification in Sub-Saharan Africa by FEEM researcher Giacomo Falchetta et al. In the work “A high-resolution gridded dataset to assess electrification in sub-Saharan Africa” [56] they present an updatable and fully-reproducible 1-km resolution dataset of electricity access built on updated gridded nighttime light (NTL), with which we extrapolated the regional electrification rate for Ghana. The data are expressed as percentages and are referred to each administrational region of the country.

Next we collect urban and rural growth rate for the country Ghana from World Bank Databank, an analysis and visualization tool that contains collections of time series data on a variety of topics [23]. We focused on three indicators mainly:

- Population growth (annual %): it is the exponential rate of growth of midyear population from year t-1 to t, expressed as a percentage, considering population all residents regardless of legal status or citizenship. It is calculated on the assumption that rate of growth is constant between two points in time, using the formula r = ln(pn/p0)/n, where r is the exponential rate of growth.
- Urban population growth (annual %): urban population is calculated using World Bank population estimates and urban ratios. Countries differ in the way they classify population as “urban” or “rural” depending on each statistical office. Then the same formula is applied as before.
- Rural population growth (annual %): Rural population is calculated as the difference between the total population and the urban population. Rural population is approximated as the midyear nonurban population. While a practical means of identifying the rural population, it is not a precise measure.

$$r = \frac{ln\left(\frac{P_n}{P_0}\right)}{n} \tag{3.1}$$

Once collected the values of the three indicators we use Formula 3.1 in order to evaluate the population expansion, with “r” as growth rate, “n” number of years, Pn as population after “n” years and P0 as starting population. Here we introduce an important assumption, which is the consideration of all the growth rates equal over the whole country, neglecting the different distribution of the population at regional level.

Finally, we collect the vector files, as shapefile usable on Geospatial software, of the administrative boundaries of Ghana at national and regional level from the governmental platform “Ghana’s Open Data Initiative” (GODI) [66], which scope is to ensure public accessibility of all data. In this way we are fully able to localize and associate to each region the percentage of rural and urban population.

The next step is to find geospatial information about the remaining sector, which are industrial and commercial.

For the industrial the choice of the sector division permits us to localize the industries thanks to their peculiarity. In fact, the metal sector can be represent in his totality by the major Ghanaian company, Volta Aluminum Company or VALCO in short, an aluminum company based in Tema, Grater Accra Region, founded by Kaiser Aluminum and now wholly owned by the government of Ghana. The company, which gave the economic justification for the building of the Akosombo Dam, represent a consistent consumer in the national balance, and their installed capacity and peak demand, as well as the localization can be found on the literature and in the technical report drawn up by Energy Commission and GRIDCo, “Electricity Supply Plan 2019” [67].

The next one, the mining sector, is easily traceable due to the dimension of each mines.

From several online dataset as “Mining Data Online” [68] and from World Bank dedicated database “Africa – PowerMining Projects Database” [69] which shows ongoing and forthcoming mining projects in Africa categorized by the type of mineral, ore grade, size of the project. The database draws on basic mining data from Infomine surveys, the United States Geological Survey, annual reports, technical reports, feasibility studies, investor presentations, sustainability reports on property-owner websites or filed in public domains, and mining website. From this extensive database is possible to extract all the needed information about mines in Ghana, as location, energy needs in MW and energy consumption in GWh.

The last step is the acquisition of data in order to characterize the electricity load profile of the categories that we choose in the stochastic open source software RAMP as applied in previous works [54]. For this purpose, it is convenient to employ the data collected in a study in Kenya, for the characterization of electricity grid users. Given the similarity between Ghana and Kenya in terms of geographical position and socio-economic background, we can assume a similarity between the users of the grid and use the same tabulated behavior for Households and Commercial. In terms of Industrial electricity load characterization, we have to rely on the literature, which in terms of aluminum smelters and gold mining is quite generous and from which we can extract significant information, as shown in the figure below [70], which represent the percentage of power used over power installed for different types of heavy industries, among which we can find an Aluminum Smelter.

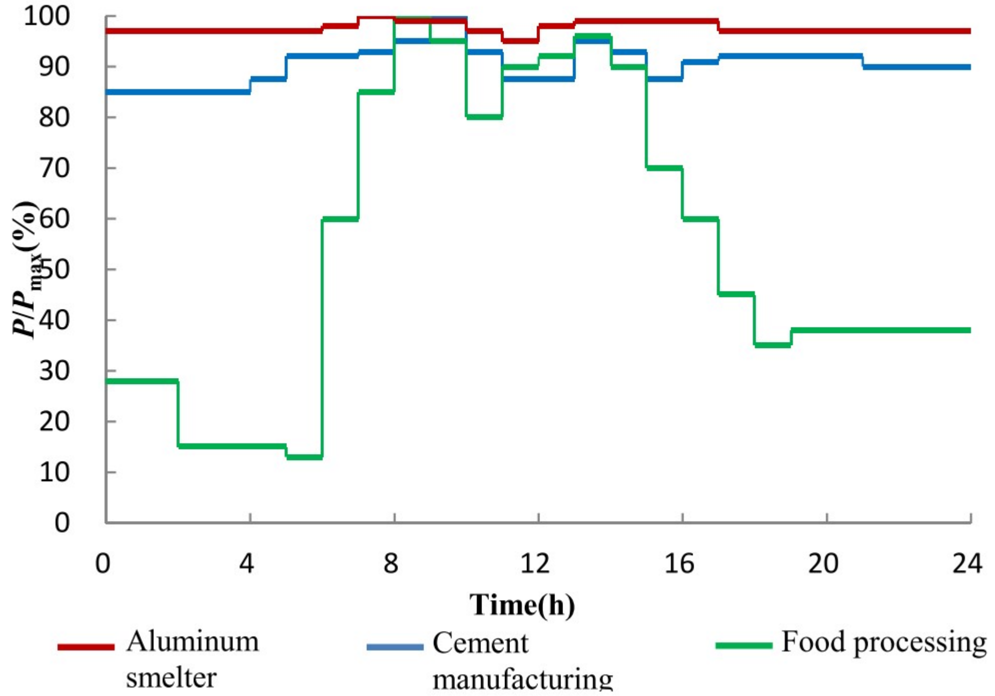


Figure 3.1 Daily load curve of typical industrial users in China (Source: [70])

3.2 Electricity load demand estimation

In this section we show the methodology followed for the estimation of the electricity demand using a hybrid approach, combining macroeconomic indicators, energy statistics, geospatial information, and bottom-up open-source software.

The process has been divided into 3 parts explained and visualized below.

3.2.1 Quantitative Disaggregation

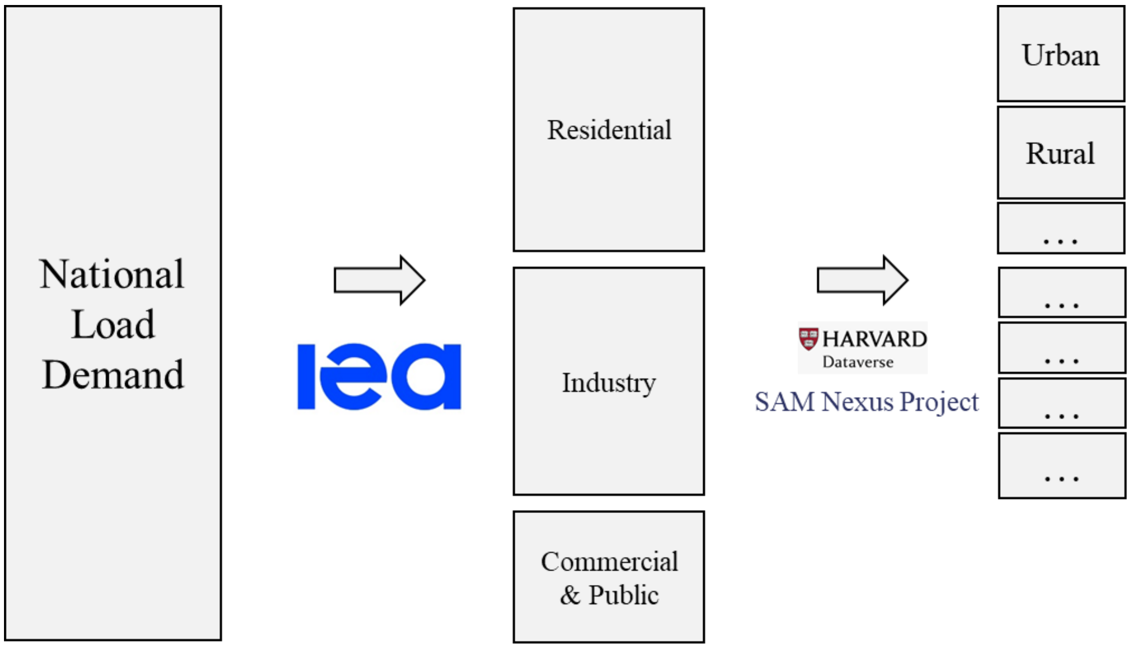


Figure 3.2 Qualitative visualization of Quantitative Disaggregation process

In this part, IEA World Energy Balance & Statistic database, which presents comprehensive energy balances for all the world's largest energy producing and consuming countries with detailed data on the supply and consumption of energy for 150 countries and more other key indicators [71], has been the first source of information. With this database we analyzed the total final electricity consumption by sector, expressed in GWh, and defined the quantity, expressed in percentage, of the final consumption of the national load demand to attribute to Residential, Industry and Commercial & Public sector of Ghana.

A second and more specific disaggregation has been performed with the use of the Social Accounting Matrix (SAM) of Ghana.

The National Social Accounting Matrix (SAM) is an economy-wide data framework that captures the detailed economic structure of a country. A SAM is a square matrix in which each account is represented by a row and a column. Each cell reflects a payment from the column account to the row account, i.e., incomes appear along rows and expenditures along columns. Double-entry accounting requires that, for each account, total revenue (row total) equals total expenditure (column total).

SAMs are constructed and updated, following established common data standards, by the Nexus Project, a collaboration between various international organizations and national statistical agencies and research institutions with the scope to improve the quality of SAMs used for country-level computable general equilibrium (CGE) modelling.

The Nexus Project is led by the International Food Policy Research Institute (IFPRI). Participating organizations include the Food and Agriculture Organization (FAO), the International Fund for Agricultural Development (IFAD), and the European Community's Institute for Prospective Technological Studies (JRC-IPTS). Nexus SAMs are usually constructed together with national statistical agencies and are regularly updated to include the most recent available data. The African Growth and Development Policy Modeling (AGRODEP) network helps disseminate Nexus SAMs to African researchers [72].

In the SAM of Ghana, we identified the commodity electricity as the central row for our research, being focused on the electricity consumption of all the on-grid customers. From this we identified all the new sub-disaggregation, knowing that being a first-time study, we should focus on the solidity and clarity of the division and localization.

Keeping in mind this, we divide each sector previously defined as reported in Table 3.2:

Table 3.2 Sectors disaggregation

Sector	Costumers	Identifier
Residential	Urban	hhd-uX
	Rural	hhd-rX
Industry	Metal Industry	metl
	Mining Industry	omin
	General Industry	*Other*
Commercial & Public	Miscellaneous	*Other*

For the identification of the right activities, we used the International Standard Industrial Classification (ISIC) tables, provided by the Ghana Statistical Service.

The reasons of the choice of these categories are double: firstly, they represent the major consumers in the SAM and all of them are on the same magnitude of consumption, which is useful in the comparison process, secondly these categories are the more favorable to be localized thanks to the literature found online, the historic information about the industries development globally and in Ghana and the geospatial information available, as shown in the previous section.

Furthermore, Urban and Rural categories are subdivided into 5 other categories each, representing different types of households present in the country in order to better characterize the load duration curve in the open-source software RAMP later.

Finally, it has to be noted that rural category was divided into Rural farm and Rural nonfarm depending by crop and/or livestock incomes, but in this work they are collapsed into the same category for the sake of localization.

Once completed the Quantitative Disaggregation, the next step is to localize and quantify each category previously defined.

3.2.2 Geographical Disaggregation

In this part of the process, the first step has been to process GHSL datasets in order to quantify and localize the population distribution of the country.

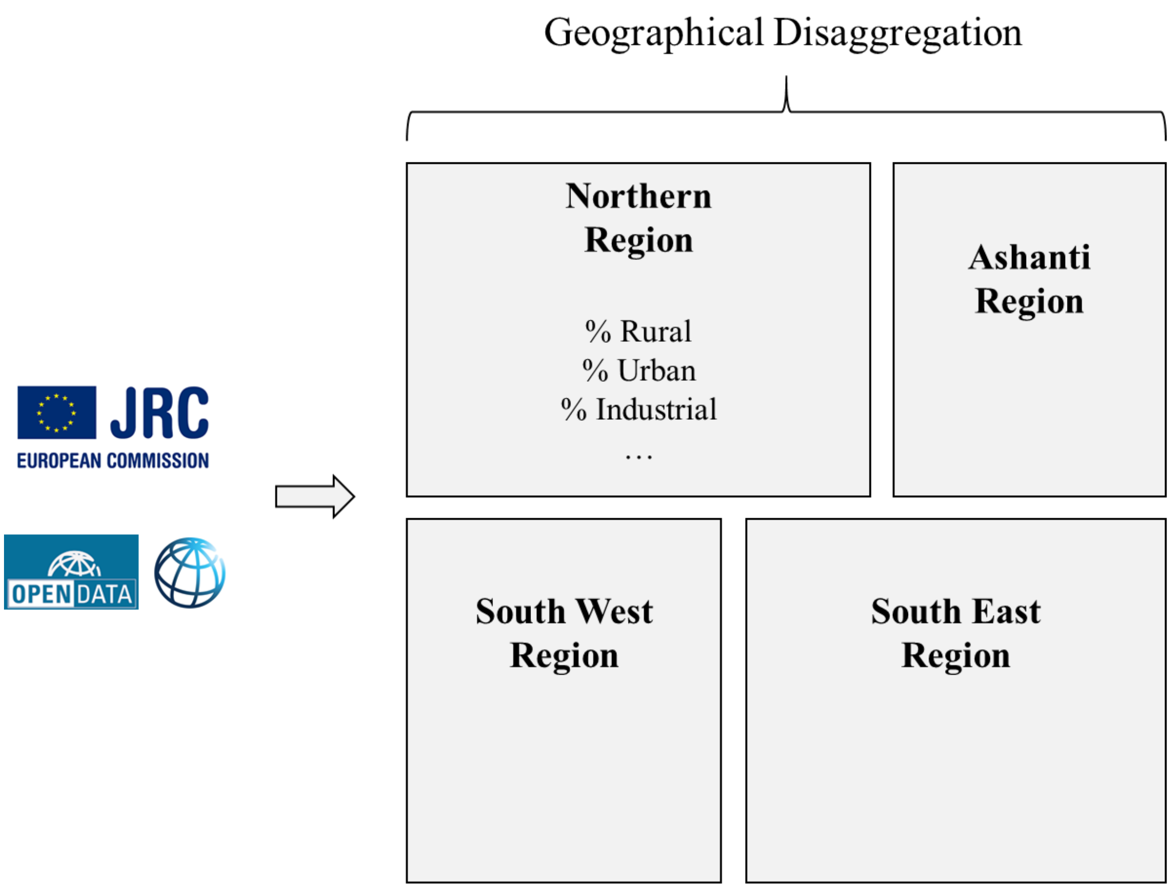


Figure 3.3 Qualitative visualization of Geographical Disaggregation process

The data has been processed in Quantum-GIS, or QGIS in short, a Geographic Information System. GIS are a framework for gathering, managing, and analyzing geographical features and tabular data in order to map, analyze and assess real-world problems. QGIS is a user-friendly Open-Source Software licensed under the GNU General Public License.

For the processing, the first step is to evaluate the administrative regional division of the country. Understanding locational differences in a power system landscape is a key element to better planning of generation resources, as it helps in understanding where power plants should be located and the implications of transmission constraints within and across regions and options to reduce the transmission bottlenecks [27].

Ghana was divided into 10 administrative regions until 2018 when, after a national referendum proposed by the flag bearer of the New Patriotic Party (NPP), Nana Akufo-Addo, the number increased to 16, in order to ensure a effective administration and devolution of power [73]. The administrative regional division however, in terms of energy modelling, is excessive since it would not lead to a clearer picture of the country from an energetic point of view. Hence, in order to better visualize the energy dispatchment system, the resource potential, and the consumption patterns of the country, in our energy model Ghana has been divided into 4 principal macro-regions:

- South-East region (SEAR)
- South-West region (SWER)
- Ashanti region (ASHR)
- Northern region (NORR)

For the division we referred to the 10 pre-2018 administrative regions and in Table 3.3 is possible to see at how they have been divided and assessed into the 4 zones.

The choice of these macro regions was suggested by another energy model approach performed in the "Integrated Power System Master Plan for Ghana" (IPSMPG) by the Energy Commission and the United States Agency for International Development (USAID) [27].

The demarcation of the grid system into four zones in the IPSMPG modelling is an update to the demarcation used in the 2011 GRIDCo Transmission Master Plan, which had five zones. The change from five zones to four is due to the transmission upgrades that were implemented in the NEDCo distribution region: the commissioning of Bui hydropower plant and its associated transmission lines; the completion of the transmission loop in Upper West region of the country. These two system upgrades, therefore, eliminated the need to maintain a separate zone for Brong Ahafo region [27].

The scope of the thesis is to create energy and peak demand forecasts using simulated energy profiles and econometric indicators.

