Leapfrogging in the African Power Sector:

The Effect of Mitigation Policies on Regional African Power Sector Development

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Abstract

Africa severely lacks generation capacity, despite possessing an abundance of natural resources that could be used for electricity generation. Generation capacity will need to be increased to achieve economic and social development benefits. There are many initiatives to increase generation capacity in Africa, both from local governments and from international organizations such as the UN SE4ALL and US Power Africa initiatives. It is expected that Africa will undergo rapid electrification in the coming decades. Little research has been done with regards to how this generation capacity will develop. If it follows the example of other developing regions such as China and Brazil, it is expected that a fossil fuel intensive grid will develop. It is speculated that Africa can 'leapfrog' into a low-emissions grid as the late-comer effect makes renewable energy relatively more competitive than in other regions.

Based on a scenario analysis with the Integrated Assessment Model TIAM-ECN, we estimate potential for leapfrogging for African sub-regions under different mitigation scenarios. From the baseline scenario it was established that electricity demand in Africa is expected to increase 5-fold by 2050 and that gas-fired power plants will become the dominant form of generation capacity for most of the continent. From simulation results it is found that African carbon emission can be reduced by 50% in a \$10/tonne carbon tax scenario to 92% in a stringent \$50/tonne carbon tax scenario. Mitigation potential differs significantly between African sub-regions. Morocco and Ethiopia show particular leapfrogging potential. Carbon tax could lead South Africa to divert from its coal-intensive grid. Oil and gas producing countries are least susceptible to mitigation measures. More research is needed to indicate which policies would be best suited to achieve mitigation in Africa.

Preface

Hereby I am proud to present my final thesis for the Master Degree of Energy Science of Utrecht University. The work discussed in this thesis was performed during an internship the Policy Studies department of the Energy Research Centre of the Netherlands (ECN) in Amsterdam. The purpose of the internship was to expand the current TIAM-ECN model by including 17 African sub-regions and evaluating different scenarios for future generation capacity for the sub-regions. My work at ECN consisted of several stages:

- Perform a literature review of energy & electricity use in Africa
- Identify sub-regions for modeling in consultation with ECN project manager
- Gather data for each identified sub-region for key aspects of energy use in the generation, transport, residential/commercial/agriculture, industrial and upstream sectors
- Identify trade links between African sub-regions and other world regions
- Perform regression analysis on this data and extrapolate trends in demand drivers
- Adapt the model to be better suited for African data
- Calibrate the TIAM-36 model to 2005 and 2010 data
- Base-Year construction for the different African sub-regions
- Scenario analysis of different mitigation options for the electricity sector of the model
- Identify future project and prepare pitches

This thesis will focus on my work on the electricity sector, both in the area of data collection and the scenario analysis. Results and analysis for the base-year are extensively included as much of the data collected for this thesis was not earlier summarized in a single database. The creation of this database therefore provides significant insights in its own right. The TIAM-36 model that I build for this thesis is currently being used by ECN to evaluate future electricity generation capabilities for several African regions. It is the hope that in the future the other sectors included in the model will be explored further as well.

Acknowledgements

This thesis could not have be completed without the help and support of those around me. First of all I would like to thank my supervisors Bob van der Zwaan and Tom Kober for their supervision and patience – I have learned from you endlessly. Secondly I would like to extend my gratitude to my supervisor Mrs. Ramirez for her motivation and help, Machteld van den Broek for her supervision as a second reader, and Pieter Louwman for keeping me sane. Lastly, I would like to express my appreciation to my friends and family for their constant and unconditional support over the past months.

Abbreviations

AEEP	Africa-EU Energy Partnership
AfdB	African Development Bank
AGECC	United Nationa Advisory Group on Energy and Climate Change
AICD	Aviation International Certificates Database
ARGeo	The African Rift Geothermal Development Facility
BAU	Baseline Scenario
CAPP	Central African Power Pool
CCS	Carbon Capture and Storage Technology
CEMAC	Economic Community of Central African States
CO_2	Carbon Dioxide
COMELEC	Comité Maghrébin de l'Electricité - Mahgreb Power Pool
COP	Convention of the Parties
CRCC	China Railway Construction Company
CSP	Concentrated Solar Power
Ctax	Carbon tax - here in te context of the carbon tax scenarios
DBFZ	Deutsches Biomasse Forschungs Zentrum - German Biomass Research Center
DERA	Deutsche Rohstoffagentur - German Mineral Resources Agency
DRC	Democratic Republic (of the Congo)
EAPP	East African Power Pool
ECN	Energieonderzoek Centrum Nederland - Energy Research Center of the Netherlands
ECOWAS	Economic Community Of West African States
EIA	United States Energy Information Administration
ETSAP	Energy Technology Systems Analysis Program
FEMA	Forum of Energy Ministers in Africa
GCAM	Global Change Assessment Model - IAM developed at the PNNL
GDP	Gross Domestic Product
GHG	Green House Gas
IAM	Intergrated Assessment Model
IATA	International Air Transport Association
IEA	International Energy Agency
IISP	Institute of Information Security Professionals
IMAGE	Integrated Model to Assess the Global Environment - IAM developed at PBL the Netherlands
INDC	Intended Nationally Determined Contributions
INTPOW	Norwegian Renewable Energy Partners
IPCC	Intergovernmental Panel on Climate Change
IRDB	International Reconstruction and Development Bank
IRENA	International Renewable ENergy Agency
IUC	International Union of Railways
LCEO	Levelized Cost of Electricity
LDC's	Least Developed Countries
MDG	Millenium Development Goals
MIDT	Travelport Marketing Information Data Tapes
MIT	Massachusetts Institute of Technology

NAMA	Nationally Appropriate Mitigation Actions
NASA	National Aeronautics and Space Administration
NEPAD	New Partnership for Africa's Development
NGCC	Natural Gas Combined Cycle power plant
NGO	Non-governmental Organisation
PBL	PlanBureau Leefomgeving the Netherlands Environmental Assessment Agency
PNNL	Pacific Northwest National Laboratory
ppm	Parts per million
PV	Photo Voltaic technology
PWC	Price Waterhouse Coopers
REN21	Renewable Energy Policy Network for the 21st Century
SAPP	South African Power Pool
SE4ALL	Sustainable Energy for All
TIAM	Times Integrated Assessment Model
TIAM-ECN	Version of the Times Integrated Assessment Model as adapted by ECN
TIMER	Targets IMAGE Energy Regional simulation model - predecessor of the TIAM model
UN	United Nations
UNDP	United Nations Development Programme
USAID	United States Agency for International Development
USEA	United States Energy Association
USGS	United States Geological Society
WAPP	West African Power Pool
WB	World Bank
WEC	World Economic Forum
WRI	World Resources Institute

Region Terminology

General Regions

Africa	The entire continent of Africa exluding small island regions
North Africa	Morocco, Western Sahara, Algeria, Tunesia, Libya and Egypt
Sub Saharan Africa	Africa excluding Northern Africa
Developing Sub-Saharan Africa	Sub Saharan Africa excluding South Africa
Mahgreb region	North Africa excluding Egypt

Model Regions

Africa Region	The original TIAM-20 African region covering entire Africa and using data based on South Africa for the whole region
Aggregated Africa Region	The updated TIAM-36 Africa region, consisting of an aggregate of the 17 African Sub-Regions each with their own data
African Sub Regions	The 17 new African regions as specified below, together covering entire Africa. Each Region is colour coded as shown below.

MAR	Morocco & Western Sahara
DZA	Algeria
TUN	Tunisia
LBY	Libya
EGY	Egypt
AWE	Benin, Burkina Faso, Côte d'Ivoire, Gambia, Ghana, Guinea, Guinea Bissau, Liberia, Mauritania, Mali, Niger, Senegal, Sierra Leone, Togo
NGA	Nigeria
ACE	Cameroon, Central African Republic, Chad, Equitorial Guinea, Gabon, Republic of the Congo
AEA	Burundi, Djibouti, Eritrea, Rwanda, Somalia, South Sudan, Sudan, Uganda
ETH	Ethiopia
KEN	Kenya
COD	Democratic Republic of the Congo
AGO	Angola
ASE	Mozambique, Tanzania
ASO	Botswana, Lesotho, Malawi, Namibia, Swaziland, Zambia, Zimbabwe
MDG	Madagascar
ZAF	South Africa

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Chapter 1: *Introduction*

Electricity is a vital commodity for socio-economic development but its use is also closely related to climate change and pollution. Whereas global electricity demand was historically dominated by industrialized countries, presently the demand of developing nations is rapidly rising. The rapid rise of electricity consumption in developing nations is driven by increased wealth, grid expansion, and increase in local generation capacity. Increasing electricity access is necessary for socio-economic development, however expanding this access through fossil fuel generation capacity will increase greenhouse gas emissions and exacerbate the problems related to these emissions.