Table 3.3 Description of Ghana Model Zones and Regions

Ghana Zone	Identifier	Administrative Region Coverage
South-East region	SEAR	Greater Accra Volta Eastern
South-West region	SWER	Western Central
Ashanti region	ASHR	Ashanti
Northern region	NORR	Brong Ahafo Northern Upper East Upper West

The following step was to process in QGIS the information about administrative regions and population density and distribution. In doing so we used in the software the function to manipulate raster images, which are the files we have.

The first passage was to extract from the world raster image the country considered, Ghana. Secondly, we divide the new raster file representing the country into the defined 4 zones, again using the extraction function.

The results are 8 raster files, 2 for each zone. Of the 8 files, 4 are obtained from the population dataset GH-POP describing the population density in absolute number, and 4 from the settlement layer GH-SMOD describing the type of settlement present in each zone.

From this we used the *"raster layer zonal statistics"* algorithm from the Zonal Statistics Plugin in QGIS. The plugin permits to analyze the results of a thematic classification. The specific algorithm calculates statistics for a raster layer's values, categorized by zones defined in another raster layer. If the reference layer parameter is set to "Input layer", then zones are determined by sampling the zone raster layer value at the centroid of each pixel from the source raster layer. If the reference layer parameter is set to "Zones layer", then the input raster layer will be sampled at the centroid of each pixel from the zones' raster layer. If either the source raster layer or the zone raster layer value is NODATA for a pixel, that pixel's value will be skipped and not including in the calculated statistics.

By overlapping GH-POP raster layer with GH-SMOD raster layer, we can use the algorithm to evaluate the portion of population that is present in each settlement classification as defined in the GH-SMOD dataset.

The results of the QGIS data manipulation are the distribution of rural and urban population in each zone of the model. The distribution is expressed as percentage of the total. The percentage are referred to the year of the dataset, hence 2015. For this reason before continuing the manipulation is mandatory using the urban and rural population growth rate to obtain the projection of the population in the reference year, which is 2018.

The next step is to convert the population number into household number, in order to use the consumption quantities obtained by the Social Accounting Matrix of Ghana to assess where and how much energy the residential sector consumes.

Once obtained the georeferenced data about population, is possible to continue the sectoral consumption assessment.

For metal sector and mining sector, thanks to the literature and the dataset present online is easily achievable since the number of figures present in the scene.

For the remnant part of industrial sector and the commercial & service sector, we need to use the population distribution as a proxy in order to estimate their distribution.

This means that depending on how much urban population is present in the 4 zones, we assess different share of sectoral consumption, assuming that more urbanized regions contain more industries and commercial activities. This assumption seems reasonable given the dependency between the increase in GDP per capita and the amplification of electricity consumption in low-income and lower-middle-income countries, as previously reported [41].

Under the given assumptions, we found the geospatial information about how much and where the categories we defined in the beginning of our estimation consumes in the country for our reference year 2018.

3.2.3 Shape characterization

The last stage of our electricity consumption estimation at regional level consist in the shape characterization of the users we defined in the quantitative and geographical disaggregation previously performed.

To do so we exploit the RAMP, an open-source bottom-up stochastic model, which support the creation of stochastic, seasonal-heterogeneous energy demand profiles.

The model is based on three main layers of modelling: the User type, the User and the Appliance layers as shown in the Figure 3.4.

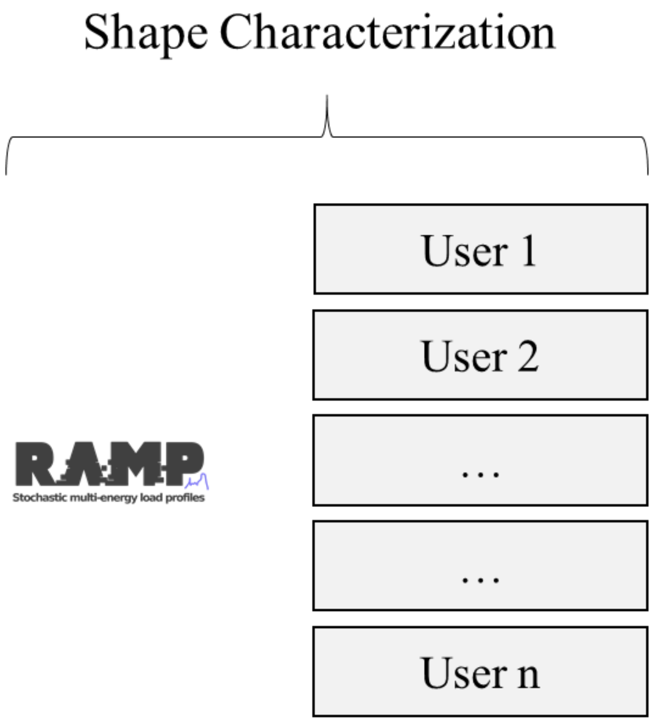


Figure 3.4 Qualitative visualization of the Shape Characterization process

For our model, we defined User type and User during the disaggregation process and now we characterize each of them by the Appliances they use.

The refinement of the process is defined by the literature found online, due to the impossibility to perform and collect questionnaires to the local population.

From a project carried on in Kenya [54], we can obtain residential demand of rural and urban households, both divided into five tiers of consumption, computed by estimating electric appliances ownership across different tiers of consumers. In the Appendix B is reported the compiled database, where every category of users is characterized by a corresponding usage pattern of the owned appliances, differentiating every month to account for seasonality of the uses.

Thanks to the similarities in terms of socio-economic indicators such as GDP, GDP per capita and Human development index, and in terms of geographical position for parameters such as latitude and meteorology, it is assumed to be acceptable to use the same database of User and Appliances.

For the other Users precise literature lacks and inaccuracies loom. The consumption profiles are hypnotized by the scarce literature and estimated using official reports. Again, the updated database can be found in the Appendix B..

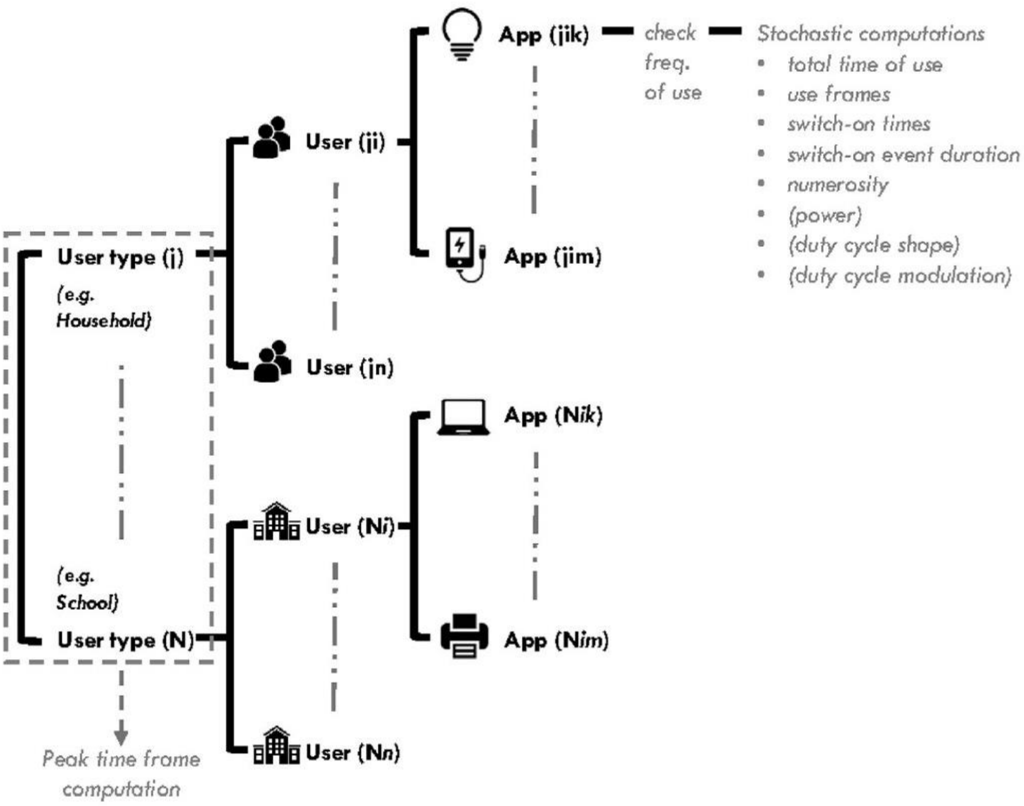


Figure 3.5 Graphical sketch of the modelling layers constituting the simulation process (Source: [55])

Once the peak demand, the appliances and the hours are defined the model creates different consumption profile for each user, which is distributed to each geographical location in the amount previously defined.

Once all the users are characterized, is possible to sum up the consumption profile for the entire zone, 'creating' the electricity load demand at one-hour timestep for the entire year at regional level.

The process could potentially be reproduced for every country for which basic socio-economic and geospatial information are available and depending on the literature could be refined with a major detail.

3.3 Single-node and Multi-node Energy System Model of Ghana

The final stage of the thesis work is to create the Ghanaian energy system model both using a single-node and multi-node approach.

To do so we use Calliope, a framework to build energy system models, designed to analyze systems with arbitrarily high spatial and temporal resolution, with a scale-agnostic mathematical formulation permitting analyses ranging from single urban districts to countries and continents with several key features including the ability to handle high spatial and temporal resolution.

Calliope was designed with the following goals in mind:

- Designed from the ground up to analyze energy systems with high shares of renewable energy or other variable generation
- Formulated to allow arbitrary spatial and temporal resolution, and equipped with the necessary tools to deal with time series input data
- Allow easy separation of model code and data, and modular extensibility of model code Make models easily modifiable, archivable and auditable (e.g. in a Git repository), by using well-defined and human-readable text formats
- Simplify the definition and deployment of large numbers of model runs to high-performance computing clusters • Able to run stand-alone from the command-line, but also provide an API for programmatic access and embed- ding in larger analyses
- Be a first-class citizen of the Python world (installable with conda and pip, with properly documented and tested code that mostly conforms to PEP8)
- Have a free and open-source code base under a permissive license

The model consists of a collection of YAML and CSV files that define technologies, locations, links between locations, resource potentials, and other constraints [51].

In the multi-node approach, we define for each node a list of existing technologies and parameters to define the location, the demand and the resource available, as define below:

Demand power: defined as a technology, we load the power demand, with an hourly timestep and expressed in [kW], estimated from the previous section to each node in a csv file. The software will use all the technologies present in the model of all the connected node in order to fulfill the load minimizing the system costs.

Locations: latitude and longitude of each node are defined, representing the area that need to be analyzed. In our thesis work we consider 4 zone, as shown in Figure 3.6, South-East Region (SEAR), South-West Region (SWER), Ashanti Region (ASHR) and Northern Region (NORR), chosen by grouping the 10 administrative regions as described in the previous section, and linked by the transmission system. To each location we have to assess different constraints as the type of technologies present, the available resource and the installed capacity of each technology, calculated from the literature or inserted as timeseries, and the power demand in the node, as calculated in the previous section. In this part of the modelling process, as suggested in our interviews, with installed capacity we referred to the dependable capacity declared by each power plants as it is the one which the grid accounts for as stipulated in the contract.

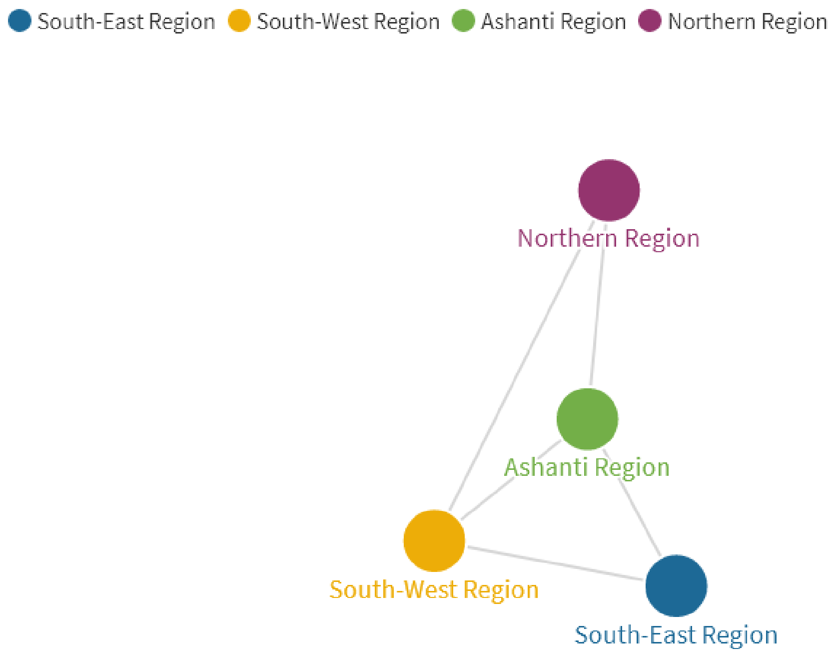


Figure 3.6 Conceptual visualization of Multi-node approach

Techs: here we collect all the essentials characteristics about the existing production technologies in each node, in order to provide a name, specify the type of technology group and set the carriers with which the technology works. Technical constraints, such as lifetime [years], installed capacity [kW] and conversion efficiency, and economical constraints, such as fixed costs [$/kW], variable costs [$/kWh], cost of the fuel [$/kWh] and interest rate, are defined to characterized specifically the behavior of each technology. The types of technologies present in the model are different, but can be group mainly 3 categories:

- **Fossil fuels**: all fossil fuel plants are described like supply, with a determined amount of resource. The choice of the fuel depends on the type of plant, but when possible, Natural Gas has been preferred due to the new extraction reality happening in Ghana. A fully description is then achieved by providing just technical and economical constraints. The types of power plants of this group are:

- Combined Cycle Gas Turbine Power Plant (CCGT_pp)
- Gas Turbine Power Plant (GT_pp)
- Internal Combustion Engine Power Plant (ICE_pp)

The technical and economical constraints are derived from authors data collection, literature and open access online databases [74].

- **Large Hydro**: as before, the hydropower plants are described like supply technology, but the resource availability is accounted by including a timeseries of the production availability for each plant. As before, technical and economical constraints are presented.
- **Renewables**: renewable technologies are typically strictly related to resource availability, and for this reason a timeseries containing the renewable potential is included, as well as technical and economical parameters.

Transmission tech & Links: carriers transmission technologies are defined introducing parameters and constraints as cost and efficiency, in order to describe the connection between each node. For our model, we outlined two different means of transportation given the information found on the literature and provided by the institutional stakeholders interviewed during the data collection phase:

- **High voltage grid operating at 161kV:** this is the most widely used means of power transmission in Ghana and connect all four nodes considered in the model**.**
- **High voltage grid operating at 330kV:** this is a newer structure that is being implemented in the transmission system of Ghana. At the present time, the working connection work for SEAR and SWER but future expansion is planned**.**

The technical and economical parameters are assessed through the data collected from the institutional stakeholders and the online literature, comprehensive of length [km], thermal limit of operation [MVA] and power factor, hypnotized equal and constant for the entire infrastructure from the study [75]. Finally, the connections between each node are listed in the model to enable power transmission during the modelling process.

Once defined the model, Calliope through its optimizer, which can be chosen depending on the availability and the processing power, will solve the problem, satisfying the power demand minimizing the total system cost.

The complete database of power plants and transmission system can be found in the Appendix D with all the technical parameters for each power plants and power transmission lines considered for the creation of the energy system modelling.

The principal difference between Multi-node and Single-node is that for the second all the technologies and the power demand are collapsed into a single point representing the country. This can be considered a simplification of the reality as it is but the open access data and generally the available timeseries are a huge limitation as explained in the introduction. Hence the creation of the energy system model for Ghana using a single-node approach is the same as previously descripted for the multi-node approach, neglecting the transmission lines technologies and the localization of the different power plants as well as power demand.

Chapter 4
Results

In this chapter, the results of the hybrid disaggregation approach will be shown, focusing on each category weight in the load formulation. A comparison between the estimated load demand and the one obtained by the institutional stakeholders will help to understand the efficacy of our approach.

After this first part, the results of the open-source optimization software will be shown, and the differences between the two model will be assessed.

The results of the first part will be expressed as population and consumption shares, also visualizing the different electricity consumption for each category, while in the second part we will focus on the energy share and energy dispatch.

4.1 Load Demand Estimation

After a complete and comprehensive data collection process, the methodology has been processed as explained in the previous chapter. The results obtained are analyzed in sequential order. During the whole work the objective was to estimate the power demand of Ghana as a timeseries of one-hour timestep, using only open access database and data from interviews, combined with the use of open-source software.

4.1.1 Quantitative Disaggregation

From IEA's open access database, the sectoral disaggregation of Ghana's energy system was easily traceable. The subdivision has been pursued by means of Total Final Consumption expressed in terms of consumed GWh. The result, as show in Figure 4.1, is a percentage division between the 3 major sectors, and the remaining amount, which accounted for less than 0.1%, has been equally distributed between the three sectors.

As we can see from, the major consumption comes from the Residential sector, which in our case study can be considered as a benefit due to the great quality of population geospatial data.

The second principal consumer is the Industrial sector, again a benefit due to the great number of information found about the principal player in the Ghanaian industrial sector.

Finally, we find Commercial and Public Services, for which information are not abundant.

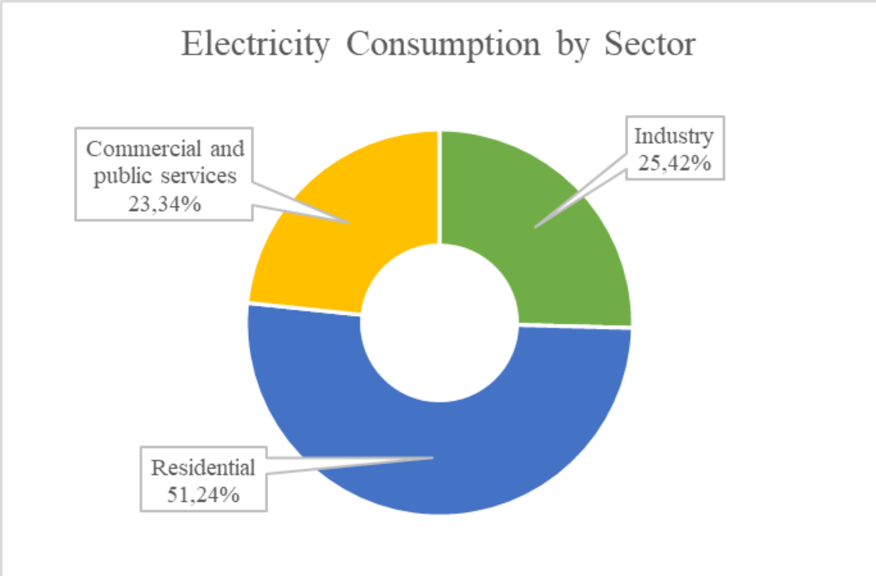


Figure 4.1 Total Final Consumption by Sector [GWh] (Source: IEA)

The second part in the Quantitative Disaggregation process is dedicated to the sub-sector division with reference to the Social Accounting Matrix of Ghana, a comprehensive accounting framework capable of describing the entire country's economy.

Here the choice about sub-sectors was guided by reasons of information availability, and the information about sectoral division came from the International Standard Industrial Classification.

In fact, the first step was to find which categories present in the SAM represent at best the three major sector with which IEA classify the major consumers in the energy system of Ghana, using ISIC tables.

After this step, the next one was to find between these categories the most traceable in terms of open access databases. The final choice, as stated before, was the categories summed in the Table 4.1. The expenditures of the SAM are expressed as Millions of Ghanaian Cedis, the local currency, and there is no need to convert into more known currency due to the fact that the numbers are used to obtain percentages of the total in order to divide the demand.

As we can from Table 4.1, the largest part of consumption for the Residential sector comes from Urban households, as we could expect, representing a total of more than the 83% of the total.

In terms of Industrial sector, the Mining industry is the largest consumer. We have to notice that due to the lack of useful geospatial information, Commercial sector has been left untouched and will be treated as a whole.

Finally, we have to notice that the year of reference of the Social Accounting Matrix is 2013, hence it does not represent the reality about our model, but it is fundamental in order to under the categories to localize and the share of power they need.

Table 4.1 Quantitative Disaggregation of Ghanaian Economy by SAM (Source: SAM Ghana 2013)

Sector (IEA)	Costumers	Identifier (SAM)	Value [MGH₵]
Residential	Urban	hhd-u5	655
		hhd-u4	316
		hhd-u3	185
		hhd-u2	91
		hhd-u1	61
	Rural	hhd-r5	81
		hhd-r4	56
		hhd-r3	45
		hhd-r2	42
		hhd-r1	30
Industrial	Metal Industry	metl	48
	Mining Industry	omin	681
	General Industry	*Other*	486
Commercial & Public	Commercial	*Other*	1887

4.1.2 Geographical Disaggregation

After the sector and sub-sector categorization, the following step is to localize their power consumption and divide them between the regions of interest. Here comes the regional division of Ghana, which as shown in Figure 4.2, aggregate the 10 administrative regions of the country in 2018 into four macro-regions. The choice followed previous modelling examples, power transmission technical parameters and demographic consideration in order to characterize every region in the best way possible.

After the regional aggregation, the characterization of the coordinates of reference for modelling purposes followed. The choice was to use a point capable of represent both the major source of power and consumption.

Once the macro-regions of interest have been defined, we can start to localize the sub-categories identified in the quantitative disaggregation.

To do so, we use the Global Human Settlement Layer raster files, which provide geospatial information about population and settlement type distribution.

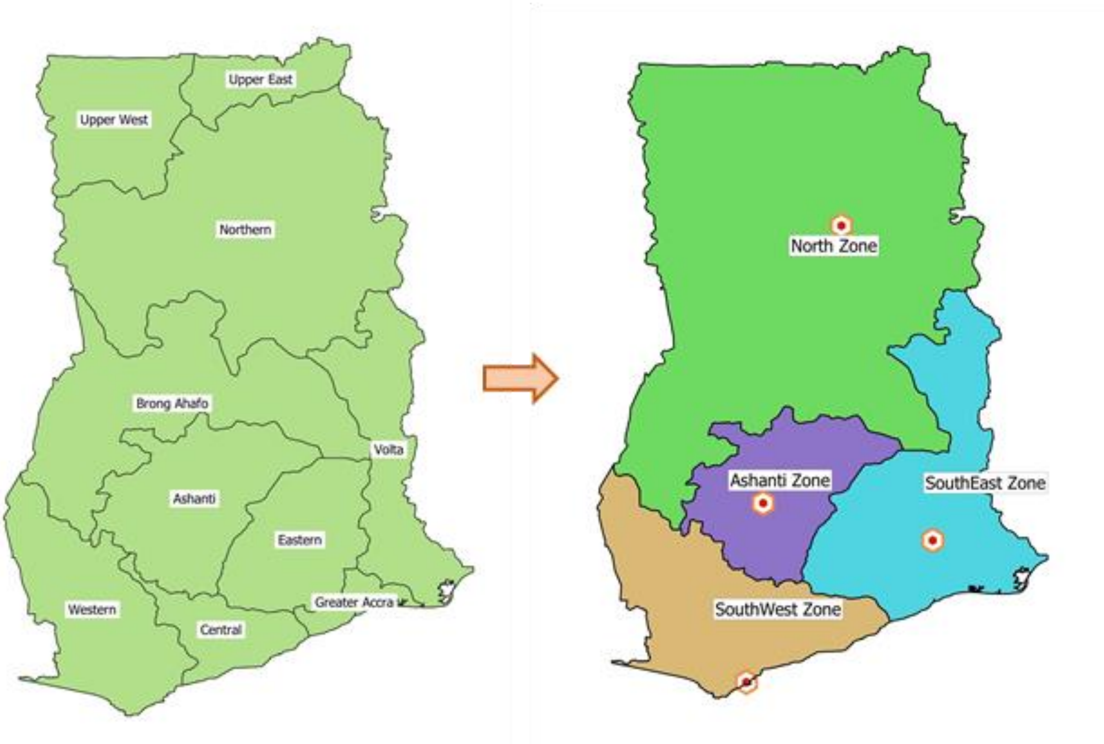


Figure 4.2 Macro-regions aggregation

Through the use of specific algorithms available on the open-source geospatial software QGIS, it is possible extract from the global dataset the rater images containing all the geospatial information about Population density and Settlement distribution, as shown in **Errore. L'origine riferimento non è stata trovata.** and **Errore. L'origine riferimento no n è stata trovata.**.

The algorithms manipulate the data and return the numbers of population living in each type of settlement for each region, divided in the 10 considered sub-categories from GHSL classification.

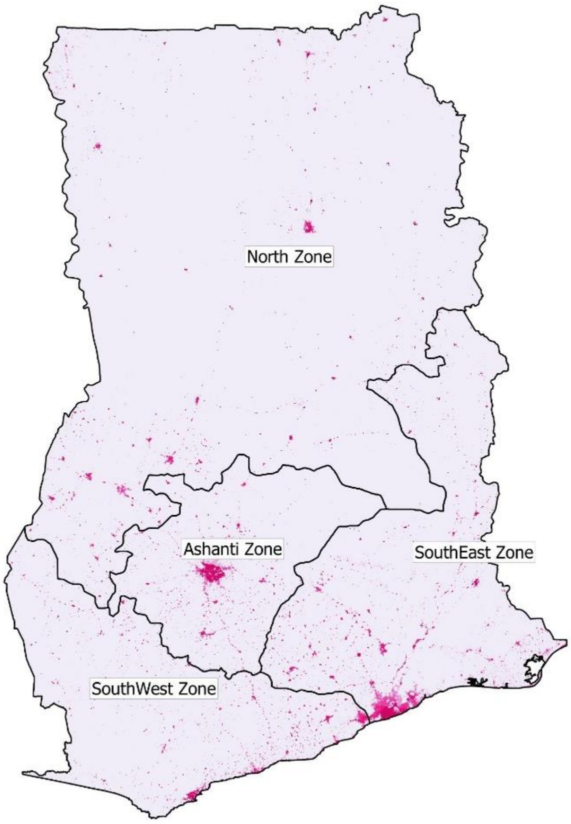


Figure 4.4 Population density distribution, Ghana (Source: JRC)

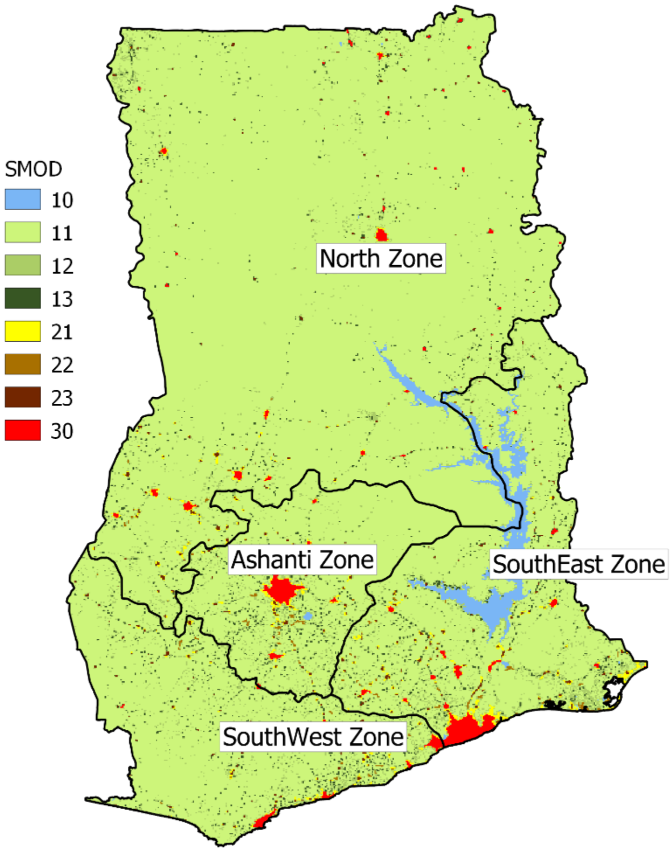


Figure 4.4 Settlement distribution, Ghana (Source: JRC)

It has to be noticed that the information obtained from the geospatial database manipulation are referenced to the year 2015. For this reason, we need to assess population growth for each region, using urban and rural growth rates. Here we introduce an important assumption, that is the equality of growth rates for every region of the country. The assumption has to be introduced due to the lack of more precise information available.

Once projected, the population distribution can be used as a proxy for the power demand estimation and for the categorization and localization of the sub-categories defined in the previous part of the thesis work, as collected in Table 4.2.

Table 4.2 Population disaggregation using GHSL, projected to 2018 (Source: JRC)

Identifier (GHSL)	**Northern Region [NORR]**	**Ashanti Region [ASHR]**	**South-East Region [SEAR]**	**South-West Region [SWER]**
Class 10	0	0	0	0
Class 11	34697.8795	38290.33	56764.31428	40402.96525
Class 12	495769.381	305854.3987	590966.754	436036.7952
Class 13	1261732.051	690704.6416	1171734.752	1143978.478
Class 21	293370.1432	368651.9219	719883.7809	363945.3249
Class 22	76374.75917	132294.6186	254398.392	135680.6583
Class 23	2042725.211	813500.829	1777076.972	1409204.423
Class 30	3515682.554	3669093.64	5926600.587	1847812.128

From these results it is possible to assess a percentage of the total referred to each category in order to divide it to each region of interest. For each category we need to do different consideration in order to project the most realistic scenario for our model creation.

The considerations are:

- Since there is no universal definition of Urban and Rural household and different sources use different parameters to classify the population, we will use Class 30 from GHSL as proxy to localize the urban households, which will be equally divided into the five categories presented in the SAM of Ghana. From Class 11 to Class 23 will represent rural households of the SAM, and again the total will be divided into five categories presented in SAM. This assumption must be introduced due to the fact that the classification in the GHSL is defined by geographical means, while in SAM economic parameters are considered.

- Different electrification rates affect the effectively connected population both from the Rural as well as from Urban Households. In order to assess this regional difference, the electrification rate obtained from [56] is weighted over the Macro-regional distribution of population and inserted in the disaggregation process for the Residential Sector only.
- Mining Industry is localized using online database which describe the operating plants. No further information is found on smaller plants and for this reason the localization will be based on the largest players in the industry. Consumption in SAM on electricity commodity comprise electricity, gas and steam under the same commodity. For this reason, the expenses of this sector for the commodity are overestimated, which is considered in the shape characterization process.
- It is possible to use VALCO as a proxy for the Metal Industry since no other companies are present in the market, hence the whole consumption of this category will be placed in the South-East Region.
- The remaining share of Industrial Sector will be proxied considering the assumption that all the major industries represent are located near high density population clusters. For this reason, Class 30 seems to represent at best this condition for its intrinsic definition, and it will be used as proxy.
- Due to the lack of information about this category, the Commercial sector will be localized considering the fact that commercial activities in Sub-Saharan Africa often are a conversion of the house of the vendor into a shop and for this reason Class 21, Class 22, Class 23 and Class 30 are used as a proxy for the distribution of Commercial consumption.

The final division, expressed as percentage of the total of each sub-category, is grouped in Table 4.3.

Table 4.3 Final Disaggregation into four Macro-Regions

Identifier (SAM)	**Northern Region [NORR]**	**Ashanti Region [ASHR]**	**South-East Region [SEAR]**	**South-West Region [SWER]**
Urban	19.150%	26.129%	42.172%	12.549%
Rural	23.826%	17.404%	33.835%	24.934%
Metal	0%	0%	100%	0%
Mining	32.856%	0%	31.198%	35.946%
General	23.502%	24.527%	39.618%	12.352%
Commercial	25.392%	21.346%	37.171%	16.091%

4.1.3 Shape Characterization

In this part of the work, we will use the open-source stochastic software RAMP in order assess the electricity load estimation at regional level of the country Ghana.

The objective is to create a timeseries representing the power load demand of each sub-category, and through the data obtain with the manipulation of the geospatial database GHSL from JRC, assign the correct share of consumption to the designed macro-regions.

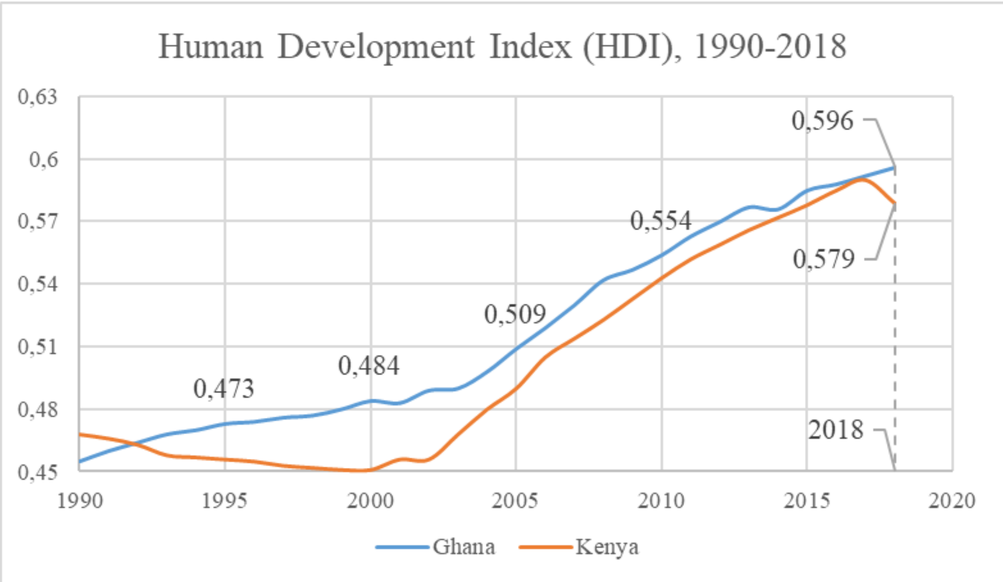


Figure 4.5 Human Development Index evolution, Ghana and Kenya (Source: UNDP)

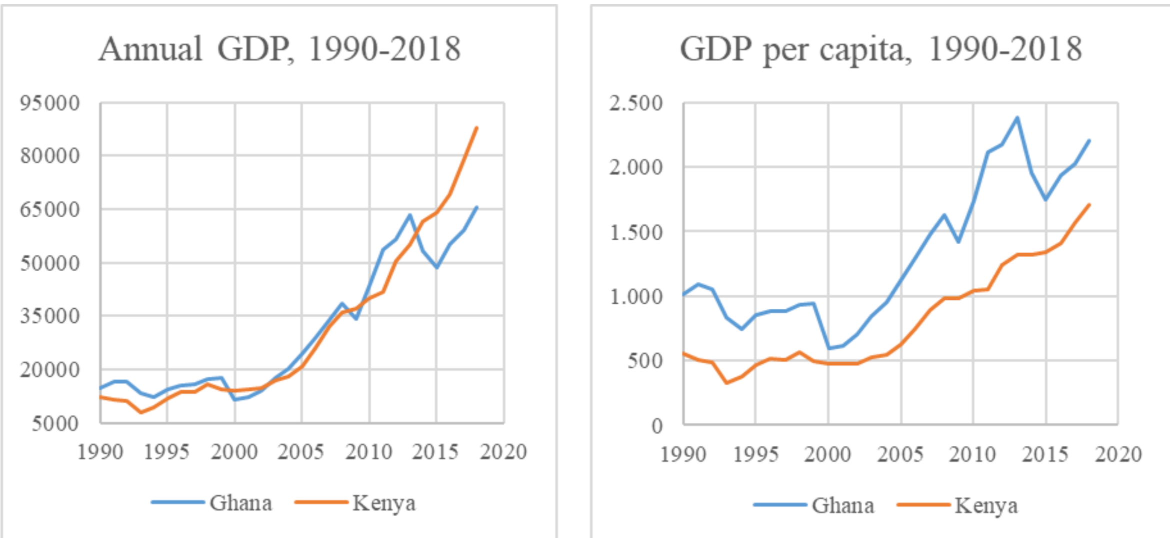


Figure 4.6 Annual Gross Domestic Product and GDP per capita evolution, Ghana and Kenya (Source: World Bank)

For the first sub-categories, Urban and Rural Households, it is possible to use the database from a similar project, for which surveys analysis have been taken in an on-the-field study. The country considered is Kenya, an Eastern Africa country with similar socio-economic properties such as Human Development Index, which as shown in Figure 4.5 presents similar characteristics as trend and value, and also GDP and GDP per capita, as found in Figure 4.6.