Africa has a dual electricity problem. North African countries have near universal electricity access, but a fossil fuel and emission intensive grid. In Sub-Saharan Africa only 24% of the population has access to electricity. Recently there has been increased focus on energy poverty in Africa. Ambitious energy access targets have been set by intergovernmental organizations, NGO's and local governments. The United Nations initiative 'Sustainable Energy for All' has the objective of ensuring universal access to modern energy services – including electricity - by 2030. Often renewables are promoted before least-cost generation capacity, indicating a possible conflict of priorities.

It is expected that Africa will undergo rapid electrification in the coming decades. To reach the internationally agreed 2°C climate target the addition of generation capacity will have to be reconciled with climate change mitigation strategies. Based on variations in current electricity access, natural resources and economic development, it is expected that African countries will develop different climate change mitigation strategies for their electricity grids over the coming decades. The lack of existing carbon-based generation capacity creates the opportunity for Sub-Saharan Africa to develop a low emission electricity sector by expanding electricity access mainly through renewable technologies. Northern African countries will face the combined challenges of greening their electricity, reducing their reliance on fossil fuels and expanding their generation capacity to meet increasing demands.

This thesis looks at the possible developments of the African electricity system under different carbon pricing and mitigation caps. It will do so using the TIAM-ECN integrated assessment model for the whole energy system. This model has been expanded for this thesis to include 17 separate African regions in greater detail. The results obtained with the TIAM-ECN are intended to be used as a foundation for further research into the mitigation possibilities for different African regions both for theoretical research and as a support for designing NAMA's. In addition, the results of the model can be soft-linked to other models such as LEAP to identify further policy strategies for African countries on shorter time-scales.

This thesis is structured as follows: Chapter 2 formulates our problem definition. Chapter 3 gives the results of a literature review of the current energy situation in Africa with a focus on the electricity sector. In chapter 4 an overview of our methodology is given, focusing on energy models in general and TIAM-ECN model and its scenarios in particular. Chapter 5 elaborates on the data gathering process. Chapter 6 reviews our results and chapter 7 addresses additional discussion topics . We analyze and formulate our conclusions in chapter 8.

Chapter 2: *Problem Definition*

There are several paths toward energy development in Africa. It is expected that emissions in Africa will rise sharply with increased economic development and electricity access following the pattern of other developing regions such as China, South-East Asia, India and Latin America. But Africa is different – different in its lack of existing energy infrastructure and its widespread availability of renewable reserves. The hope is that Africa can avoid an emission intensive development path and directly transition into a less emission intensive energy grid [Szabo 2013]. This process is called ´leapfrogging´. Little is known about the feasibility of leapfrogging and the possibilities for the development of a sustainable grid in Africa. Mitigation policies supported by external funding could provide the incentive needed for this transition to occur. Due to the large differences between African regions, it is expected that these regions will follow different paths of electricity network development and have a different response to mitigation policies. This research has attempted to shed light on possible power sector development pathways for 17 different African regions.

The purpose of this thesis is to research how different regional and global mitigation scenarios will influence the development of (renewable) electricity in Africa and the future CO_2 emissions of these regions, in order to identify opportunities for the development of low-emission grids in Africa. Although this research will focus on analyzing the results for the electricity sector, the goal is to develop a model that can later be expanded and used to analyze the other sectors as well.

Research Question:

Can African sub-regions leap-frog into a sustainable electricity grid, with or without the help of mitigation scenarios?

Secondary Questions:

- How does African Electricity Demand develop over the coming decades?
- How do different CO2 mitigation scenarios the electricity technologies deployed in different African regions?

Possible applications

It is the hope that this thesis provides the foundation for more work on regional appropriate electrification targets both within ECN and in the broader development discussion. This work could provide support to African governments in defining Nationally Appropriate Mitigation actions (NAMA's) - actions that reduce emissions in developing countries and are prepared under the umbrella of a national governmental initiative. Currently the model build for this thesis is used by ECN in tenders for policy makers and NGO's to evaluate different paths for achieving adequate future generation capacity.

Adaptation of research questions

The research questions addressed in this thesis differ slightly from those posed in the original research proposal as shown below. The original research question is now a secondary research question, with the research question slightly rephrased to incorporate the term 'Leapfrogging'. This was done as the reason we were interested in the African power sector development was to see if they could reach the leapfrogging ideal. The new research question portrayed this purpose clearer. The secondary research question concerning the African Energy Model is still discussed at length in section 7.1. However, it was determined that identifying the benefits and limits of the updated TIAM-ECN 36 model were the purpose of the internship, not the thesis. The results were therefore not included in the main results section.

Original Research Questions:

Research question

- How do different carbon mitigation scenarios influence the electricity development of African regions?

Secondary Questions

- What are the potential mitigation pathways for different African regions?
- What compromises have to be made to develop a specialized African energy model?

Chapter 3: *Background*

Africa severely lacks generation capacity, despite possessing an abundance of natural resources that could be used for electricity generation. Generation capacity will need to be increased to achieve economic and social development benefits. There are many initiatives to increase generation capacity in Africa, both from local governments and from international organizations such as the UN SE4ALL and the US Power Africa initiatives. Little research has been done with regards to how this generation capacity will develop. If it follows the example of other developing regions such as China and Brazil, it is expected that a fossil fuel intensive grid will develop. It is speculated that Africa can 'leapfrog' into a low-emissions grid as the late-comer effect makes renewable energy relatively more competitive than in other regions. This research will review the possibilities for different African regions to leap-frog with and without mitigation policies.

3.1. African Power Sector

A joint report by the World Bank and the International Bank for Reconstruction and Development (IBRD) found that lack of generation power was the greatest challenge for the African continent[1] [Foster 2010]. Electrification rates range from as low as 3.7% in Uganda, 4.7% in Ethiopia and 5.0% in Malawi to as high as 45% in Ghana 66% in South Africa and 100% in the North African countries as shown in figure 3.1 [IEA 2014(I), Wolde-Rufael 2006, World Bank 2015]. In 2012 Africa had an installed capacity of 140GW – equal to the capacity China has added every two years over the past decade [IRENA 2012]. Most of this generation capacity is found in South Africa and the North African countries, with only 40GW installed in developing Sub-Saharan Africa. To raise the level of electrification (per capita) of developing Sub-Saharan to that of current South Africa would require a 33-fold generation capacity increase – to the level of the United States a 137-fold increase (fig 3.3) [IRENA 2012, 2013(I)]. The lack of electricity impedes both economic and social development as reviewed in section 3.2 [Deichman 2011, Pereira 2011].

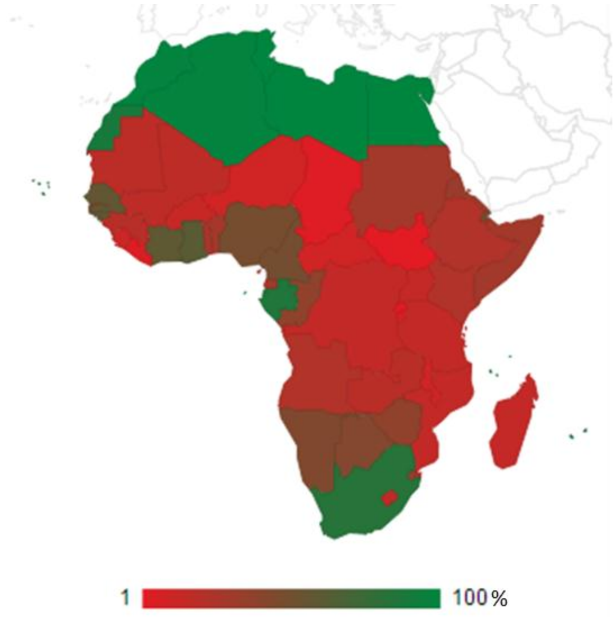

Fig. 3.1. Electricity Access per country (2010) [IEA 2014(I), Wolde-Rufael 2006, World Bank 2015]

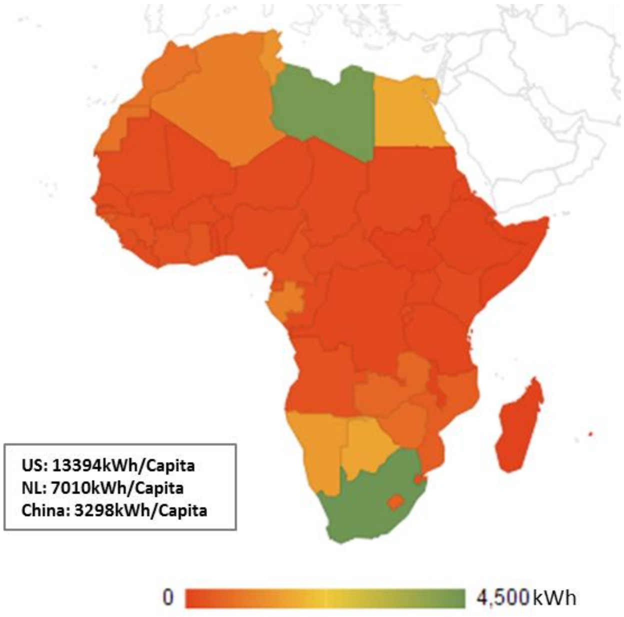

Fig. 3.2. Electricity per capita (KWh/year) per country (2010) [IRENA 2012, IEA 2014(I), World Bank 2015]

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[1] Although many studies simply refer to 'Africa' when discussing the energy poverty problems in the continent, in fact these problems are mainly limited to developing Sub-Saharan Africa and in a lesser degree to South Africa.