Thanks to the Kenyan database, tailor-made for the use in RAMP, it is possible to create the stochastic load demand profile of the ten categories chosen to describe the Residential sector of Ghana.

The simulation led to the following result, as shown in Figure 4.7, with the curve representing one Macro-Region. The curve represents the typical load demand of the household sector, composed by both Urban and Rural Households. The differences between region in terms of shape are minimal, while the population distribution determine the magnitude of the total load demand. It has to be noticed that differences between wet and dry seasons are considered too.

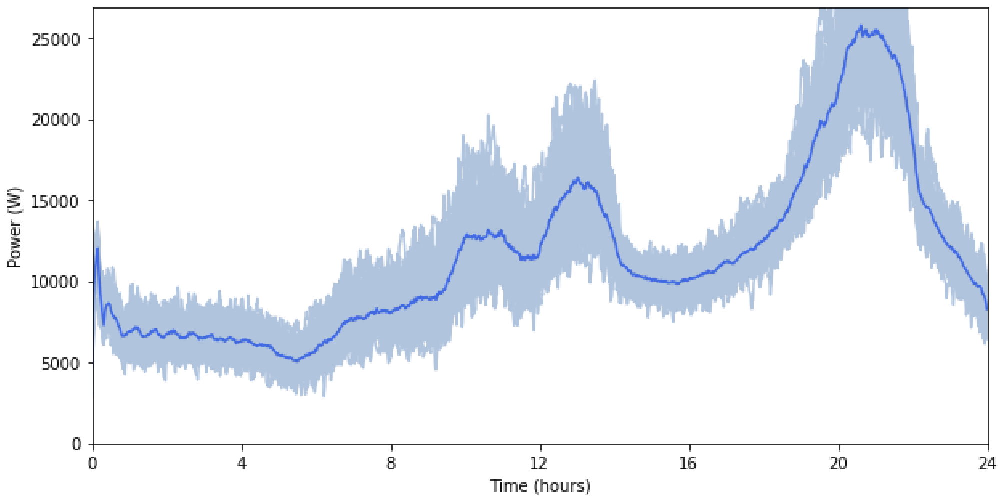


Figure 4.7 Typical estimated Load Demand profile for Residential Sector in NORR

After repeating the algorithm, the whole Residential Sector is represented and can be localized using the data from the Geographical Disaggregation.

The next step is to repeat the process for the remaining sectors, starting from the Metal Industry, composed by Ghanaian largest industry Volta Aluminum Company (VALCO). From the literature it was possible to collect valuable information about the shape that the load profile should recall [70], as well as the installed capacity of approximately 147MW in total considering both the electromagnetic aluminum smelting pots operative, which in an industrial aluminum plant represent the almost totality of power consumption [70]. Once considered all these characteristics the resulting load demand profile is shown in Figure 4.8.

The characteristic of the load profile of the Metal Industry is that works at almost the maximum power all day long in order to minimize thermal and economical losses.

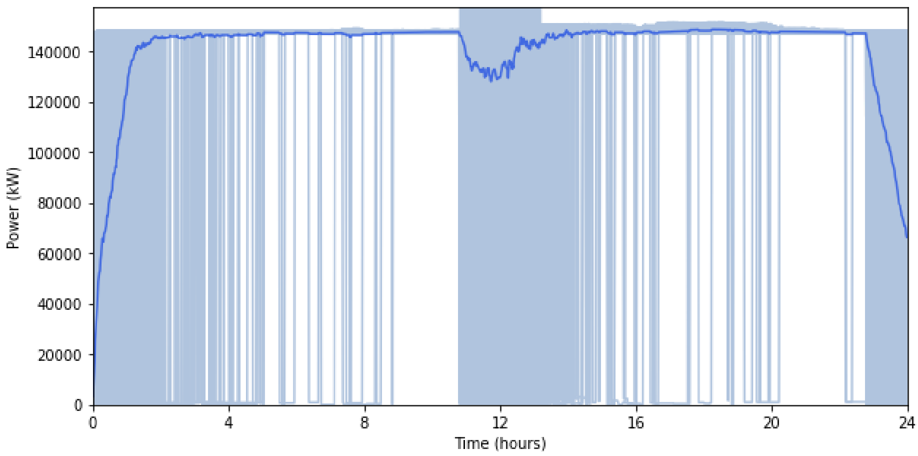


Figure 4.8 Typical estimated Load Demand profile for Metal Industry in SEAR

For the Mining Industry categories, a useful and handy database freely available was provided by World Bank.

The database, as shown in Appendix D, characterize the largest operational plants, describing their capacity needs, their power requirements over the year and the presence of a dedicated power plant.

Once sorted and considered the shape of the typical mines as reported in [76], [77], it is possible to simulate the load profile, as shown in Figure 4.9.

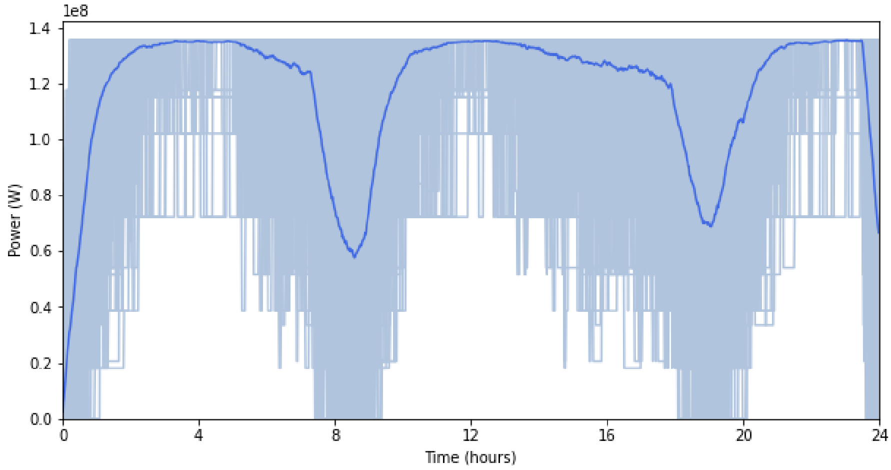


Figure 4.9 Typical estimated Load Demand profile for Mining Industry

The sudden power decreases represent the increase of electricity prices during the morning and evening hours for which the plants adapt their power consumption in order to reduce the electricity expenses, as well as the different pumping system operational scheduling.

The mining load profile is then distributed between the four regions as found in the Geographical Disaggregation and summed to the Macro-regional load demand.

The two final categories to characterize are the remaining share of Industrial sector and the Commercial and Public Services sector. For both of them the information are in short supply, hence different consideration must be introduced.

For the General Industry sub-category, it is possible to evaluate the total power requirements from the analysis of the national hourly load demand timeseries provided by FEEM. The Industrial sector is composed by three parts, Metal, Mining and General Industry, two of which have been analyzed from the literature in an extensive way. Given that, it was possible to evaluate the power requirements from timeseries manipulation, end evaluate the mean installed capacity that the General Industry present. Calculation have been made taking into consideration that most industrial plants work continuously and constantly during the day and hence the load profile could present a flat shape over the day. Due to lack of precise information the assumptions made for this estimation were based on previous research and the other two industrial sub-categories, Metal and Mining. Hence, the installed capacity has been calculated considering a generic work shift of 20 hours spread during the whole day resulting in an average installed capacity of 226 MW and the result of this estimation is shown Figure 4.10. The total load demand has been divided into the four Macro-Regions as previously estimated.

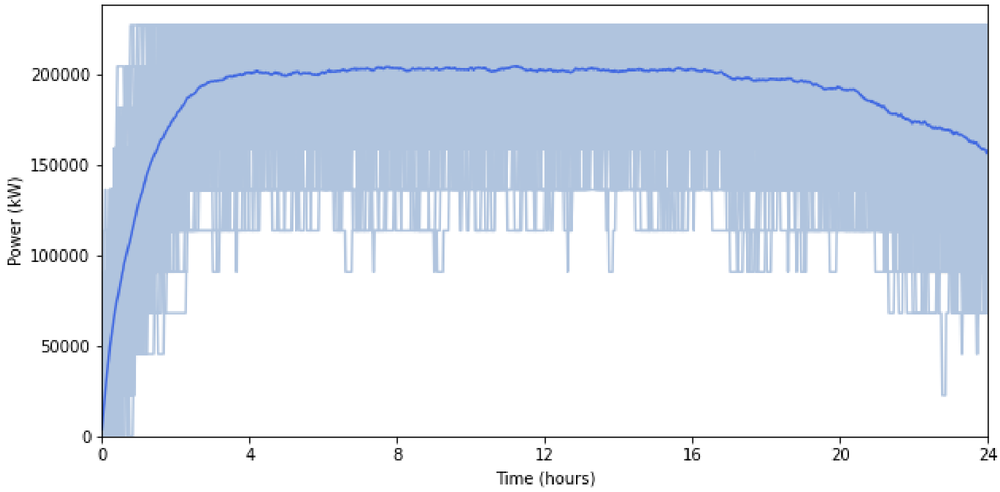


Figure 4.10 Typical estimated Load Demand profile for General Industry

Finally, the load profile of the Commercial sector has been estimated accounting for an average installed capacity calculated with the same assumption of the General Industry. An average installed capacity of just above 1100 MW has been considered over a 10-hours work shift, resulting in the load profile of Figure 4.11 which has been properly divided between the four Macro-Regions.

Alle the appliances and operating windows are collected in Appendix B.

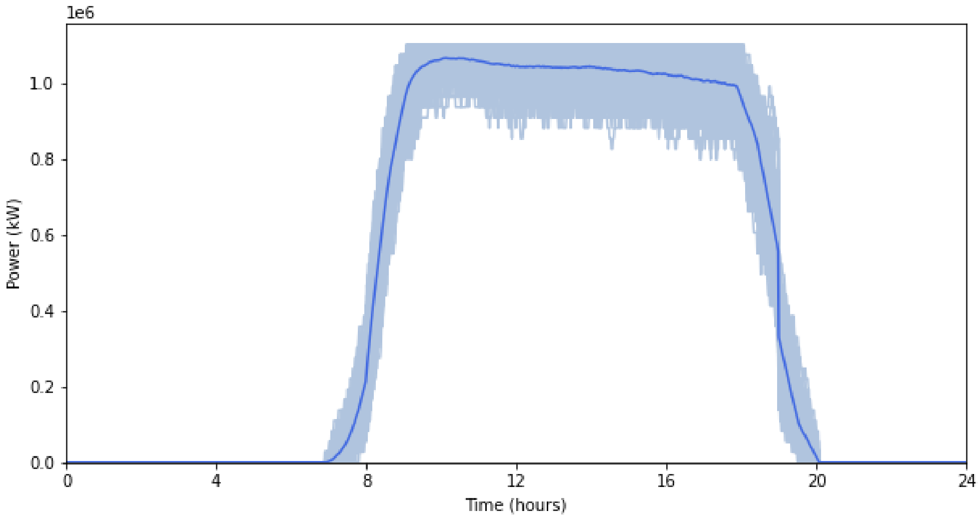


Figure 4.11 Typical estimated Load Demand profile for Commercial Sector

Once finished the estimation process, through timeseries manipulation it is possible to create for each Macro-Region a dedicated high-resolution estimated yearly Load Demand, expressed in kW with one-hour time step.

The final resulting estimated regional Load Demand is shown from Figure 4.12 to Figure 4.15.

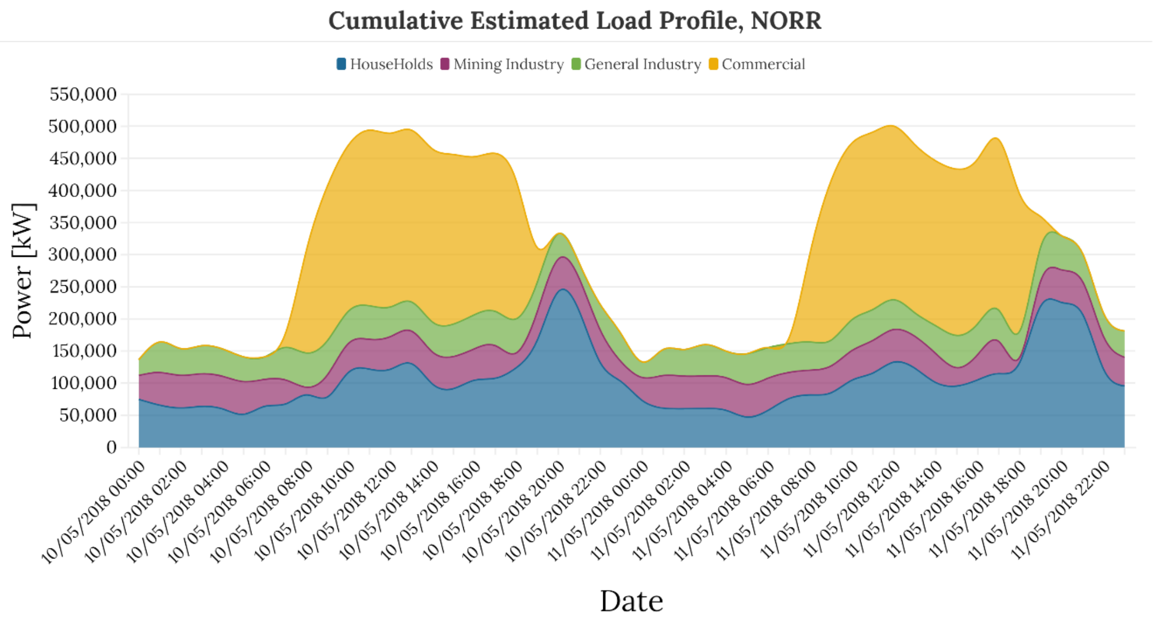


Figure 4.12 Estimated Load Demand Northern Region

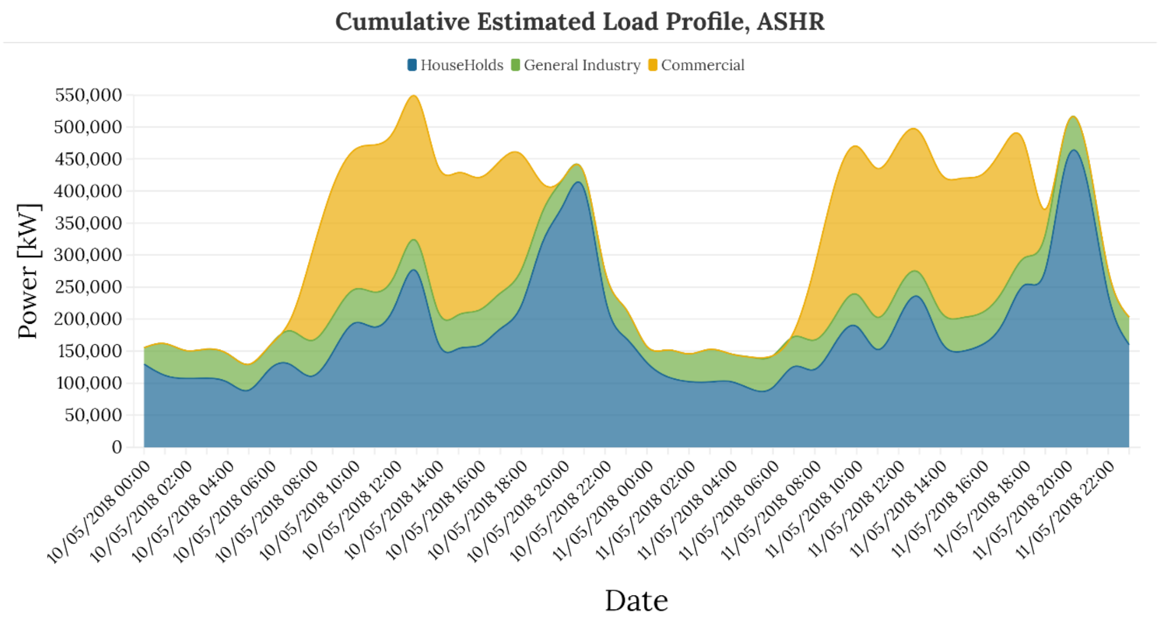


Figure 4.13 Estimated Load Demand Ashanti Region

The resulting estimated Load Demands give an overview of the different elements which compose the energy system of the country, their behavior variations during the day and the share they occupy in the system. This can be defined as a preliminary examination and proper databases should be built in order to describe at best an energy system, but the results seem promising and, given the generic information used during the thesis work, the output present satisfying characteristics.

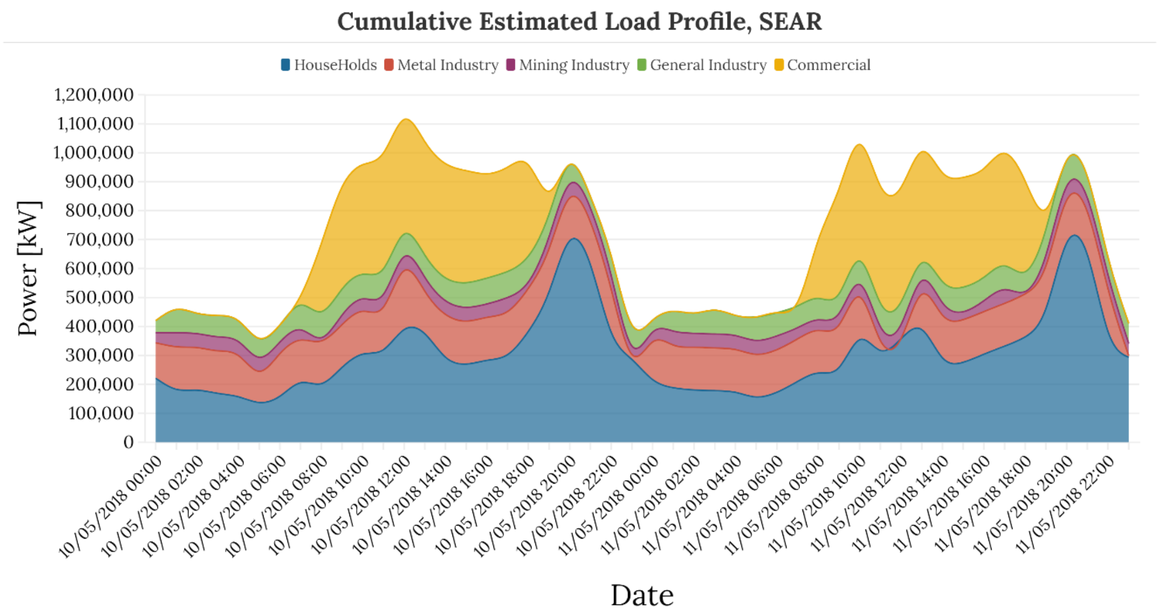


Figure 4.14 Estimated Load Demand South-East Region

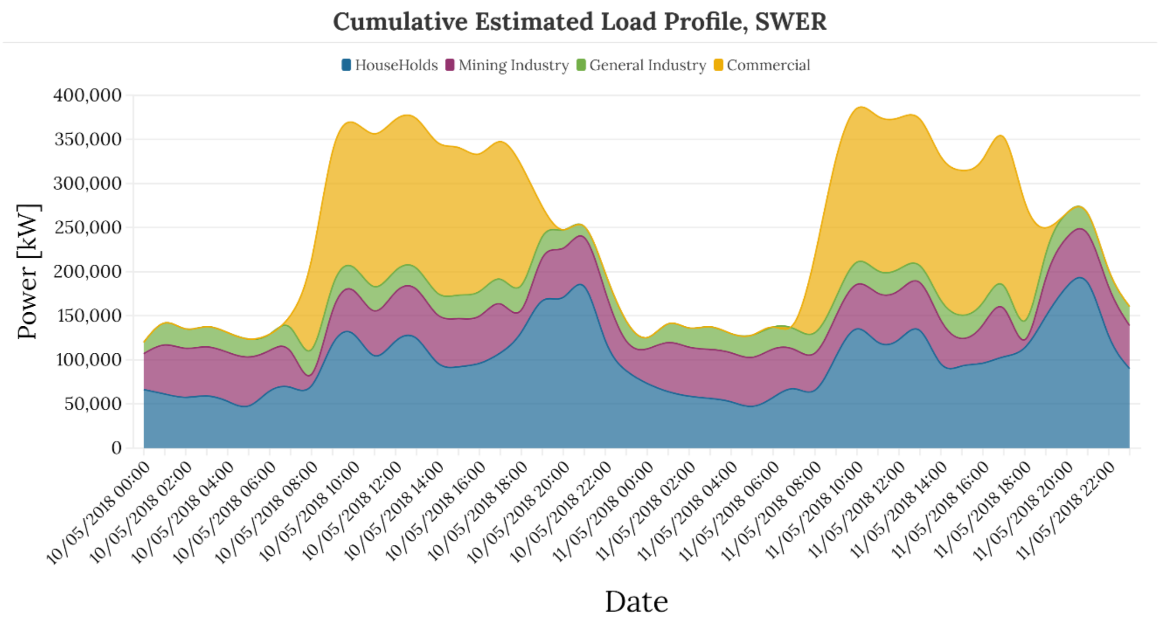


Figure 4.15 Estimated Load Demand South-West Region

The final timeseries, which is the aggregation of the four Macro-Regions, is shown in Figure 4.16 and will be used to run the Multi-Node Energy System of Ghana as applicative case study of the Load Demand Estimation process, as shown in the next section. For comparison, the real Load Demand acquired from an on-site research is shown in Figure 4.17. Here we can see a number of differences, such the different magnitude of the demand in the night and the absence of a sharp division between night and day, but the overall peak demand and the trends presented in the output of the methodology is satisfactory for modelling purposes. The methodology seems to provide an accountable output even with the limited databases available, but it immediately shows the limitations that affects an experimental study of this kind. It should be required to create consistent database to use for this type of study, by defining protocols and rigorous categorization, in order to be able to repeat the same methodology on other developing countries which face the same problems.

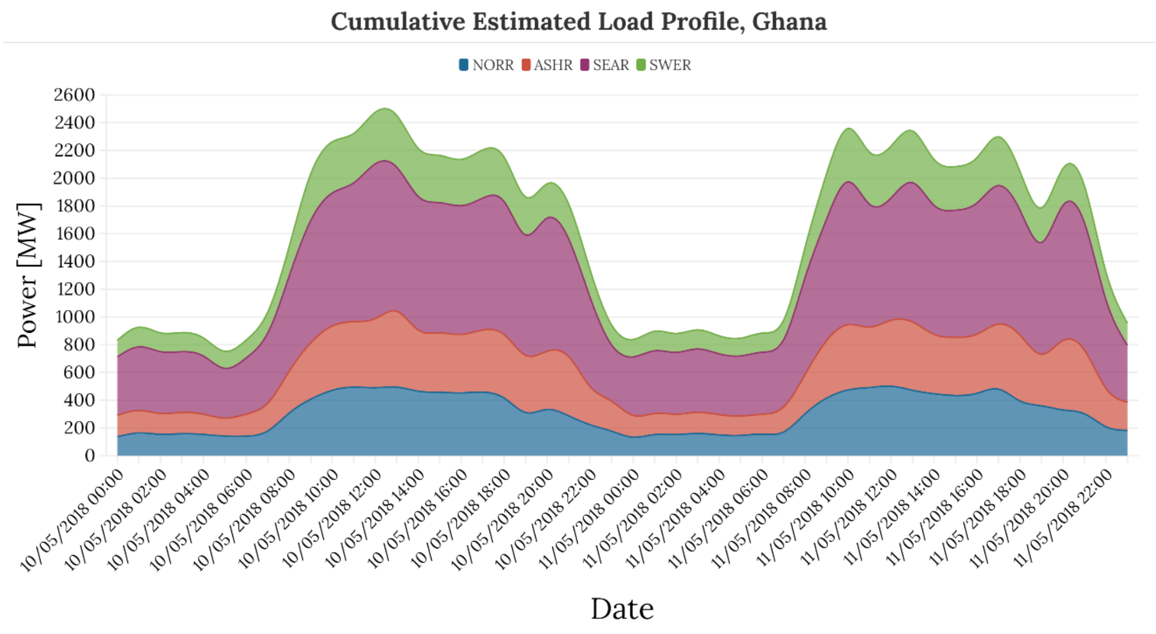


Figure 4.16 National Disaggregated Load Demand, Ghana

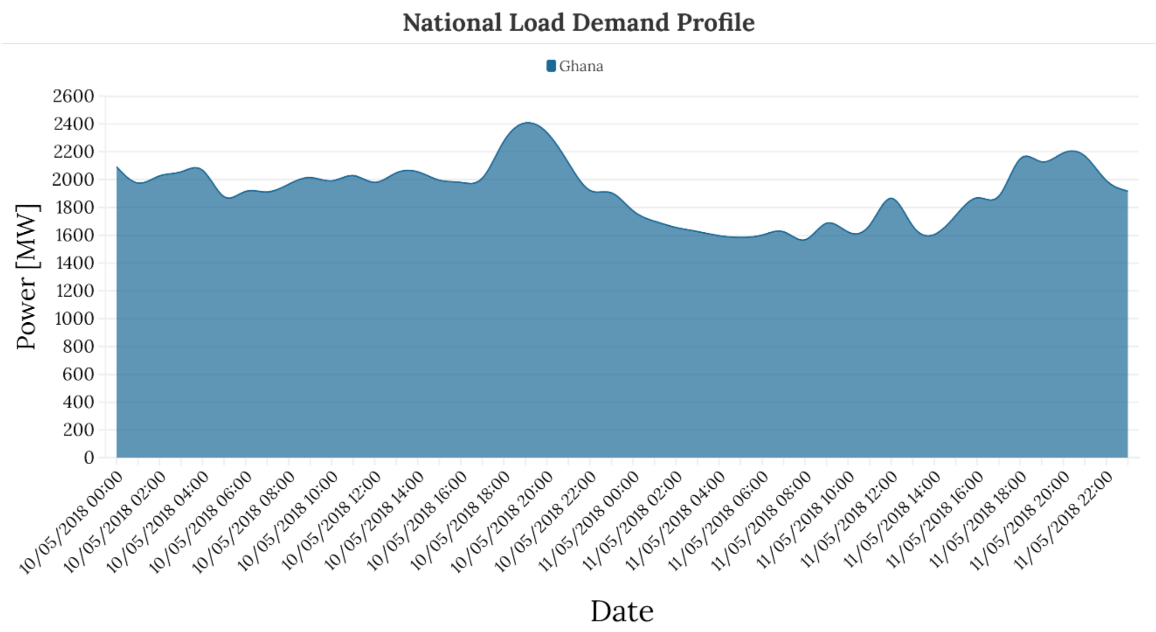


Figure 4.17 Real Load Demand, Ghana

4.2 Single-Node and Multi-Node Energy System Model of Ghana

The final step of this thesis work is to use the Hybrid Approach for Geographical Disaggregation of High-resolution National Load Demand in an applicative case.

In this work the case study is Ghana, a Sub-Saharan Africa country, which has been extensively analyzed from a socio-economic perspective as well as from an energetic point of view. In order to test the consistency of the Hybrid Disaggregation Approach, we simulated two optimization scenarios:

- 2018 Business as usual, based on a Single-Node approach with as input files the national electricity load demand provided by FEEM and power plants' information acquired through an extensive literature review and stakeholders' interviews.
- 2018 Business as usual, based on a Mingle-Node approach with as input files the disaggregated national electricity load demand estimated using the Hybrid Approach for Geographical Disaggregation of high-resolution National Load Demand and transmission network as well as power plants' information acquired through an extensive literature review and stakeholders' interviews and databases manipulation.

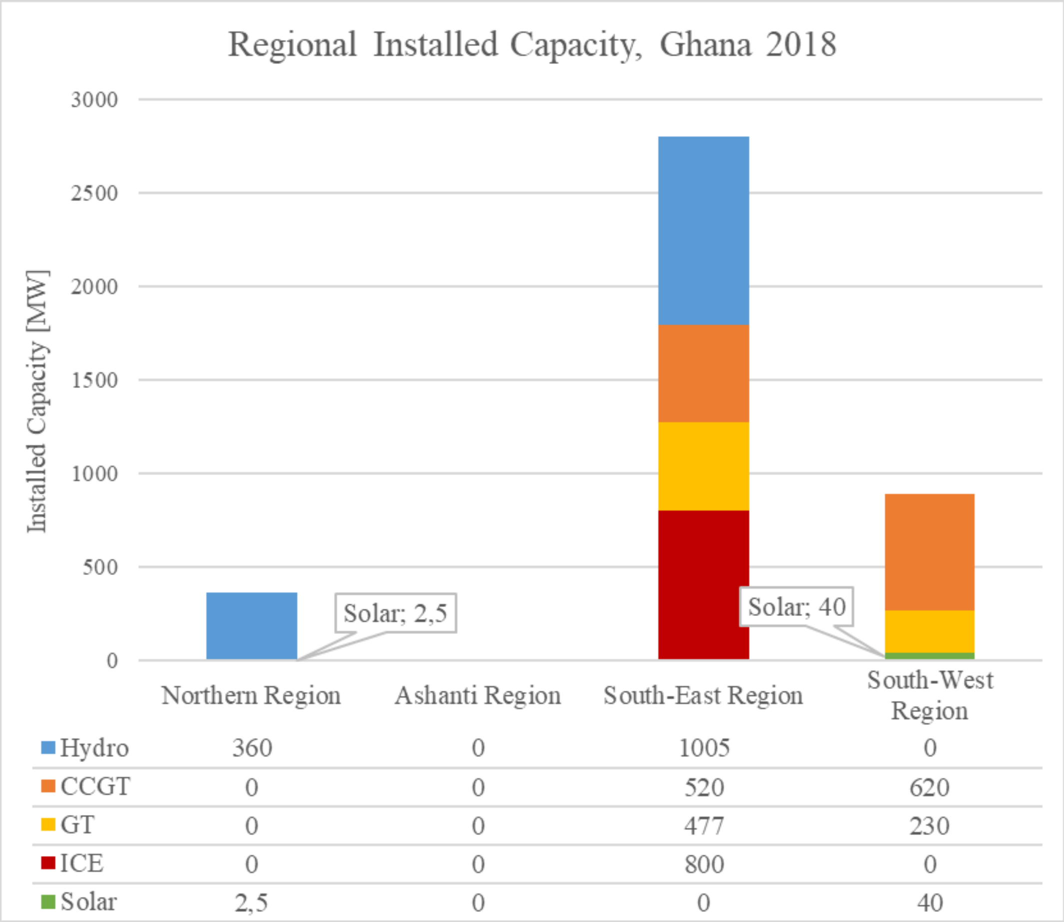
The objective of the two approaches is to verify the functioning of the output generated through the Hybrid Approach, in order to validate the process in sight of future research.

The paucity of freely available timeseries with regional resolution does not allowed to verify the correctness of the disaggregation itself, which will have to be studied in future.

The input database for the generation systems is the same, but in the Multi-Node Model they are suitably localized between the Macro-Regions. Their installed capacity is what the Ghanaian Energy System refers to as "Dependable Capacity" which is the power capacity that by contract the system detect. For each type of power plant, a technical capacity factor is considered based on the type of technology used for power generation. The considered capacity factors refer to the fossil-fuel generating plants and their values are:

- Combined Cycle Gas Turbine Power Plants: 8000/8760 [h/h]
- Gas Turbine Power Plants: 7500/8760 [h/h]
- Internal Combustion Engine Power Plants: 6500/8760 [h/h]

The final generation-side layout is composed as shown in Figure 4.19 and Figure 4.18..



	Northern Region	Ashanti Region	South-East Region	South-West Region
Hydro	360	0	1005	0
CCGT	0	0	520	620
GT	0	0	477	230
ICE	0	0	800	0
Solar	2,5	0	0	40

Figure 4.18 Installed Capacity by Macro-Regions, Ghana 2018

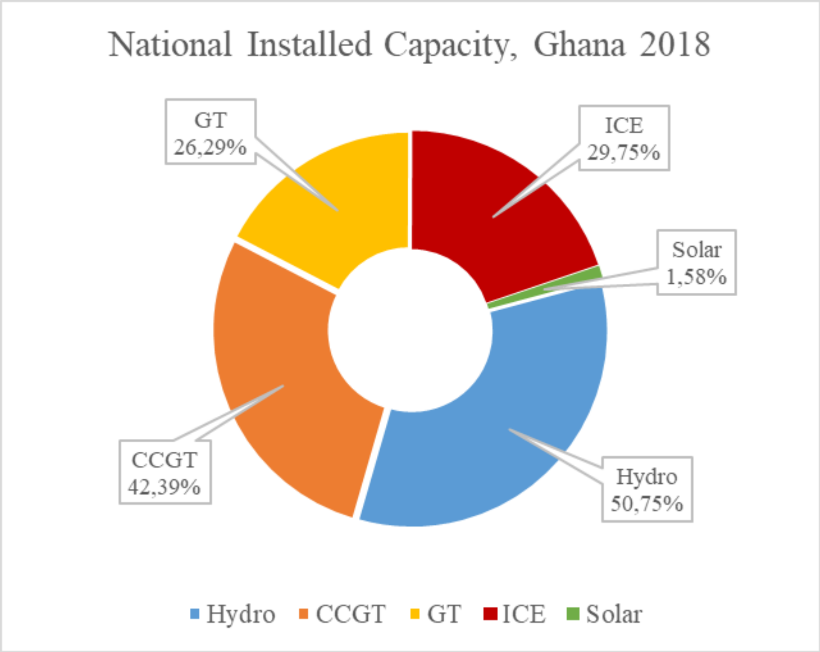


Figure 4.19 Share of Total Installed Capacity based on technologies, Ghana 2018

The input timeseries for the Single-Node Model is the one provided by FEEM from an on-the-field survey, representing the national load demand in an hourly timestep, while for the Multi-Node Model the Disaggregated National Load Demand developed in the previous section is the input to compute. Both the electricity load demands are shown in **Errore. L'origine riferimento non è stata trovata.** and Figure 4.20. The different peak capacity depends on the daily resampling, showing one big difference between the real and the computed one. This could be caused by underestimation of the load demand during the night and further investigations are needed. Other differences appear in the homogeneity of the disaggregated load demand, which does not fully account for extreme events as shortages, typical in the country considered, and that due to the resolution of the disaggregation considered it is more difficult to stochastically represent big variations in peak capacity.