Power consumption per capita is woefully low for most African regions (fig. 3.3). Even in those regions where electricity is available, the amount of electricity generated is often not sufficient to meet demand. Even Libya and South Africa, with the highest power generation per capita, suffer from frequent black-outs [Foster 2009]. Electricity from the grid is characterized by losses, and transmission and distribution averages at 15-25% of output, compared to the 8-10% world average (fig. 3.4) [Wolde-Rufael 2005]. To remedy the lack of a reliable electricity grid, the commercial and industrial sector often rely on expensive and polluting diesel generators. Because of small networks lacking the benefits of scale, large generation losses and reliance on self-generation, typical electricity costs in Sub-Saharan countries are often more than double that of other developing countries [Eberhard et al. 2012]. For mobile-phone companies across West-Africa, electricity costs can represent up to 60% of total network costs [McKinsey 2015]. The economic cost of the poor performance of the electricity sector has been estimated at 2.1% of GDP in 2012 [IEA 2014(I)] and has reduced African per capita GDP growth by up to 0.2% per year over the decade 2000-2010 [Foster 2010]. Until electricity supply is widely accessible, reliable and affordable, economic growth in sub-Saharan Africa will most likely be restrained [Ebohon 1996].

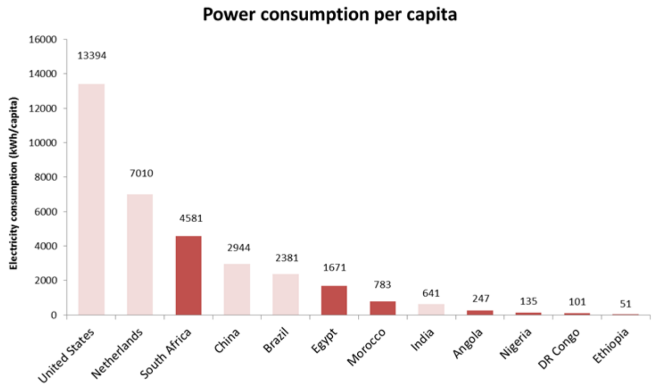


Fig. 3.3. Power Consumption per Capita (2010) [World Bank Database]

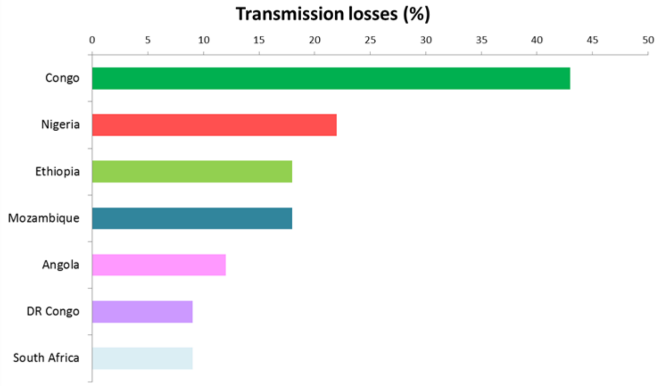


Fig. 3.4. Transmission losses for selected African countries (2010) Adapted from the [IEA 2014(I)]

Generation Capacity

The characteristics of the African power sector can best be understood when the continent is split into three distinctive regions, each with their own generation characteristics. An overview of generation capacity installed per country can be seen in figure 3.5. More details on capacity mix are found in section 5.3.3 and on electricity targets in appendix 3. Here generation capacity mix and the main electricity policies will shortly be discussed for North Africa, developing Sub-Saharan Africa and South Africa.

North Africa: All North African countries have reached near universal electricity access (99%) in the past decade. The amount of electricity generated per capita is low, leading to frequent blackouts and reliance on back-up generators. Most electricity is generated through domestic oil and gas, with only Morocco possessing no significant domestic fossil fuel reserves. Economic growth, population growth and urbanization are causing energy demand to rise rapidly [Brand 2011] and all countries aim to double their generation capacity between 2010 and 2030 [Climate Scope 2014, Stambouli 2011]. To meet demands A problem for renewables in the region are the high subsidies on electricity. Although these subsidies make electricity more accessible, they discourage private investment in the electricity sector as low electricity prices mean less return on investment for generation capacity. The subsidies are also a great burden on the government budget - in Egypt, the government spends up to 10.2% of GDP on subsidizing electricity [AfdB 2010]. Removing these subsidies is essential to establishing competitive renewable capacity.

Developing Sub-Saharan Africa: Nearly 70% of the population of developing sub-Saharan Africa lacks electricity access, compared to 5% and 9% for Latin America and developing Asia respectively. Population growth currently outpaces increased generation capacity, and the International Energy Agency (IEA) predicts that without intervention the absolute number of people in developing sub-Saharan Africa without electricity will increase from 600 million in 2010 to 635 million by 2030 [IEA 2014(I)]. Most sub-regions in Sub-Saharan Africa are reliant dominantly on hydropower, and as such essentially have large share of renewable electricity. Current installed capacity is extremely low, and it is expected that to meet electricity demand the share of fossil fuels will increase leading to a more emissions intensive grid [Collier 2013]. Noteworthy is also the relatively large share of oil based generation capacity in West Africa, installed during the low oil prices of the 1990s. Due to the long lifetime of generation capacity, this caused a lock-in on the expensive and emission intensive oil plants [IRENA 2012].

South Africa: Due to the large share of coal in its generation capacity, South Africa has one of the most emission intensive electricity sectors in the world [WRI 2011]. Most coal plants were installed in the eighties to establish rapid electrification and energy security during the Apartheid era [Winkler 2008] and have been a vital component of South Africa's economic development and poverty reduction over the past decades. Due to rising demand and transmission losses, South Africa has been suffering from rolling blackouts since 2005 [Krupa 2011, Fig 2015, Sebitosi 2008]. In recent years South Africa has begun to diversify its generation capacity, with small-scale investments in renewable energy and gas turbines as well as the establishment of feed-in tariffs. South Africa is the only country in Africa that currently possess nuclear power with two nuclear generators at Koeberg generating 5% of the country's electricity [Eskom 2015]. Many studies have been done, mainly by the Energy Research Center of the University of Cape Town, on the policy measures and technology that could be used to transition to a lower emission grid in [Pegels 2010, Sebitosi 2008, Winkler 2005, 2006, 2007, 2009]. These studies showed that the policies in currently in place – renewable subsidies, tax exemptions, reductions targets – and the proposed carbon tax are adequate to meet global targets but the execution of policies is lacking and targets are of a conditional nature [Climatescope 2014, Sebitosi 2008]. Without the implementation of policies it is expected that emissions will increase by 172% in 2030 from 1990 levels [Climate Action Tracker 2015].

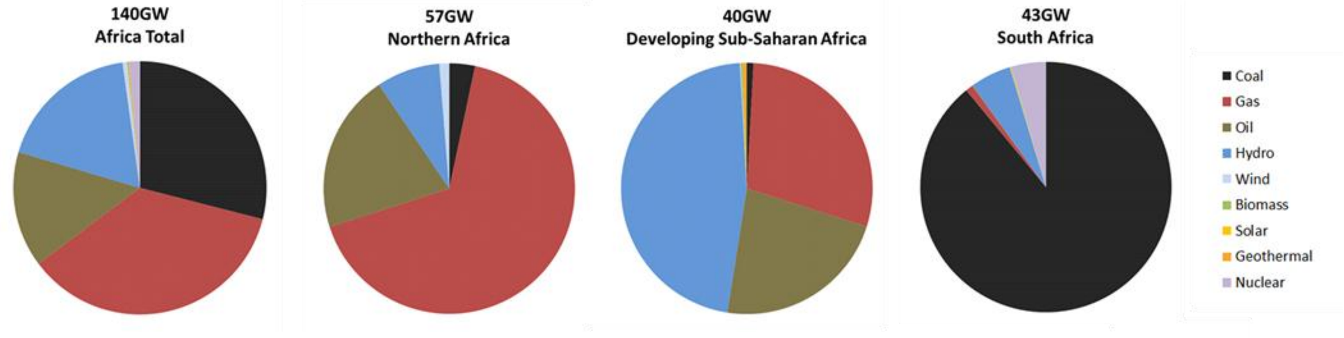


Fig. 3.5. Electricity Generation Mix for Africa (2010). Information from government reports, Platts and others (see section 5.3.3)

Resources

Africa has abundant, diverse and unexploited renewable and non-renewable energy resources that are yet to be used for improving the livelihood of the vast majority of the population. In recent years, Africa has slowly begun increasing exploitation of its resources, both for domestic use and for export. In 2013, Africa led the world in oil and gas discoveries and currently is believed to hold up to 9% of global oil reserves and 8% of global gas reserves [KPMG 2013, EIA 2012]. The main reserves lie in Northern Africa, Nigeria and Angola, but other nations such as Mozambique, Uganda, and Tanzania are now investing into exploiting their fossil fuels as well.