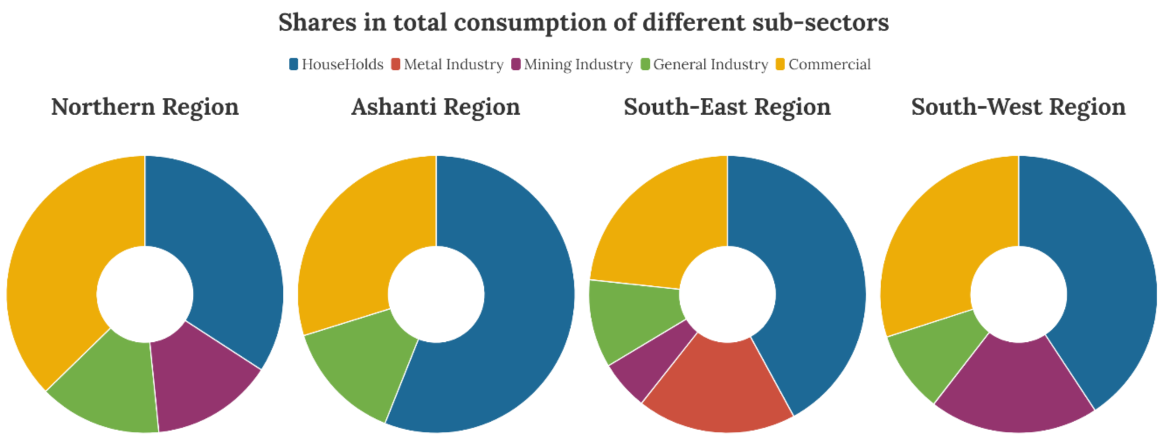


Figure 4.20 National Disaggregated Load Demand, Ghana

Finally, the main difference between the two models stands in the consideration of the transmission network in the Multi-Node Energy System Model. Here, as shown in Figure 4.21, the High Voltages 161 kV and 330 kV Lines composing the National Interconnected Transmission System (NITS) are considered. Thanks to the database obtained during the data acquisition process, it was possible to identify which lines connect the different macro-regions and their technical parameters. As already explained, a constant power factor of 0.9 has been chosen because of information found on the literature as in [75], and from that and the information obtained from the database the transmission network configuration has been included into the Multi-Node Energy Model System. The reasons of choice of the location of the nodes in the model were double, in order to represent the consumption and transmission epicenters and to consider the right distances of the transmission network.

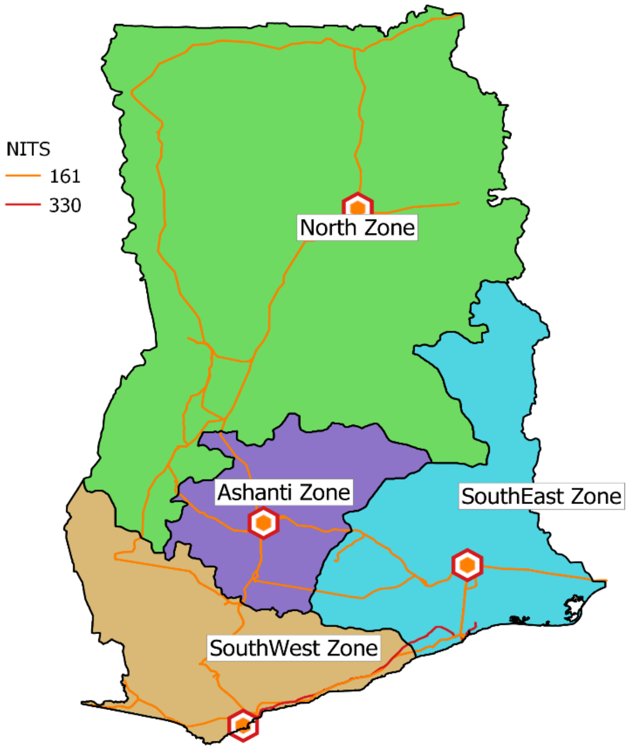


Figure 4.21 Simplified National Interconnected Transmission Network (NITS) for the Multi-Node Energy Model of Ghana

Once both optimization analysis of the open-source software Calliope have been processed, the output of the Single-Node Energy System Model of Ghana results in Figure 4.22, which represent the system dispatchment of the country during the entire year. The power dispatchment is optimized by the software Calliope, which try to reduce the system cost by power supply adjustments varying the power plant to operate.

From the Multi-Node Energy System Model of Ghana, the domestic power production in respect to the country’s consumption is shown in Figure 4.23, where the input is the power load demand generated with the Hybrid Approach.

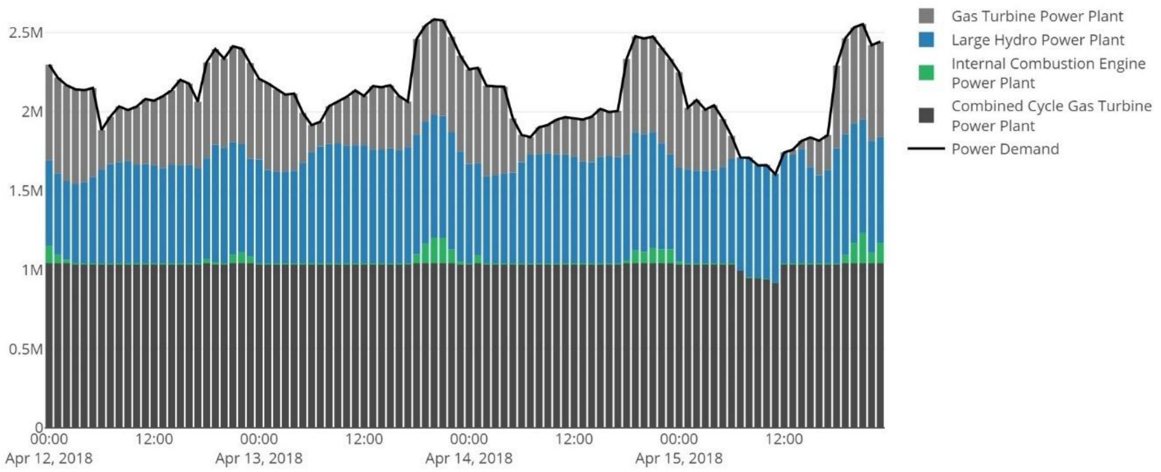


Figure 4.22 Single-Node system dispatchment, Ghana

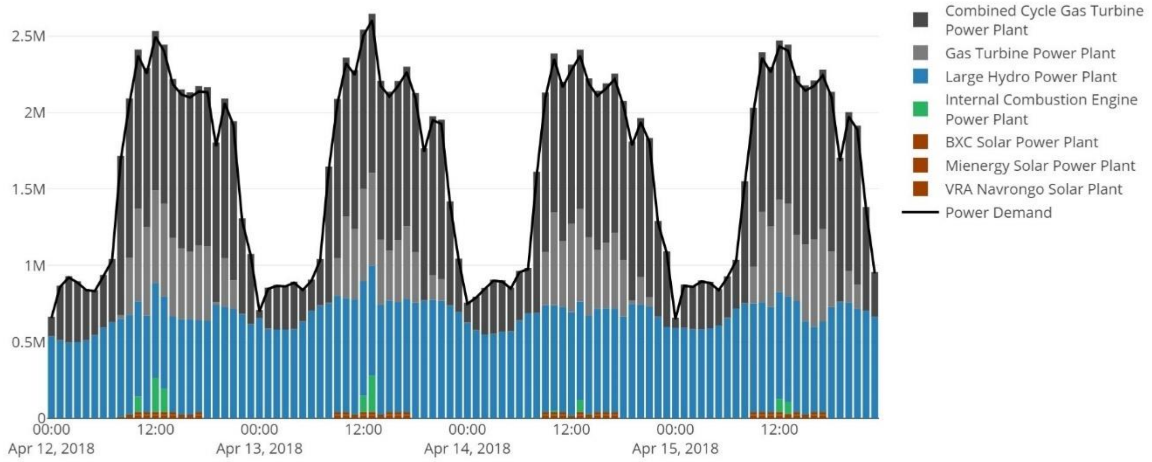


Figure 4.23 Multi-Node system dispatchment, Ghana

Several differences are shown between the two results, with different dispatchment methods which aim to satisfy a different load demand. The consumption is flatter in the

The two models though, present several similarities as the peak demand and the intensive exploitation of Hydropower plants and Combined Cycle Gas Turbine and Simple Cycle Gas Turbine power plants and system technical and economical parameters as sorted in

Table 4.4. We can appreciate a lower overall Levelized Cost of Energy (LCOE) for the Multi-Node Energy System Model, result of the better exploitation of the resources given the additional geospatial information.

Table 4.4 Total Levelized Cost of Energy (LCOE) [carrier: power; cost: monetary]

TOTAL LEVELIZED COST	
SINGLE NODE	MULTI NODE
0.145970875	0.140262158

Finally, we can consider the results of the Hybrid Approach for Geographical Disaggregation of High-Resolution National Load Demand accountable from a technical point of view: their behavior once processes in the optimization analysis are similar to the real ones, as well as the produced results are similar. The advantage of a Multi-Node Energy System Model is reflected even with the estimated load demand and generally the results seems realistic.

Obviously, different shortcomings are present in the results, as the great difference in the Load Demand Profile, especially during the night, and the inhomogeneity that the real Load Demand shown along the year. These considerations and the assumptions introduced along the process must be taken into account in further research in order to validate the process and create a methodology that could be applied to a number of developing countries that present similar conditions from an energetic and statistical points of view, that lack of proper database to tackle a National Energy System analysis to assess the proper policies.

Chapter 5
Conclusion and Future Work

The scope of this thesis work was to develop a disaggregation methodology capable to estimate high-resolution load demand defined at regional level of developing countries, where data paucity represent a limitation to progress, which could be used to develop a multi-node modelling framework all based on open access databases and open source software given the topical pandemic situation that the entire world is constrained to face in order to analyze and assess proper policies to tackle the modern energy challenges and not to stop the precedent progresses achieved from the pledge of the UN 2030 Agenda for Sustainable Development in 2015.

Data Acquisition

The first phase of the study, consisting of the data acquisition process, was carried out through an extensive literature review of the freely available open access databases as well as interviews to key institutional stakeholders and gave the possibility to delineate the available data on which to base the methodology research. As expected, there was full availability of a wide range of data online and no problem arose from the exemplary collaboration with the stakeholders. This led to a solid start of the research but also to the discovery of the first drawbacks as the lack of consistent, organized and up-to-date databases describing the energy sector in developing countries.

Electricity Load Demand Disaggregation

Once collected and sorted the databases, the research started to delineate the core information needed for modelling purposes. The timeseries describing the National Load Demand with a higher resolution of the Nation level seems to be the shortcoming in different modelling techniques. Hence a methodology based on and hybrid Top-Down and Bottom-Up approach took shape. The core concepts of the methodology are in the use of consolidated Top-Down framework as the Social Accounting Matrix and open access socio-economic databases as the ones of IEA and WorldBank to create a general overview and division of the economic as well as energetic system, given the widespread consideration that economic factors usually proxy energetic systems [78]. Once defined the main characters present in the energy system and defined the resolution of the timeseries which we were working on, through the use of open-source geospatial software as QGIS and open access geospatial information as the Global Human Settlement Layers it was possible to group and localize the categories delineated in the previous part of the work. Finally, after the quantitative and geographical disaggregation, each defined category's load demand profile has been characterized through the use of the stochastic open-source software RAMP, calibrating the Appliances in inputs for each User Type with the use of external database, literature review and generic assumptions. The resulting Load Demand profiles were then distributed between the delineated Macro-Regions by previously-calculated shares.

Single-Node and Multi-Node Energy Model Optimization

Once the disaggregation process was terminated and the results refined, they were used as input in the Calliope framework with the scope of generating a Multi-Node Energy Model of Ghana. The output has finally been compared to the one obtained by a Single-Node Energy Model of Ghana in order to evaluate the behavior.

Key Findings

The results seem promising, with the estimated timeseries producing results comparable to the real ones over different point of view such as the Yearly Load Demand profile and the magnitude of the peak energy demand as well as the Total Levelized Cost of Energy of the system or the systemwide Capacity Factor for different technologies.

However different bugs have been found, mainly due to the roughness of the methodology but also to the widespread paucity of consistent and up-to-date databases freely available. Some of them are the difficulty of the quantitative disaggregation process in finding the proper categories due to consequent insufficiency of geospatial information about a large number of the possibilities, the difficulty in understanding the most effective resolution in which disaggregate the National Load Demand, ranging between the overestimation or underestimation od the resolution for modelling purposes and the problem of appliances calibration for the stochastic process related to impossibility to carry out proper survey analysis. These limitations have to be properly studied in future research in order to validate the methodology, by the refinement of the data acquisition process, the creation and completion of databases dedicated to both the geospatial information as well as the categories' appliances calibration, and the definition of rigorous parameters on which to base the Top-Down quantitative disaggregation, and to recursively apply the Hybrid Approach for Geographical Disaggregation of National Load Demand to a wide number of Developing Countries where data paucity represents an obstacle to policy assessment and to a more straightforward energetic as well as socio-economic progress.

Appendix A

Questionnaire administered to the institutional stakeholders. Source: Authors

1. Power Plants

FEEM through a detailed literature review was able to collect a list of existing Power Plants in the country, both privately and publicly owned. We found anyway some discrepancies between our sources in terms of the operational situation of the power plants, and each document have a different list of Power Plants.

a) Does your institution hold an official list of existing Power Plants in Ghana?

…………………………………………………………………………………………

b) Would you be willing to comment the list of Power Plant that we created in order to understand which of them are really installed and which not, whether there are cases of overlapping or similar issues?

…………………………………………………………………………………………

c) For many of the power plants we found that some valuable information are missing, for instance geographical coordinates, year of deployment, scheduled lifetime (and many more). Could you help us fill this information gap?

…………………………………………………………………………………………

d) Do you have knowledge of under construction / scheduled / planned power plants both national and private?

…………………………………………………………………………………………

2. Transmission and Market

a) Do you have a map of the HV (high voltage) and MV (medium voltage) lines of the country? Or any other document reporting the existing status of the national grid?

…………………………………………………………………………………………

b) Are there existing transmission lines that serve for electricity exchange with neighboring countries for electricity import/export? Do you know if there are planned interconnections?

……………………………………………………………………………………

c) Is your national electricity market divided in regions? If yes, which are those regions?

……………………………………………………………………………………

d) Do you know if there is a national plan for grid expansion? Do you know which new lines are going to be deployed?

……………………………………………………………………………………

3. Electricity Demand

a) Do you keep track of the national electricity demand? If yes, can you please give details about either time resolution and geographical resolution of the track?

……………………………………………………………………………………

b) Are you willing to share such data with us?

……………………………………………………………………………………

c) Do you know if any institution measures the electricity demand of the country with a spatial resolution lower than the national one? (i.e. electricity consumption per region)

……………………………………………………………………………………

Appendix B

RAMP inputs for load generation profiles.