Africa's renewable potentials are the highest in the world [WEC 2013, IRENA 2012] and have the possibility to meet the continents entire current and future energy demand. The Democratic Republic of Congo alone harbors the world's third largest hydropower potential at an estimate 100'000MW, of which less than a percent is utilized currently. Along the Rift Valley there is a large geothermal potential for countries such as Kenya, Ethiopia and Djibouti [Kebede 2012, Moussa 2015, Simiyu 2008] and the solar potential of the Sahara has even been suggested as a potential exportable electricity source for Europe [Komendantove 2012, Trieb 2012, Ummel 2008]. In spite of this large renewable resource endowment, development of renewable capacity has been slow. This can be explained due to several factors, among which the high investment costs, abundance of fossil alternatives and low technical competence [Brew-Hammond 2009]. The continent's lack of electricity generation is not the result of a lack of natural resources - but rather the result of a range of economical, sociological and political issues [Szabo 2013]. More detail on resources potentials can be found in section 5.2.1.

3.2. Energy, Electricity and Development

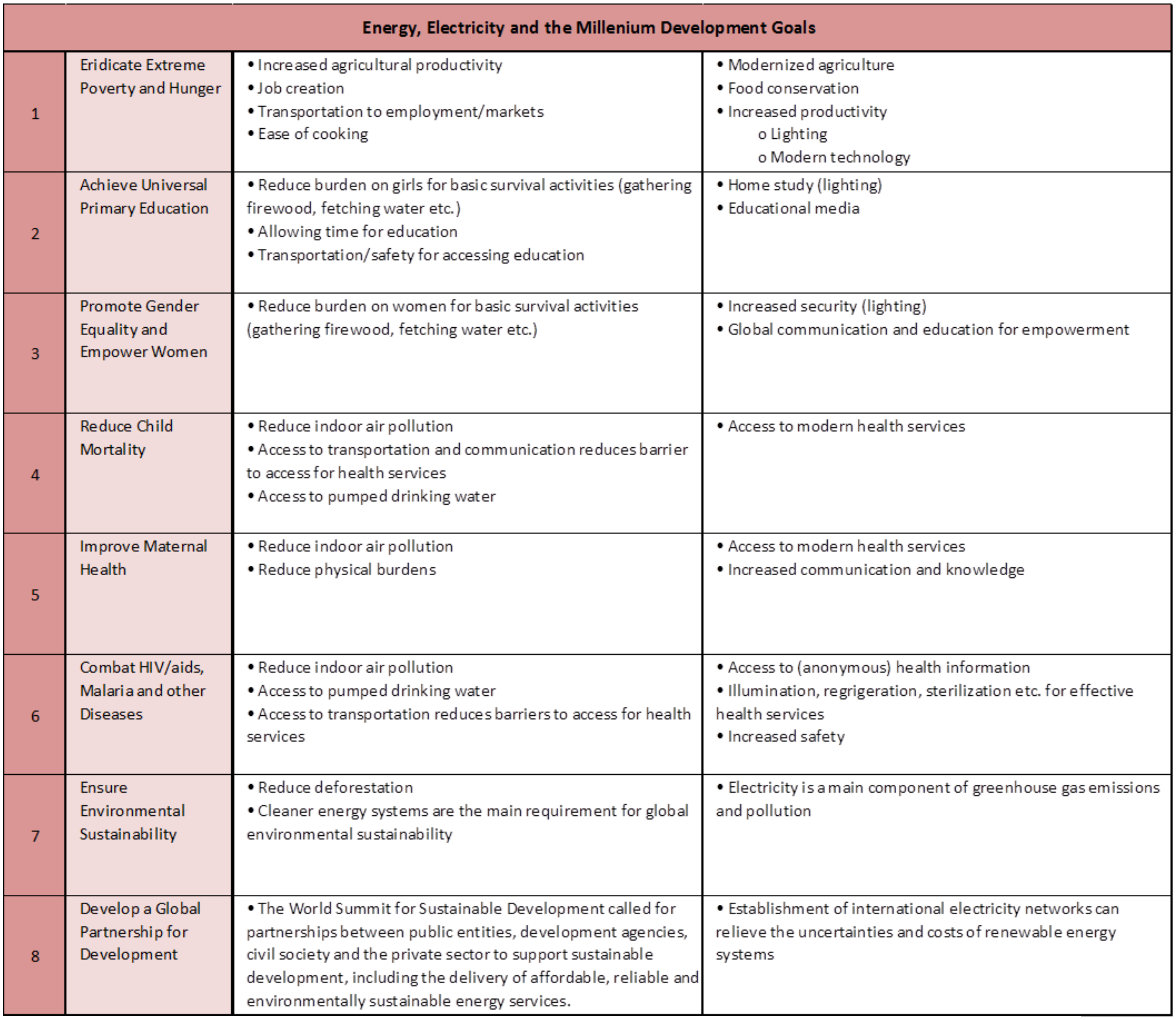
In recent years the alleviation of energy poverty has become one of the focal points of development efforts. In 2011, UN Secretary-General Ban Ki-moon launched the Sustainable Energy for All (SE4ALL) initiative, which set 2030 as the target year for achieving universal access to modern energy services [SE4ALL 2015]. The provision of reliable, secure and affordable energy services is central to addressing a range of development issues including education, poverty, inequality, women's rights and health. Reducing energy poverty plays an important role in fulfilling the Millennium Development Goals (MDG's) [Modi 2005, AGECC 2010, Karakezi 2012, UNDP 2005] although none of the MDG's mention energy explicitly. Table 1.1. provides an overview of the role of energy in achieving different MDG's. Due to its importance is likely that energy – and electricity – access will be an explicit part of the post-2015 MDG's [Brew-Hammond 2009].

The relation between economic development and electricity has proven to be even stronger than that between primary energy use and electricity [Ferguson 2002, Payne 2010] although most of the work on the relation between GDP and electricity use has been conducted for developed economies. Although most developed countries show a bi-directional causality between electricity use and GDP, Lee [2005] analyzed the economic and electricity data of 18 developing countries to demonstrate a unilateral short term causal relationship from energy consumption to GDP for developing regions. This indicates that for developing countries a high energy consumption would lead to high economic. Increasing energy access is vital to economic development in these countries. His views are supported by amongst others work on Malaysia by Chandran [2010], work on Tanzania by Odhiambo [2009] and Nigeria by Akinlo [2009]. However, there is still debate in the literature, especially for Least Developed Countries (LDC's) where either a unilateral causal relation between GDP and electricity consumption has been demonstrated [Jumbe 2004, Payne 2010] or no relation between electricity consumption and GDP at all [Wolde-Rufael 2006] This is likely due to a high dependence on small-scale agriculture in GDP, a sector relatively unaffected by electricity use, reducing the impact of electricity consumption on GDP creation.

Expansion of electricity networks has shown to be one of the most effective ways to increase long-term socio-economic development through its effects on productivity, education and access to the world system [Kanagawa 2008, Kaygusuz 2012]. Access to electricity greatly increases agricultural productivity through technologies such as irrigation, water pumping and post-harvest storage, and is vital in the shift from an agricultural to an industry-based economy [Kirubi 2009]. The effects of electricity on education are well documented [Barnes 2002, Lomofsky 2001] and include both direct effects such as increasing studying hours through availability of light and indirect effects such as reducing hours spend on housework allowing girls to attend school. Kanagawa [2008] documented that literary rates for household in the rural Indian province of Assam increased over 10% in the 5 years following electrification. Electricity also influences many other aspects of development, such as improving health facilities through access to refrigeration and increasing safety through street lighting [Haines 2007, Kanagawa 2007, UNDP 2005]. With increased technological development, the role of electricity is becoming even important. It has been shown that one of the first purchases in electrified households is a television

[Kebede 2010]. Access to a television allows for a drastic increase in access to information as well as entertainment and quality of life. Whereas the importance of electricity was before expressed in productivity increases, access to electricity has come to equal access into the modern world system [Rosenberg 1998].

It is widely accepted that if Sub-Saharan African countries are to pursue the sustained economic growth which is vital to social development and eradicating poverty, the availability of financially feasible, reliable and efficient supply of electricity is crucial [Turkson 2001]. Through the previously mentioned United Nations (UN) Sustainable Energy for All (SE4ALL) initiative 2030 has been set as the year for achieving universal access to modern energy services, defined in an electricity access target of 250-500kWH/year per household [SE4ALL 2015]. The Power Africa initiative of the United States Development Council has pledged to install 30GW of generation capacity throughout Sub-Saharan Africa by 2030 [USAID 2015]. Finally, energy access has made its way to a broader public discussion, both in business publications such as the McKinsey ‘Powering Africa ’report [2015] focused on the electricity sector and in the media such as the Economist (i.e. ‘A Brightening Continent’ [2015], ‘Lighting a Dark Continent’ [2014] ‘Eastern El Dorado?’ [2012]) .



Energy, Electricity and the Millenium Development Goals			
1	Eridicate Extreme Poverty and Hunger	• Increased agricultural productivity • Job creation • Transportation to employment/markets • Ease of cooking	• Modernized agriculture • Food conservation • Increased productivity o Lighting o Modern technology
2	Achieve Universal Primary Education	• Reduce burden on girls for basic survival activities (gathering firewood, fetching water etc.) • Allowing time for education • Transportation/safety for accessing education	• Home study (lighting) • Educational media
3	Promote Gender Equality and Empower Women	• Reduce burden on women for basic survival activities (gathering firewood, fetching water etc.)	• Increased security (lighting) • Global communication and education for empowerment
4	Reduce Child Mortality	• Reduce indoor air pollution • Access to transportation and communication reduces barrier to access for health services • Access to pumped drinking water	• Access to modern health services
5	Improve Maternal Health	• Reduce indoor air pollution • Reduce physical burdens	• Access to modern health services • Increased communication and knowledge
6	Combat HIV/aids, Malaria and other Diseases	• Reduce indoor air pollution • Access to pumped drinking water • Access to transportation reduces barriers to access for health services	• Access to (anonymous) health information • Illumination, regrigeration, sterilization etc. for effective health services • Increased safety
7	Ensure Environmental Sustainability	• Reduce deforestation • Cleaner energy systems are the main requirement for global environmental sustainability	• Electricity is a main component of greenhouse gas emissions and pollution
8	Develop a Global Partnership for Development	• The World Summit for Sustainable Development called for partnerships between public entities, development agencies, civil society and the private sector to support sustainable development, including the delivery of affordable, reliable and environmentally sustainable energy services.	• Establishment of international electricity networks can relieve the uncertainties and costs of renewable energy systems

Table 3.1. The role of Energy and Electricity in fulfilling the Millennium Development Goals. Compiled by author.

For in-depth information on these topic the reader is referred to:
Energy Access & Education: Barnes [2002], Lomofsky [2001], Sathaye
Energy Access & Poverty: Khandker [2012], Pachauri [2004]
Energy Access & Gender Equality: Ceceliski [2004], Clancy [2002], Fatona [2013], Köhlin [2011]
Energy Access & Health: Haines [2007], Smith [2009]
MDG’s: UN [2000], UNDP [2004], Modi et al. [2005]

3.3. Electricity, Development & Climate Change

In the past decades, global electricity consumption has increased exponentially – and with it, the emissions of greenhouse gasses causing climate change. In order to mitigate climate change below the two degree warming target set in Cancun, greenhouse gas emissions will have to be drastically reduced on a global scale [IPCC 2014]. Mitigation discussions have primarily focused on developed countries, but the importance of developing and emerging economies is rising. In recent years emissions from emerging economies and developing economies have increased rapidly, reaching 50% of all emissions in 2008. Under a business as usual scenario developing countries are expected to contribute up to 85% of global emissions in 2100 [IPCC 2014, MIT 2014]. There is a significant difference in the energy policy agendas of industrialized and developing nations. Whilst industrialized countries mainly focus on the negative impacts of energy use (climate change, pollution), developing countries focus primarily on the positive effects of increased energy access [Birol 2007, 2014, van Ruijven 2008]. Global climate policy can only be effective if it connects to the policy agenda of developing countries [Metz and Kok 2008]. The role of developing countries was recognized during the Conference of the Parties (COP) on Climate Change in Lima last year, where it was stated that countries bear '"common but differentiated responsibilities and respective capabilities in light of different national circumstances" with regards to mitigation and adaptation.

Even more than other developing regions, Africa has mostly been overlooked in climate change mitigation discussions. After all, it is currently only a small contributor to the global greenhouse gas emissions. In 2012, Africa produced 4% of global carbon dioxide (CO_2) emissions, with Sub-Saharan Africa accounting for a mere 1% of global emissions [IEA 2014(I)]. Emissions are low due to both low economic activity and low access to modern fuels and electricity. In 2010, Africa produced only 4.7% of global GDP and consumed 3.3% of global final energy whilst being home to more than 15% of global population (table 3.2) . If Africa however achieves its targets for energy access, emissions could exponentially increase, as observed in other developing regions such as China and Brazil in the last decades [MIT 2014]. Based on economic activity and population growth dynamics, Calvin et al. [2014] found that Africa could account up to 20% of global emissions by 2030 if growth is achieved with equal emission intensity, up from 4% currently. It must be said that extrapolating current emission intensity for Africa is likely to overestimate future emissions, as this projection is heavily influenced by the emission intensive energy use in South Africa.

	Population in Millions	% of global population	Final Energy Use in 10^{15} btu	% of global final energy
Africa	1080.9	15.3%	17335	3.31%
North Africa	168.7	2.39%	7433	1.42%
Sub-Saharan Africa	912.2	13.0%	9902	1.89%
Developing Sub-Saharan Africa	911.5	12.9%	4224	0.81%
South Africa	73.6	0.01%	5678	1.08%
Rest of the World	5951	84.7%	506665	96.69%
World (Total)	7 032	100%	524000	100%

Table 3.2. Energy use as share of global energy use for the different African regions. Based on the World Bank indicators database.

Electricity generation is one of the most energy and emission intensive industries, representing 14% of global primary energy use and 37% of global CO_2 production [IEA 2015]. Low electricity generation capacity is one of the main reasons for the low CO_2 emissions of many sub-Saharan countries [IPCC 2014]. Many analysts and policy makers have taken the current low modern energy use and CO_2 emissions as an indication that the future environmental impact of African generation capacity is not a significant concern for the global system [UNDESA 2004]. This view ignores the facts that rapid electrification is possible, and that it is likely that this electrification will occur through use of low-cost fossil fuel generation [Collier 2013]. As generation capacity has a long life time – up to 40 years – any emission intensive installments made now will affect the future for a long time. Curbing emissions from electricity generation in developing countries is necessary to reach any ambitious climate goal [IPCC 2011]. The goal of increased electricity access will therefore have to be reconciled with the need for reduced CO2 emissions [Deichman 2011].

3.4. Leapfrogging

The absence of generation capacity has also been viewed as an opportunity for Africa to develop while benefitting from the global shift to sustainable electricity generation. Renewable electricity could contribute to expanding electricity access without drastically increasing GHG emissions. It is not surprising that the provision of renewable electricity to developing economies is one of the main pillars in many energy access initiatives [SE4ALL 2015, USAID 2015, Energy+ 2015]. In many cases renewable electricity is promoted ahead of other generation capacity options with a lower cost of electricity (LCEO). The promotion of renewables is based on the assumption that due to the absence of a conventional energy grid and the high renewable potential in many regions renewable technologies have a greater chance to succeed in Africa, with some studies finding renewable generation to be near economically competitive with fossil generation [Backer-McKenzie 2013, IRENA 2012, Onyeji 2014] .

Several studies have stated that Africa could circumvent a fossil fuel dominant electricity grid altogether, and immediately transition into a low-emission grid [Deichman 2012, Sebitosi 2010]. This skipping of a stage of development is often referred to as ‘leapfrogging’. The idea that Africa can ‘leapfrog’ with regards to electricity generation has been a recurrent theme in literature for several decades [Acker 1996, Karakezi 1994]. Western economies are hampered in their installment of renewable capacity by the large investments done into conventional electricity infrastructure in the past, leaving them essentially ‘locked-in’ to a fossil fuel intensive grid. As Africa has not yet established conventional electricity generation in many regions they would benefit from a ‘late-comer’ advantage and would be able to install renewables relatively easy. This advantage has indeed been observed in the rapid growth of mobile phone technology and internet banking in Africa, both of which have observed a growth rate of 30% per year – far exceeding those of Western nations when adopting the same technologies [Aker 2010, Beck 2013].

Despite the focus on the potential for leapfrogging in the literature, research on how to reach this ideal scenario have been woefully absent. The statement that renewables are competitive in Africa has yet to be researched for different technologies, regions and timeframes. The least-cost mix of renewable and conventional power will depend on the relative costs of locally available energy sources [Parshall 2009] and will differ per region [Sokona 2012]. Even if renewables are not currently competitive, relative costs may be strongly affected by international measures to reduce carbon emissions, including international markets for carbon or low-carbon-energy credits and/or carbon taxes that will be instated in the near future. Few studies have analyzed the effectivity of mitigation instruments and incentive mechanisms in promoting the development of renewable electricity in African nations [Thiam 2011] and none for regions other than South Africa or the North African countries. From modeling exercises in other developing regions several interesting conclusions are found. Research on the use of different mitigation strategies in China and India showed that a carbon tax would show neglible emission reduction against a cost of at least several percent of GDP [Massetti 2011, Fang 2013] while mitigation targets or emissions ceilings at a future point would lead to postponing emission reduction until '*better technologies were available*' . The high discount rate inherent in energy and emission decisions increased the reliance on future zero and negative carbon emission technologies to reduce emissions drastically toward 2050, with potential high future costs [Saveyn 2012]. Such in depth modelling exercises have not been undertaken for Africa.