Residential Sector:

Urban 5 Dry Season	Number	Power [W]	Daily Time [min]	Time %	Min Time [min]	W1 Start	W1 End	W2 Start	W2 End	W3 Start	W3 End	Window %	Occasional Use
Light Bulb	4	20	120	0.2	10	19:30	00:00	00:00	00:30	-	-	0.35	no
Pro Light Bulb	6	8	120	0.2	10	19:30	00:00	00:00	00:30	-	-	0.35	no
Stereo	1	50	30	0.2	10	12:00	15:00	19:30	00:00	-	-	0.35	no
TV	2	70	90	0.1	5	12:00	15:00	19:30	00:00	-	-	0.35	no
DVD	1	20	90	0.1	30	19:30	00:00	-	-	-	-	0.35	no
Decoder	1	15	90	0.1	5	12:00	15:00	19:30	00:00	-	-	0.35	no
Electric Cooker	1	800 +/- 0.4	30	0.1	5	06:00	10:00	12:00	14:00	19:00	22:00	0.10	0.2
Oven	1	1500 +/- 0.4	60	0.1	10	12:00	14:00	19:00	22:00	-	-	0.10	0.2
Kettle	1	1000	10	0.1	1	06:00	10:00	12:00	14:00	19:00	22:00	0.10	0.33
Microwave	1	600 +/- 0.3	10	0.1	5	12:00	14:00	19:00	22:00	-	-	0.35	0.33
DishWasher	1	500	60	0.1	60	19:00	22:00	-	-	-	-	0.10	0.33
Fan	1	1000	120	0.2	15	12:00	15:00	17:00	21:00	-	-	0.35	no
PC	1	65	180	0.1	10	08:30	12:30	13:30	18:00	-	-	0.35	no
Phone Charger	3	7	240	0.2	10	19:30	00:00	-	-	-	-	0.35	no
Fridge	1	140	Specific Cycle	Specific Cycle	Specific Cycle	Specific Cycle	Specific Cycle	Specific Cycle	Specific Cycle	Specific Cycle	Specific Cycle	Specific Cycle	no
Freezer	1	100	Specific Cycle	Specific Cycle	Specific Cycle	Specific Cycle	Specific Cycle	Specific Cycle	Specific Cycle	Specific Cycle	Specific Cycle	Specific Cycle	no
Washing Machine	1	800	90	0.1	30	20:00	22:00	-	-	-	-	0.10	0.33
Iron	1	1000	30	0.2	15	17:00	22:00	-	-	-	-	0.35	0.2
Water Heater	1	500 +/- 0.3	60	0.2	15	06:00	10:00	12:00	14:00	19:00	22:00	0.25	no

Urban 5 Wet Season	Number	Power [W]	Daily Time [min]	Time %	Min Time [min]	W1 Start	W1 End	W2 Start	W2 End	W3 Start	W3 End	Window %	Occasional Use
Light Bulb	4	20	120	0.2	10	19:30	00:00	00:00	00:30	-	-	0.35	no
Pro Light Bulb	6	8	120	0.2	10	19:30	00:00	00:00	00:30	-	-	0.35	no
Stereo	1	50	30	0.2	10	12:00	15:00	19:30	00:00	-	-	0.35	no
TV	2	70	90	0.1	5	12:00	15:00	19:30	00:00	-	-	0.35	no
DVD	1	20	90	0.1	30	19:30	00:00	-	-	-	-	0.35	no
Decoder	1	15	90	0.1	5	12:00	15:00	19:30	00:00	-	-	0.35	no
Electric Cooker	1	800 +/- 0.4	30	0.1	5	06:00	10:00	12:00	14:00	19:00	22:00	0.10	0.2
Oven	1	1500 +/- 0.4	60	0.1	10	12:00	14:00	19:00	22:00	-	-	0.10	0.2
Kettle	1	1000	10	0.1	1	06:00	10:00	12:00	14:00	19:00	22:00	0.10	0.33
Microwave	1	600 +/- 0.3	10	0.1	5	12:00	14:00	19:00	22:00	-	-	0.35	0.33
DishWasher	1	500	60	0.1	60	19:00	22:00	-	-	-	-	0.10	0.33
Fan	-	-	-	-	-	-	-	-	-	-	-	-	-
PC	1	65	180	0.1	10	08:30	12:30	13:30	18:00	-	-	0.35	no
Phone Charger	3	7	240	0.2	10	19:30	00:00	-	-	-	-	0.35	no
Fridge	1	140	Specific Cycle	Specific Cycle	Specific Cycle	Specific Cycle	Specific Cycle	Specific Cycle	Specific Cycle	Specific Cycle	Specific Cycle	Specific Cycle	no
Freezer	1	100	Specific Cycle	Specific Cycle	Specific Cycle	Specific Cycle	Specific Cycle	Specific Cycle	Specific Cycle	Specific Cycle	Specific Cycle	Specific Cycle	no
Washing Machine	1	800	90	0.1	30	20:00	22:00	-	-	-	-	0.10	0.33
Iron	1	1000	30	0.2	15	17:00	22:00	-	-	-	-	0.35	0.2
Water Heater	1	500 +/- 0.3	60	0.2	15	06:00	10:00	12:00	14:00	19:00	22:00	0.25	no

Urban 4 Dry Season	Number	Power [W]	Daily Time [min]	Time %	Min Time [min]	W1 Start	W1 End	W2 Start	W2 End	W3 Start	W3 End	Window %	Occasional Use
Light Bulb	5	20	120	0.2	10	19:30	00:00	00:00	00:30	-	-	0.35	no
Pro Light Bulb	3	8	120	0.2	10	19:30	00:00	00:00	00:30	-	-	0.35	no
Stereo	1	50	30	0.2	10	12:00	15:00	19:30	00:00	-	-	0.35	no
TV	1	70	90	0.1	5	12:00	15:00	19:30	00:00	-	-	0.35	no
DVD	1	20	90	0.1	30	19:30	00:00	-	-	-	-	0.35	no
Decoder	1	15	90	0.1	5	12:00	15:00	19:30	00:00	-	-	0.35	no
Fan	1	50	300	0.2	15	08:00	11:00	18:00	22:00	-	-	0.35	no
PC	1	65	180	0.1	10	08:30	12:30	13:30	18:00	20:00	00:00	0.35	no
Phone Charger	3	7	240	0.2	10	19:30	00:00	-	-	-	-	0.35	no
Fridge	1	140	Specific Cycle	Specific Cycle	Specific Cycle	Specific Cycle	Specific Cycle	Specific Cycle	Specific Cycle	Specific Cycle	Specific Cycle	Specific Cycle	no
Freezer	1	100	Specific Cycle	Specific Cycle	Specific Cycle	Specific Cycle	Specific Cycle	Specific Cycle	Specific Cycle	Specific Cycle	Specific Cycle	Specific Cycle	no
Iron	1	1000	30	0.2	15	17:00	22:00	-	-	-	-	0.35	0.2
Water Heater	1	500 +/- 0.3	60	0.2	15	06:00	10:00	12:00	14:00	19:00	22:00	0.25	no

Urban 4 Wet Season	Number	Power [W]	Daily Time [min]	Time %	Min Time [min]	W1 Start	W1 End	W2 Start	W2 End	W3 Start	W3 End	Window %	Occasional Use
Light Bulb	5	20	120	0.2	10	19:30	00:00	00:00	00:30	-	-	0.35	no
Pro Light Bulb	3	8	120	0.2	10	19:30	00:00	00:00	00:30	-	-	0.35	no
Stereo	1	50	30	0.2	10	12:00	15:00	19:30	00:00	-	-	0.35	no
TV	1	70	90	0.1	5	12:00	15:00	19:30	00:00	-	-	0.35	no
DVD	1	20	90	0.1	30	19:30	00:00	-	-	-	-	0.35	no
Decoder	1	15	90	0.1	5	12:00	15:00	19:30	00:00	-	-	0.35	no
Fan	-	-	-	-	-	-	-	-	-	-	-	-	-
PC	1	65	180	0.1	10	08:30	12:30	13:30	18:00	20:00	00:00	0.35	no
Phone Charger	3	7	240	0.2	10	19:30	00:00	-	-	-	-	0.35	no
Fridge	1	140	Specific Cycle	Specific Cycle	Specific Cycle	Specific Cycle	Specific Cycle	Specific Cycle	Specific Cycle	Specific Cycle	Specific Cycle	Specific Cycle	no
Freezer	1	100	Specific Cycle	Specific Cycle	Specific Cycle	Specific Cycle	Specific Cycle	Specific Cycle	Specific Cycle	Specific Cycle	Specific Cycle	Specific Cycle	no
Iron	1	1000	30	0.2	15	17:00	22:00	-	-	-	-	0.35	0.2
Water Heater	1	500 +/- 0.3	60	0.2	15	06:00	10:00	12:00	14:00	19:00	22:00	0.25	no

Urban 3 Dry Season	Number	Power [W]	Daily Time [min]	Time %	Min Time [min]	W1 Start	W1 End	W2 Start	W2 End	W3 Start	W3 End	Window %	Occasional Use
Light Bulb	4	20	120	0.2	10	18:00	00:00	00:00	00:30	06:00	08:00	0.35	no
Stereo	1	50	30	0.2	10	12:00	15:00	18:00	00:00	-	-	0.35	no
TV	1	70	90	0.1	5	18:00	00:00	-	-	-	-	0.35	no
DVD	1	20	60	0.1	5	18:00	00:00	-	-	-	-	0.35	0.5
Decoder	1	15	90	0.1	5	18:00	00:00	-	-	-	-	0.35	0.5
Fan	1	50	300	0.2	15	07:00	09:00	18:00	22:00	-	-	0.35	0.8
PC	1	65	180	0.1	10	18:00	00:00	-	-	-	-	0.35	no
Phone Charger	2	7	240	0.2	10	00:00	00:00	-	-	-	-	0	no
Fridge	1	140	Specific Cycle	Specific Cycle	Specific Cycle	Specific Cycle	Specific Cycle	Specific Cycle	Specific Cycle	Specific Cycle	Specific Cycle	Specific Cycle	no

Urban 3 Wet Season	Number	Power [W]	Daily Time [min]	Time %	Min Time [min]	W1 Start	W1 End	W2 Start	W2 End	W3 Start	W3 End	Window %	Occasional Use
Light Bulb	4	20	120	0.2	10	18:00	00:00	00:00	00:30	06:00	08:00	0.35	no
Stereo	1	50	30	0.2	10	12:00	15:00	18:00	00:00	-	-	0.35	no
TV	1	70	90	0.1	5	18:00	00:00	-	-	-	-	0.35	no
DVD	1	20	60	0.1	5	18:00	00:00	-	-	-	-	0.35	0.5
Decoder	1	15	90	0.1	5	18:00	00:00	-	-	-	-	0.35	0.5
Fan	-	-	-	-	-	-	-	-	-	-	-	-	-
PC	1	65	180	0.1	10	18:00	00:00	-	-	-	-	0.35	no
Phone Charger	2	7	240	0.2	10	00:00	00:00	-	-	-	-	0	no
Fridge	1	140	Specific Cycle	Specific Cycle	Specific Cycle	Specific Cycle	Specific Cycle	Specific Cycle	Specific Cycle	Specific Cycle	Specific Cycle	Specific Cycle	no

Urban 2 Dry Season	Number	Power [W]	Daily Time [min]	Time %	Min Time [min]	W1 Start	W1 End	W2 Start	W2 End	W3 Start	W3 End	Window %	Occasional Use
Light Bulb	4	20	120	0.2	10	18:00	00:00	00:00	00:30	06:00	08:00	0.35	no
Radio	1	10	60	0.1	5	06:30	09:00	18:00	21:00	-	-	0.35	no
Stereo	1	50	30	0.2	10	12:00	15:00	18:00	00:00	-	-	0.35	no
TV	1	70	90	0.1	5	18:00	00:00	-	-	-	-	0.35	no
DVD	1	20	60	0.1	5	18:00	00:00	-	-	-	-	0.35	0.33
Decoder	1	15	90	0.1	5	18:00	00:00	-	-	-	-	0.35	0.33
Fan	1	50	300	0.2	15	07:00	09:00	17:00	20:00	-	-	0.35	0.8
Phone Charger	2	7	240	0.2	10	00:00	00:00	-	-	-	-	0	no
Fridge	1	140	Specific Cycle	Specific Cycle	Specific Cycle	Specific Cycle	Specific Cycle	Specific Cycle	Specific Cycle	Specific Cycle	Specific Cycle	Specific Cycle	no

Urban 2 Wet Season	Number	Power [W]	Daily Time [min]	Time %	Min Time [min]	W1 Start	W1 End	W2 Start	W2 End	W3 Start	W3 End	Window %	Occasional Use
Light Bulb	4	20	120	0.2	10	18:00	00:00	00:00	00:30	06:00	08:00	0.35	no
Radio	1	10	60	0.1	5	06:30	09:00	18:00	21:00	-	-	0.35	no
Stereo	1	50	30	0.2	10	12:00	15:00	18:00	00:00	-	-	0.35	no
TV	1	70	90	0.1	5	18:00	00:00	-	-	-	-	0.35	no
DVD	1	20	60	0.1	5	18:00	00:00	-	-	-	-	0.35	0.33
Decoder	1	15	90	0.1	5	18:00	00:00	-	-	-	-	0.35	0.33
Fan	-	-	-	-	-	-	-	-	-	-	-	-	-
Phone Charger	2	7	240	0.2	10	00:00	00:00	-	-	-	-	0	no
Fridge	1	140	Specific Cycle	Specific Cycle	Specific Cycle	Specific Cycle	Specific Cycle	Specific Cycle	Specific Cycle	Specific Cycle	Specific Cycle	Specific Cycle	no

Urban 1 Dry Season	Number	Power [W]	Daily Time	Time %	Min Time	W1 Start	W1 End	W2 Start	W2 End	W3 Start	W3 End	Window %	Occasional Use
Light Bulb	3	20	120	0.2	10	18:00	00:00	00:00	00:30	06:00	08:00	0.35	no
Radio	1	10	60	0.1	5	06:30	09:00	18:00	21:00	-	-	0.35	no
TV	1	70	90	0.1	5	18:00	00:00	-	-	-	-	0.35	no
Fan	1	50	300	0.2	15	07:00	09:00	17:00	20:00	-	-	0.35	0.8
Phone Charger	2	7	240	0.2	10	00:00	00:00	-	-	-	-	0	no

Urban 1 Wet Season	Number	Power [W]	Daily Time	Time %	Min Time	W1 Start	W1 End	W2 Start	W2 End	W3 Start	W3 End	Window %	Occasional Use
Light Bulb	3	20	120	0.2	10	18:00	00:00	00:00	00:30	06:00	08:00	0.35	no
Radio	1	10	60	0.1	5	06:30	09:00	18:00	21:00	-	-	0.35	no
TV	1	70	90	0.1	5	18:00	00:00	-	-	-	-	0.35	no
Fan	-	-	-	-	-	-	-	-	-	-	-	-	-
Phone Charger	2	7	240	0.2	10	00:00	00:00	-	-	-	-	0	no

Rural 5 Dry Season	Number	Power [W]	Daily Time [min]	Time %	Min Time [min]	W1 Start	W1 End	W2 Start	W2 End	W3 Start	W3 End	Window %	Occasional Use
Light Bulb	6	20	120	0.2	10	18:00	00:00	00:00	00:30	06:00	08:00	0.35	no
Radio	1	10	60	0.1	5	06:30	09:00	18:00	21:00	-	-	0.35	no
Stereo	1	50	30	0.2	10	12:00	15:00	18:00	00:00	-	-	0.35	no
TV	2	70	90	0.1	5	12:00	15:00	18:00	00:00	-	-	0.35	no
DVD	1	20	60	0.1	30	18:00	00:00	-	-	-	-	0.35	no
Decoder	1	15	90	0.1	5	12:00	15:00	18:00	00:00	-	-	0.35	no
Fan	2	50	300	0.2	15	09:00	21:00	-	-	-	-	0.35	0.80
Toaster	1	1000	5	0.2	1	06:00	10:00	12:00	14:00	19:00	22:00	0.1	0.33
Fridge	1	140	Specific Cycle	Specific Cycle	Specific Cycle	Specific Cycle	Specific Cycle	Specific Cycle	Specific Cycle	Specific Cycle	Specific Cycle	Specific Cycle	no
Phone Charger	3	7	240	0.2	10	18:00	00:00	00:00	00:30	-	-	0.2	no
PC	1	65	180	0.1	10	08:30	12:30	15:00	18:00	20:00	00:00	0.35	no
Iron	1	1000	30	0.2	15	09:00	12:00	-	-	-	-	0.35	no

Rural 5 Wet Season	Number	Power [W]	Daily Time [min]	Time %	Min Time [min]	W1 Start	W1 End	W2 Start	W2 End	W3 Start	W3 End	Window %	Occasional Use
Light Bulb	6	20	120	0.2	10	18:00	00:00	00:00	00:30	06:00	08:00	0.35	no
Radio	1	10	60	0.1	5	06:30	09:00	18:00	21:00	-	-	0.35	no
Stereo	1	50	30	0.2	10	12:00	15:00	18:00	00:00	-	-	0.35	no
TV	2	70	90	0.1	5	12:00	15:00	18:00	00:00	-	-	0.35	no
DVD	1	20	60	0.1	30	18:00	00:00	-	-	-	-	0.35	no
Decoder	1	15	90	0.1	5	12:00	15:00	18:00	00:00	-	-	0.35	no
Fan	-	-	-	-	-	-	-	-	-	-	-	-	-
Toaster	1	1000	5	0.2	1	06:00	10:00	12:00	14:00	19:00	22:00	0.1	0.33
Fridge	1	140	Specific Cycle	Specific Cycle	Specific Cycle	Specific Cycle	Specific Cycle	Specific Cycle	Specific Cycle	Specific Cycle	Specific Cycle	Specific Cycle	no
Phone Charger	3	7	240	0.2	10	18:00	00:00	00:00	00:30	-	-	0.2	no
PC	1	65	180	0.1	10	08:30	12:30	15:00	18:00	20:00	00:00	0.35	no
Iron	1	1000	30	0.2	15	09:00	12:00	-	-	-	-	0.35	no

Rural 4 Dry Season	Number	Power [W]	Daily Time [min]	Time %	Min Time [min]	W1 Start	W1 End	W2 Start	W2 End	W3 Start	W3 End	Window %	Occasional Use
Light Bulb	4	20	120	0.2	10	18:00	00:00	00:00	00:30	06:00	08:00	0.35	no
Radio	1	10	60	0.1	5	06:30	09:00	18:00	21:00	-	-	0.35	no
Stereo	1	50	30	0.2	10	12:00	15:00	18:00	00:00	-	-	0.35	0.5
TV	1	70	90	0.1	5	12:00	15:00	18:00	00:00	-	-	0.35	no
DVD	1	20	60	0.1	5	18:00	00:00	-	-	-	-	0.35	0.33
Decoder	1	15	90	0.1	5	18:00	00:00	-	-	-	-	0.35	0.33
Fan	1	50	300	0.2	15	07:00	09:00	17:00	20:00	-	-	0.35	0.8
Fridge	1	140	Specific Cycle	Specific Cycle	Specific Cycle	Specific Cycle	Specific Cycle	Specific Cycle	Specific Cycle	Specific Cycle	Specific Cycle	Specific Cycle	no
Phone Charger	3	7	240	0.2	10	00:00	00:00	-	-	-	-	0	no