The implications of carbon mitigation schemes differ widely depending on the status of development, the primary energy structure, the economic structure and other factors of the country in question as demonstrated by Winkler [2002] for different developing regions (i.e. China, India, Brazil, South Africa, Argentina, Nigeria). The great differences between African regions will lead to different options and costs of technologies and the costs of mitigation will vary across regions. This will influence the choices regarding mitigations that will be made in the coming decades [Collier 2012] and it is to be expected that there will be marked differences in regional development and choices of mitigation options over the next century. A closer look at the responses of different African regions to different mitigation scenarios could give a first indication of the effectiveness and cost of possible policy pathways for different African regions. This thesis is aimed at possible future generation capacity development and costs under different carbon mitigation and demand scenarios, to gain more insight into the issues regarding African generation capacity development and start a further discussion. We simplify the analysis by modeling the premium value for low-carbon energy as being determined by a hypothetical carbon tax applied to domestic fossil fuel generation uses [Deichman 2011]. It is realized that the mitigation scenarios in this thesis are too costly for African nations to implement without outside support – however, they provide a good proxy to research the relative costs and possibilities for mitigation in different regions.

Chapter 4: *Methodology*

The effect of mitigation scenarios and African generation capacity development was conducted with the TIAM-ECN model, an integrated assessment simulation model that was further expanded for this study. For each scenario, TIAM-ECN optimizes for the most cost-effective technology deployment. It is a data-intensive model, and includes detailed inputs for e.g. resource potential, technologies and demand structure. Due to its flexibility and date-intensive structure this type of model is particularly suited to research the new African sub-regions. In this chapter firstly the background of Integrated Assessment models will be discussed, followed by an in-depth description of the TIAM-ECN model. In section 4.3 an overview is given of the scenarios used, and finally in section 4.4. the division of Africa into the different sub-regions used in the model is explained.

4.1. Integrated Assessment Models

Little is known about pathways for African electricity and emission development. Models allow for a coordinated exploration of the possible trajectories of system development under different policies, modeled as different scenarios. Scenario modelling can provide important insights into possible electricity and mitigation development pathways and the economic costs of these pathways [IPCC 2013]. Different policies can be modeled as constraints to the model solutions. Energy models are used to research and explore possible future scenarios for the global energy system.

Energy and climate change are interdisciplinary problems, interlinked with the environment, industry and economy. In order to research these topics interdisciplinary models are needed. Integrated assessment models (IAM's) have become the most common tool for assessing climate change policy options, including strategies for the global energy systems [Kelly 1999]. IAM's describe the complex relations between economic, social and environmental factors in order to assess different climate policy options (figure 4.1). They do so by modeling the entire causal chain of climate policies from socio-economic drivers to physical impacts, including feedback loops [van der Sluis 1997, van Ruijven 2008]. In doing so, IAM's provide insights that would not be possible by focusing on any of the parts of the causal chain in isolation. An extensive overview of the theory behind IAMs can be found in Kelly [1999].

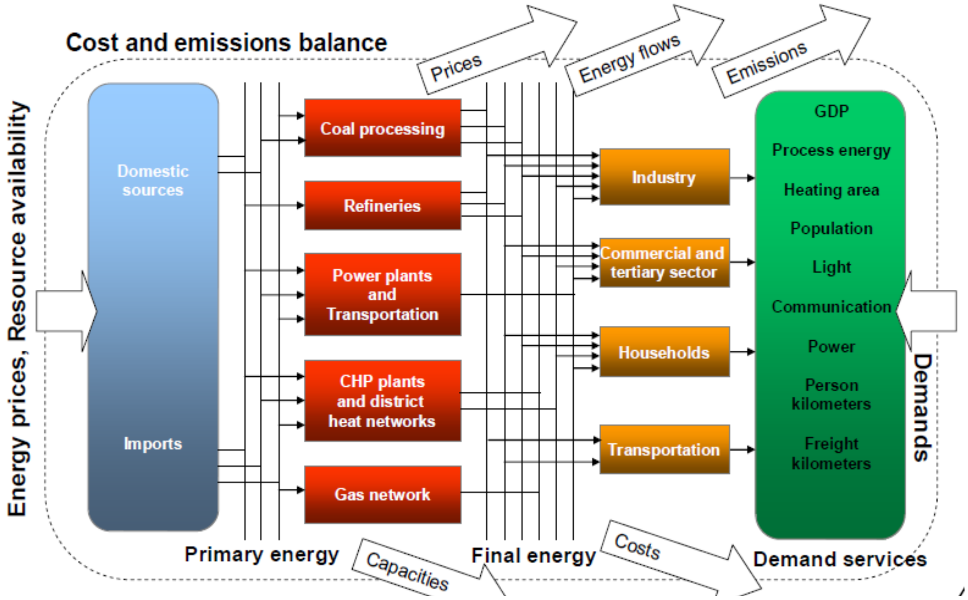


Fig. 4.1. Example of the Energy System in Integrated Assessment Models. Taken from Blesl & Remme [2008]

The Advantages of a Global Model

For this thesis we chose to use a global model instead of using a model encompassing only Africa. The model includes 36 regions of which we analyzed the 17 African regions. African electricity grids have also been researched on a national scale as discussed in section 3.6. National models can offer a insights into the functioning of a local electricity grid and provide a detailed view of the energy system. However, they ignore global economic developments and trade between (sub)regions, which are important in energy development. A global model allows sub-regions to respond to changes in other regions and on a global scale.

A global model:

- Can distinguish between policies that are applied to sub-regions, regions or globally
- Can evaluate local responses to global and regional energy policies
    - Abatement costs
    - Resource prices
    - Technology Deployment
- Contains global endogenous technology learning
- Contains trade between sub-regions

Global models also have their disadvantages. Models become increasingly complex, uncertain an time-consuming as the number of regions in the model increases. Each region requires its own database of technologies, trade, energy balances and resources. The trade between countries, especially future trade, adds additional uncertainty. Finally, the total energy system will be less specialized in a global model than in a national or local model. Global and national models should be seen as complementary tools and their results can be combined for greater insight. Some IAM's are already soft-linked with national models [Martinsen 2011, van der Broek 2011] and this could also be a future option for the TIAM-ECN model.

4.2. TIAM-ECN Description

A large range of IAM's exists, each with their own specializations. The IAM used for this thesis is the TIAM-ECN model, an ECN adaptation on the original ETSAP-TIAM model [Loulou 2008(I), 2008(II)]. TIAM, or the TIMES Integrated Assessment model, is a model for estimating the regional and global effects of greenhouse gas mitigation policies. It quantifies the effect of these policies in terms of CO_2 reduction, the deployment of different energy technologies, as well as the resulting costs. Model inputs include macro-economic scenarios, mitigation standards, assumptions on technology development and trade restrictions. The TIAM-ECN model includes several modifications, additions and simplifications to the original TIAM model such as an updated input on long term emissions abatement data and further aggregation of sectoral and technological details. While the original TIAM model incorporated 15 regions, TIAM-ECN was expanded to include 20 regions as shown in figure 4.2. For this research an additional 17 regions were added to the model by expanding the original Africa region into 17 separate parts, which from here-on will be referred to as the African sub-regions. More detail on the sub-regional division can be found in section 4.4.

TIAM-ECN is a bottom-up linear optimization model describing the entire energy system from resource extraction to final energy use over a timespan of around a hundred years [Loulou 2005, Syri 2008]. It is both a technology specific and a technology rich model. This makes TIAM-ECN particularly suited for researching energy policies, as technological transitions are explicitly represented [Keppo 2012]. Another benefit of using the data-driven TIAM model is that the model can be adapted to a large extend by changing data in datasheets, without having to rewrite the underlying code. The model and the datasheets are linked through VEDA, a set of tools that allows data to be fed into excel sheets, upon which VEDA provides the input to the TIMES code.

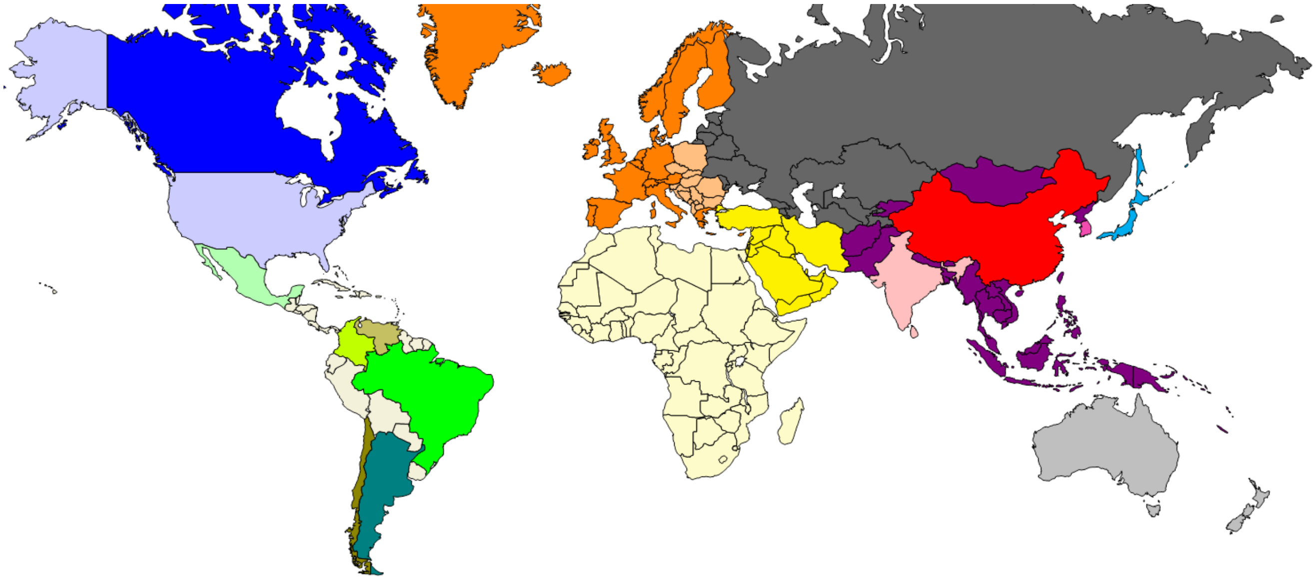


Fig. 4.2. Regions in the original TIAM-20 model. Internal ECN Use

TIAM-ECN is a linear programming model that minimizes its objective function - the total aggregated discounted costs – under the specified constraints over the entire time horizon and for all regions [van der Zwaan 2012]. In this way the TIAM-ECN model identifies the least-cost pathway to satisfy projected energy demand through different fuel options. The model encompasses five end-use sectors for energy demand (industry, electric, residential (including commercial and agriculture), upstream and transport) with a detailed technological representation of each sector, covering several hundred technologies. A simplified structure of the reference energy system in TIAM-ECN can be seen in figure 4.2. The dynamic part of a model is determined by the evolutionary development of supply and technologies and socio-economic drivers such as GDP growth, population growth and sectoral outputs [Rosler 2013, Anandarajah 2011]. Fuel to satisfy energy demands can either come from domestic resources or from trade. Trade of energy stocks is allowed where there are established trade-links input into the model. For all trade-links a maximum and a minimum trade volume are defined. An extensive overview of demand and supply data input into the model can be found in Chapter 5. The outcomes of the TIAM-ECN model are i.e. the deployment of different energy technologies, cost of energy, cost of CO_2 and CO_2 mitigated depending on the input scenarios [Loulou 2007] .

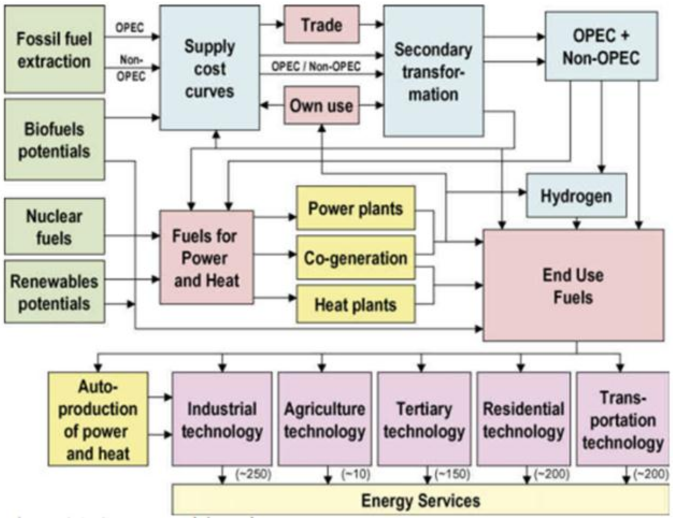


Fig. 4.3. Structure of TIAM-ECN model. Internal ECN Use

4.2.1. Technologies

The TIAM-ECN 36 model incorporates ten generation capacity technologies that can be deployed to meet electricity demand: Coal power plants, Coal power with carbon capture and storage (CCS), Natural Gas/Oil Combined Cycle power plants (NGCC), NGCC with CCS, Nuclear light water reactor, Hydropower, Solar PV, Solar CSP, Wind power onshore, Wind power offshore, Geothermal plants and Biogas plants. These technologies were taken from the original TIAM-ECN model. More information on each technology is shown in table 4.2. The CO_2 capture rate was based on previous ECN research. The levelized cost of electricity (LCOE) is calculated based on total costs of generation capacity, efficiency, lifetime and availability. A simplified version of the calculation is shown in eq. 4.1 where I stands for the investment costs, OM the annual operation and management costs, f the fuel costs, η the efficiency, t the plant lifetime, P the net rated output and H the availability in annual operating hours. All values except availability were taken from the TIAM-20 Africa region and not adapted. Where data was available, availability of both fossil fuel and renewable capacity was adapted per sub-region (table 4.1). Where data was not available, the average value for Africa was taken. It is recognized that the availability estimations for PV is optimistic and not realistic for most African sub-regions. However, due to integration with other ECN research this data could not be adapted at this time. The load factor for geothermal plants in Africa is relatively low, as the majority of the geothermal potential comes from deep saline aquifers. The properties of these aquifers require frequent maintenance of equipment resulting in a lower load factor [Nyakabwa-Atwoki 2013].

$$\text{Eq. 4.1: } LCEO = \sum_0^t \frac{I+(OM+\frac{f}{\eta})_t}{(P*H)_t}$$

The costs of the different technologies, their lifetime and their availability were based on the IEA Renewable Energy Costs [2014] report, the McKinsey 'Brighter Africa' report [2015], WEC [2013(I)] and the World Energy Outlook [2014] tables. It should be noted that the costs for fossil fuel generation capacity are specific for the African regions – and often higher than in other regions – whilst it was chosen to set a global (model-wide) price for renewables. This was done as renewables still have a strong learning and scaling curve, and that more development in other regions will directly influence the price in African sub-regions. The model adds capacity in a linear fashion; in other words, capacity is not added as realistic units of a certain capacity size (power plants). Instead the model can choose to install i.e. a single GW of coal or solar PV. Restricting the size of added capacity would increase the model to a point of complexity not possible for this model.

Full Load Hours (h/yr)		Coal	Gas	Fuel Oil	Hydro-Power	Wind-Power Onshore	Wind-Power Offshore	Biomass	Solar PV	Solar CSP	Geothermal	Nuclear
African Average		7900	7900	7900	5300	2000	3700	7900	2500	5300 (with storage)	7900	7900
Adapted Values	MAR	x	x	x	x	2708	x	x	1650	3400 (without storage)	x	x
	DZA	x	x	x	x	1789	x	x	1700	3500 (without storage)	x	x
	TUN	x	x	x	x	1789	x	x	1650	3300 (without storage)	x	x
	LBY	x	x	x	x	1912	x	x	x	x	x	x
	EGY	x	x	x	x	3015	x	x	x	x	x	x
	AWE	x	x	x	x	x	x	x	x	x	x	x
	NGA	x	x	x	x	x	x	x	x	x	x	x
	ACE	x	x	x	x	x	x	x	x	x	x	x
	AEA	x	x	x	x	x	x	x	x	x	x	x
	ETH	x	x	x	x	x	x	x	x	x	7539	x
	KEN	x	7512	7634	5511	x	x	x	x	x	7977	x
	COD	x	x	x	6136	x	x	x	x	x	8152	x
	AGO	x	x	x	x	x	x	x	x	x	x	x
	ASE	x	x	x	x	x	x	x	x	x	x	x
	ASO	x	x	x	x	x	x	x	x	x	x	x
	MDG	x	x	x	x	x	x	x	x	x	x	x
	ZAF	7500	x	x	x	2239	x	x	2263	3202 (without storage)	x	x

Table 4.1. Full load hours average and adapted per sub-region and technology. Each x means there was no information available for the sub-region, and hence the average value was taken. Data from CDM [2012], EWI [2010], Huber [2012, IEA [2014(I)] PV-insider [2014], UNDP [2013], UNEP [2007].