Rural 4 Wet Season	Number	Power [W]	Daily Time [min]	Time %	Min Time [min]	W1 Start	W1 End	W2 Start	W2 End	W3 Start	W3 End	Window %	Occasional Use
Light Bulb	4	20	120	0.2	10	18:00	00:00	00:00	00:30	06:00	08:00	0.35	no
Radio	1	10	60	0.1	5	06:30	09:00	18:00	21:00	-	-	0.35	no
Stereo	1	50	30	0.2	10	12:00	15:00	18:00	00:00	-	-	0.35	0.5
TV	1	70	90	0.1	5	12:00	15:00	18:00	00:00	-	-	0.35	no
DVD	1	20	60	0.1	5	18:00	00:00	-	-	-	-	0.35	0.33
Decoder	1	15	90	0.1	5	18:00	00:00	-	-	-	-	0.35	0.33
Fan	-	-	-	-	-	-	-	-	-	-	-	-	-
Fridge	1	140	Specific Cycle	Specific Cycle	Specific Cycle	Specific Cycle	Specific Cycle	Specific Cycle	Specific Cycle	Specific Cycle	Specific Cycle	Specific Cycle	no
Phone Charger	3	7	240	0.2	10	00:00	00:00	-	-	-	-	0	no

Rural 3 Dry Season	Number	Power [W]	Daily Time [min]	Time %	Min Time [min]	W1 Start	W1 End	W2 Start	W2 End	W3 Start	W3 End	Window %	Occasional Use
Light Bulb	3	20	120	0.2	10	18:00	00:00	00:00	00:30	06:00	08:00	0.35	no
Radio	1	10	60	0.1	5	06:30	09:00	18:00	21:00	-	-	0.35	no
TV	1	70	90	0.1	5	18:00	00:00	-	-	-	-	0.35	no
Fan	1	50	300	0.2	15	07:00	09:00	17:00	20:00	-	-	0.35	0.8
Phone Charger	2	7	240	0.2	10	00:00	00:00	-	-	-	-	0	no

Rural 3 Wet Season	Number	Power [W]	Daily Time [min]	Time %	Min Time [min]	W1 Start	W1 End	W2 Start	W2 End	W3 Start	W3 End	Window %	Occasional Use
Light Bulb	3	20	120	0.2	10	18:00	00:00	00:00	00:30	06:00	08:00	0.35	no
Radio	1	10	60	0.1	5	06:30	09:00	18:00	21:00	-	-	0.35	no
TV	1	70	90	0.1	5	18:00	00:00	-	-	-	-	0.35	no
Fan	-	-	-	-	-	-	-	-	-	-	-	-	-
Phone Charger	2	7	240	0.2	10	00:00	00:00	-	-	-	-	0	no

Rural 2 All year	Number	Power [W]	Daily Time [min]	Time %	Min Time [min]	W1 Start	W1 End	W2 Start	W2 End	W3 Start	W3 End	Window %	Occasional Use
Light Bulb	3	20	120	0.2	10	18:00	00:00	00:00	00:30	06:00	08:00	0.35	no
Radio	1	10	60	0.1	5	06:30	09:00	18:00	21:00	-	-	0.35	no
Phone Charger	2	7	240	0.2	10	00:00	00:00	-	-	-	-	0	no

Rural 1 All year	Number	Power [W]	Daily Time [min]	Time %	Min Time [min]	W1 Start	W1 End	W2 Start	W2 End	W3 Start	W3 End	Window %	Occasional Use
Light Bulb	2	20	120	0.2	10	18:00	00:00	00:00	00:30	-	-	0.35	no
Phone Charger	2	7	240	0.2	10	00:00	00:00	-	-	-	-	0	no

Industrial Sector:

VALCO All year	Number	Power [W]	Daily Time [min]	Time %	Min Time [min]	W1 Start	W1 End	W2 Start	W2 End	W3 Start	W3 End	Window %	Occasional Use
Light Bulb	60	20	540	0.2	360	17:00	00:00	00:00	06:00	-	-	0.35	no
Pro Light Bulb	10	8	120	0.2	10	17:00	19:30	-	-	-	-	0.35	no
Stereo	7	50	180	0.2	10	10:00	19:30	-	-	-	-	0.35	no
TV	3	70	90	0.1	5	12:00	15:00	-	-	-	-	0.35	no
Decoder	3	15	90	0.1	5	12:00	15:00	-	-	-	-	0.35	no
A/C	3	1000	120	0.2	15	12:00	15:00	17:00	19:30	-	-	0.35	no
Fan	10	50	360	0.2	15	10:00	18:30	-	-	-	-	0.35	no
PC	15	65	480	0.1	10	08:30	12:30	13:30	19:30	-	-	0.35	no
Phone Charger	8	7	240	0.2	10	17:00	19:30	-	-	-	-	0.35	no
Water Heater	1	500 +/- 0.3	60	0.2	15	06:00	10:00	12:00	14:00	19:00	22:00	0.25	no
Elec Cell 1	1	72000000	1440	0	1440	00:00	00:00	-	-	-	-	0.10	no
Elec Cell 2	1	75000000	1440	0	1440	00:00	00:00	-	-	-	-	0.10	no

Ahafo mine	Number	Power [W]	Daily Time [min]	Time %	Min Time [min]	W1 Start	W1 End	W2 Start	W2 End	W3 Start	W3 End	Window %	Occasional Use
Light Bulb	60	20	540	0.2	60	17:00	00:00	00:00	06:00	-	-	0.35	no
Heavy Duty	1	68500000	1260	0.02	300	00:00	08:07	08:10	18:57	19:00	00:00	0.10	no

Akyem mine	Number	Power [W]	Daily Time [min]	Time %	Min Time [min]	W1 Start	W1 End	W2 Start	W2 End	W3 Start	W3 End	Window %	Occasional Use
Light Bulb	60	20	540	0.2	360	17:00	00:00	00:00	06:00	-	-	0.35	no
Heavy Duty	1	38500000	1260	0.02	300	00:00	08:07	08:10	18:57	19:00	00:00	0.10	no

Obuasi mine	Number	Power [W]	Daily Time [min]	Time %	Min Time [min]	W1 Start	W1 End	W2 Start	W2 End	W3 Start	W3 End	Window %	Occasional Use
Light Bulb	60	20	540	0.2	360	17:00	00:00	00:00	06:00	-	-	0.35	no
Heavy Duty	1	22040000	1260	0.02	300	00:00	08:07	08:10	18:57	19:00	00:00	0.10	no

Iduapriem mine	Number	Power [W]	Daily Time [min]	Time %	Min Time [min]	W1 Start	W1 End	W2 Start	W2 End	W3 Start	W3 End	Window %	Occasional Use
Light Bulb	60	20	540	0.2	360	17:00	00:00	00:00	06:00	-	-	0.35	no
Heavy Duty	1	25550000	1260	0.02	300	00:00	08:07	08:10	18:57	19:00	00:00	0.10	no

General Industry	Number	Power [W]	Daily Time [min]	Time %	Min Time [min]	W1 Start	W1 End	W2 Start	W2 End	W3 Start	W3 End	Window %	Occasional Use
Heavy Duty	1	22694000	1200	0.1	200	00:00	00:00	-	-	-	-	0	no

Commercial Sector:

General Commercial 1	Number	Power [W]	Daily Time [min]	Time %	Min Time [min]	W1 Start	W1 End	W2 Start	W2 End	W3 Start	W3 End	Window %	Occasional Use
Miscellaneous	1	27565106.9	600	0.1	200	08:00	19:00	-	-	-	-	0.10	no

General Commercial 2	Number	Power [W]	Daily Time [min]	Time %	Min Time [min]	W1 Start	W1 End	W2 Start	W2 End	W3 Start	W3 End	Window %	Occasional Use
Miscellaneous	1	27565106.9	600	0.1	200	08:00	19:00	-	-	-	-	0.10	no

General Commercial 3	Number	Power [W]	Daily Time [min]	Time %	Min Time [min]	W1 Start	W1 End	W2 Start	W2 End	W3 Start	W3 End	Window %	Occasional Use
Miscellaneous	1	27565106.9	600	0.1	200	08:00	19:00	-	-	-	-	0.05	no

General Commercial 3	Number	Power [W]	Daily Time [min]	Time %	Min Time [min]	W1 Start	W1 End	W2 Start	W2 End	W3 Start	W3 End	Window %	Occasional Use
Miscellaneous	1	27565106.9	600	0.1	200	08:00	19:00	-	-	-	-	0.05	no

Appendix C

National Interconnected Transmission System (NITS) parameters and power plants information:

Identifer	From	Region_from	GS/SS	GPS Coordinates	To	Region_to	GS/SS	GPS Coordinates	Length [km]	Operating Voltage [kV]	Thermal Limit [MVA]
W2M	WINNEBA	SouthWest	SS	5.388597, -0.645782	MALLAM	SouthEast	SS	5.579976, -0.282669	42.9	161	170
P6B	PRESTEA	SouthWest	SS	5.437803, -2.138505	OBUASI	Ashanti	SS	6.196288, -1.663287	112.2	161	182x2
NB2D	DUNKWA	SouthWest	SS	5.963023, -1.779702	NEW OBUASI	Ashanti	SS	6.164857, -1.688072	24.9	161	170
AS3BT	ASAWINSO	SouthWest	SS	6.287241, -2.373211	OBOTAN	Ashanti	SS	6.346646, -1.994201	30.0	161	182.2
MM1JB	JUABESO	SouthWest	SS	6.352620, -2.832460	MIM	North	SS	6.916385, -2.559742	86.0	161	182X2
C1M	MALLAM	SouthEast	SS	5.579976, -0.282669	CAPE COAST	SouthWest	SS	5.117929, -1.244658	116.9	161	170
TT21V	VOLTA	SouthEast	SS	5.694900, 0.000841	ABOADZE	SouthWest	GS	4.971661, -1.658195	219.0	330	500X2
A11F	AKOSOMBO	SouthEast	GS	6.296110, 0.057673	TAFO	Ashanti	SS	6.677384, -1.615543	61.2	161	182x2
A7F	AKOSOMBO	SouthEast	GS	6.296110, 0.057673	TAFO	Ashanti	SS	6.677384, -1.615543	61.2	161	273
F1N	NKAWKAW	SouthEast	SS	6.560607, -0.775031	TAFO	Ashanti	SS	6.677384, -1.615543	59.5	161	170
N2AW	NKAWKAW	SouthEast	SS	6.560607, -0.775031	ANWOMASO	Ashanti	SS	6.694380, -1.519071	93.6	161	182 X 2
N3J	KONONGO	Ashanti	SS	6.634984, -1.218501	NKAWKAW	SouthEast	SS	6.560607, -0.775031	53.1	161	170
F2Q	TAFO	Ashanti	SS	6.677384, -1.615543	AKWATIA	SouthEast	SS	6.013133, -0.823353	56.4	161	170
K3TH	KUMASI	Ashanti	SS	6.694720, -1.519161	TECHIMAN	North	SS	7.576643, -1.925779	115.0	161	182 x 2
Q1NB	NEW OBUASI	Ashanti	SS	6.164857, -1.688072	AKWATIA	SouthEast	SS	6.013133, -0.823353	110.0	161	244

Plant Full Name	Coordinates	Macro-Region	Technology	Installed Capacity [MW]	Dependable Capacity [MW]	Efficiency [%]	Fixed O&M [$/kW-yr]	Variable O&M [$/MWh]	Primary Fuel	Secondary Fuel	Operator	Year of Construction / Online Date	Expected Lifetime
Akosombo Hydroelectric Power Station	6.299271, 0.055414	South-East	Hydro	1020	900		9.2	1	Water		VRA	1/1/66	50
Kpong Hydroelectric Power Station	6.119989, 0.125000	South-East	Hydro	160	105		9.2	1	Water		VRA	1/1/82	50
Bui Generation Station	8.278328, -2.235837	Northern	Hydro	400	360		27.7	1.6	Water		BPA	6/1/13	50
Takoradi Power Company	4.971848, -1.658452	South-West	CCGT	330	300	31%	18.7	5	NG	LCO	VRA	3/1/98	25
Takoradi International Company	4.971848, -1.658452	South-West	CCGT	340	320	41%	30.9	4.9	NG	LCO	IPP operated by VRA	6/1/00	25
Sunon Asogli Power Plant 1	5.680549, 0.047441	South-East	CCGT	200	180	42%	11.8	4.5	NG	LCO	IPP	9/1/11	25
Sunon Asogli Power Plant 2	5.679922, 0.046465	South-East	CCGT	360	340	42%	16	3.5	NG	LCO	IPP	3/1/17	25
Tema Thermal Power Plant 1	5.673967, 0.012839	South-East	GT	110	100	31%	14.3	6.5	NG	DFO	VRA	6/1/09	25
Tema CENIT Thermal Power Plant	5.674469, 0.012264	South-East	GT	110	100	28%	11.8	4.5	NG	LCO	IPP	10/1/13	25
Kpone Thermal Power Plant	5.734602, 0.009279	South-East	GT	220	200	30%	12.3	3.5	NG	DFO	VRA	10/1/15	25
Ameri Power Plant	4.974163, -1.659568	South-West	GT	250	230	34%	14.5	5	NG		IPP	2/1/16	25
Tema Thermal Power Plant	5.677047, 0.013908	South-East	GT	49.5	45	34%	11.8	4.5	NG	LCO	VRA	6/1/10	25
Expansion of Same Plant	5.677047, 0.013908	South-East	GT	38	32		11.8	4.5	NG			1/1/15	25
MV Karadeniz Powership Osman Khan	5.637025, 0.018678	South-East	ICE	470	450	42%	177.8	3.5	HFO		IPP	12/1/15	10
AKSA ENERGY HFO Power Plant	5.694290, 0.023772	South-East	ICE	370	350	41%	16	3.5	HFO		IPP	3/1/17	6.5
VRA Navrongo Solar Plant	10.880047, -1.102526	Northern	Solar	2.5	2.5			166.9	Solar		VRA	1/1/13	30
BXC Solar Power Plant	5.347959, -0.702172	South-West	Solar	20	20			201.2372	Solar		IPP	1/1/16	
Mienergy Solar Power Plant	5.370174, -0.692792	South-West	Solar	20	20			182.464	Solar		IPP	15/09/2018	

Appendix D

Ghanaian mining plants database:

Property Name	Commodity	Type of Work	Status	Current Production [grams]	Annual Energy Consumption [MWh]	Energy needs [MW]	Source of power	Energy Consumption [kwh/t product]	Mine Location
Nsuta	Manganese	Open-Pit	Producer	420000	24000	2.5	On-Grid	16	5.2666667, -1.95
Bibiani Mine	Gold	Open-Pit	Producer	1101932	37563	3.91	On-Grid	25000000	6.4666667, -2.3166667
Konongo	Gold	Surface	Producer	110355	8505	0.89	On-Grid	25000000	6.6166667, -1.1666667
Akoase	Gold	Surface	Advanced Exploration		70874	7.38	On-Grid	25000000	6.4666667, -0.8666667
Chirano	Gold	Open-Pit/ Underground	Producer	9444000	156914	16.35	On-Grid	45000000	5.7666667, -2.5333333
Ahafo / Subika - Ntotoroso	Gold	Open-Pit/ Underground	Producer	17605000	792227	82.52	Off-site Diesel, On-Grid	45000000	7.0666667, -2.65
Tarkwa Mine	Gold	Open-Pit	Producer	21934116	561320	58.47	Off-site Diesel, On-Grid	25000000	5.3, -2.0333333
Akyem	Gold	Surface	Advanced Exploration	1524066	340194	35.44	Off-site Diesel, On-Grid	25000000	6.2333333, -2.2666667
Obuasi Mine (Ashanti)	Gold	Open-Pit/ Underground	Producer	6917280	510291	53.16	Off-site Diesel, On-Grid	45000000	6.1666667, -1.6666667
Damang/Aboss o	Gold	Open-Pit/ Underground	Producer	4752600	278109	28.97	Off-site Diesel, On-Grid	45000000	5.5, -1.8333333
Idupapriem Gold Mine	Gold	Open-Pit	Producer	2645120	141747	14.77	Off-site Diesel, On-Grid	25000000	5.2333333, -2.0333333

Acronyms

DISCo	Individual Distribution Company
EC	Energy Commission
ESP	Electricity Supply Plan
FEEM	Fondazione Eni Enrico Mattei
GHSL	Global Human Settlement Layer
GNGC	Ghana National Gas Company
GNPC	Ghana National Petroleum Corporation
GODI	Ghana's Open Data Initiative
GRIDCo	Ghana Grid Company
GWh	Gigawatt hours
IEA	International Energy Agency
IPP	Independent Power Producers
kV	Kilovolts
M-LED	Multi-sectoral Latent Electricity Demand assessment
MoEn	Ministry of Energy
MVA	Mega Volt Amperes
MW	Megawatts
NITS	National Interconnected Transmission System
NTL	Nighttime Lights
OSS	Open-Source Software
PPA	Power Purchase Agreement
PURC	Public Utilities Regulatory Commission
QGIS	Quantum Geographic Information System
RAMP	Remote-Areas Multi-energy load Profiles
SSA	Sub-Saharan Africa
VALCO	Volta Aluminum Company
VRA	Volta River Authority

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