Conventional Coal Plant		2010	2020	2030	2050
Invest costs	[USD(2005)/kW]	1470	1470	1470	1470
Fixed O&M	[USD(2005)/kW]	53	53	53	53
Variable O&M	[USD(2005)/MWh]	0.2	0.2	0.2	0.2
Efficiency		41%	42%	43%	43%
CO2 capture rate		0%	0%	0%	0%
Lifetime	[years]	40	40	40	40
Availibility (average)	[hours per year]	7900	7900	7900	7900
CO2 emission factor [kg/MWh]		736	720	698	698
LCOE [USD(2005)/MWh]		65	64	63	63

Conventional Pulverized Coal with CCS		2010	2020	2030	2050
Invest costs	[USD(2005)/kW]		2520	2020	2020
Fixed O&M	[USD(2005)/kW]		88	71	71
Variable O&M	[USD(2005)/MWh]		0.2	0.2	0.2
Efficiency			30%	31%	31%
CO2 capture rate			85%	85%	85%
Lifetime	[years]		40	40	40
Availibility (average)	[hours per year]		7900	7900	7900
CO2 emission factor [kg/MWh]			149	145	145
LCOE [USD(2005)/MWh]			100	89	89

Gas/Oil Combined Cycle (NGCC)		2010	2020	2030	2050
Invest costs	[USD(2005)/kW]	610	610	610	610
Fixed O&M	[USD(2005)/kW]	21	21	21	21
Variable O&M	[USD(2005)/MWh]	0.1	0.1	0.1	0.1
Efficiency		58%	59%	60%	60%
CO2 capture rate		0%	0%	0%	0%
Lifetime	[years]	35	35	35	35
Availibility (average)	[hours per year]	7900	7900	7900	7900
CO2 emission factor [kg/MWh]		336	330	323	323
LCOE [USD(2005)/MWh]		63	62	61	61

NGCC with CCS		2010	2020	2030	2050
Invest costs	[USD(2005)/kW]		1260	1110	1110
Fixed O&M	[USD(2005)/kW]		37	32	32
Variable O&M	[USD(2005)/MWh]		0.2	0.2	0.2
Efficiency			47%	49%	49%
CO2 capture rate			85%	85%	85%
Lifetime	[years]		35	35	35
Availibility (average)	[hours per year]		7900	7900	7900
CO2 emission factor [kg/MWh]			57	54	54
LCOE [USD(2005)/MWh]			84	78	78

Advanced Nuclear Light Water Reactor		2010	2020	2030	2050
Invest costs	[USD(2005)/kW]	3150	2960	2390	2390
Fixed O&M	[USD(2005)/kW]	42	42	42	42
Variable O&M	[USD(2005)/MWh]	0.4	0.4	0.4	0.4
Efficiency		100%	100%	100%	100%
CO2 capture rate		0%	0%	0%	0%
Lifetime	[years]	40	40	40	40
Availibility (average)	[hours per year]	7900	7900	7900	7900
CO2 emission factor [kg/MWh]		0	0	0	0
LCOE [USD(2005)/MWh]		82	78	66	66

Generic Large-Scale Hydropower		2010	2020	2030	2050
Invest costs	[USD(2005)/kW]	1990	2180	2530	2530
Fixed O&M	[USD(2005)/kW]	46	51	59	59
Variable O&M	[USD(2005)/MWh]	0.3	0.3	0.3	0.3
Efficiency		100%	100%	100%	100%
CO2 capture rate		0%	0%	0%	0%
Lifetime	[years]	80	80	80	80
Availibility (average)	[hours per year]	5300	5300	5300	5300
CO2 emission factor [kg/MWh]		0	0	0	0
LCOE [USD(2005)/MWh]		50	55	63	63

Solar PV		2010	2020	2030	2050
Invest costs	[USD(2005)/kW]	3180	1960	1610	1260
Fixed O&M	[USD(2005)/kW]	22	20	19	19
Variable O&M	[USD(2005)/MWh]	0.0	0.0	0.0	0.0
Efficiency		100%	100%	100%	100%
CO2 capture rate		0%	0%	0%	0%
Lifetime	[years]	20	20	20	20
Availibility (average)	[hours per year]	2500	2500	2500	2500
CO2 emission factor [kg/MWh]		0	0	0	0
LCOE [USD(2005)/MWh]		159	101	84	67

CSP (molten salt tower) with 7-10h storage		2010	2020	2030	2050
Invest costs	[USD(2005)/kW]	7650	4970	4080	3820
Fixed O&M	[USD(2005)/kW]	165	108	88	88
Variable O&M	[USD(2005)/MWh]	0.0	0.0	0.0	0.0
Efficiency		100%	100%	100%	100%
CO2 capture rate		0%	0%	0%	0%
Lifetime	[years]	30	30	30	30
Availibility (average)	[hours per year]	5300	5300	5300	5300
CO2 emission factor [kg/MWh]		0	0	0	0
LCOE [USD(2005)/MWh]		185	120	98	94

On-Shore Wind		2010	2020	2030	2050
Invest costs	[USD(2005)/kW]	1350	1320	1300	1200
Fixed O&M	[USD(2005)/kW]	26	24	23	20
Variable O&M	[USD(2005)/MWh]	0.0	0.0	0.0	0.0
Efficiency		100%	100%	100%	100%
CO2 capture rate		0%	0%	0%	0%
Lifetime	[years]	25	25	25	25
Availibility (average)	[hours per year]	2000	2000	2000	2000
CO2 emission factor [kg/MWh]		0	0	0	0
LCOE [USD(2005)/MWh]		58	57	55	51

Off-Shore Wind		2010	2020	2030	2050
Invest costs	[USD(2005)/kW]	3900	2900	2630	2100
Fixed O&M	[USD(2005)/kW]	75	69	63	50
Variable O&M	[USD(2005)/MWh]	0.0	0.0	0.0	0.0
Efficiency		100%	100%	100%	100%
CO2 capture rate		0%	0%	0%	0%
Lifetime	[years]	20	20	20	20
Availibility (average)	[hours per year]	3700	3700	3700	3700
CO2 emission factor [kg/MWh]		0	0	0	0
LCOE [USD(2005)/MWh]		143	110	100	80

Solid Biomass Gasification		2010	2020	2030	2050
Invest costs	[USD(2005)/kW]	2410	2410	2220	2220
Fixed O&M	[USD(2005)/kW]	92	92	85	85
Variable O&M	[USD(2005)/MWh]	0.2	0.2	0.2	0.2
Efficiency		43%	45%	47%	47%
CO2 capture rate		0%	0%	0%	0%
Lifetime	[years]	30	30	30	30
Availibility (average)	[hours per year]	7900	7900	7900	7900
CO2 emission factor [kg/MWh]		0	0	0	0
LCOE [USD(2005)/MWh]		84	83	77	77

Geothermal		2010	2020	2030	2050
Invest costs	[USD(2005)/kW]	4000	3800	3610	3260
Fixed O&M	[USD(2005)/kW]	100	95	90	81
Variable O&M	[USD(2005)/MWh]	0.0	0.0	0.0	0.0
Efficiency		20%	20%	20%	20%
CO2 capture rate		0%	0%	0%	0%
Lifetime	[years]	35	35	35	35
Availibility (average)	[hours per year]	7400	7400	7400	7400
CO2 emission factor [kg/MWh]		0	0	0	0
LCOE [USD(2005)/MWh]		69	65	62	56

Table 4.2. Technology specifics for the TIAM-ECN model. Data from the previous TIAM-ECN model, the World Energy Outlook [2014], IRENA [2014].

4.2.2. Demand drivers

Future energy demands are determined by exogenous socio-economic demand drivers, such as i.e. GDP, GDP-capita, population, and household size. Different energy services have different demand drivers (table 4.3). These drivers are either obtained externally, via sources used for other integrated assessments such as the UNDP, or through extrapolation of current trends. Each demand is linked to its driver in the following manner:

$$\text{Eq. 4.2: } DM_i(t) = DM_i(2010) \cdot \Delta DR_i^{E_i}$$

where DM is the energy demand, DR the demand driver, and E the elasticity of the demand to its driver. Each demand currently has a single demand driver, as correlations between drivers and demands are not well defined for Africa. The elasticities are taken from the old total Africa region, and adapted for the different sub-regions. For sub-regions with low energy access elasticities were assumed to be large in the next decades as demand is expected grow rapidly as the population gains access to modern energy sources and commodities. Elasticities also depend on climate, as it is expected that certain demands such as heating, drying and hot water will be lower than average in Sub-Saharan whilst the demand for cooling in North Africa is suspected to grow faster than average. The transport sector energy demand is also expected to grow rapidly. Currently the number of vehicles per population is low – less than 5 passenger cars per 1000 people for developing Sub-Saharan Africa [World Bank 2015]. This number is expected to rise rapidly with increased wealth and expansion of the road network. Finally, rail transport is not available in most Sub-Saharan countries and is very limited in North Africa. Since development of rail transport has a long lead time, truck use is expected to increase faster than average.

GDP

GDP prediction for the African sub-regions are especially uncertain, as the most sub-regions are in a phase of high growth and political instability. The GDP projections for the model are based on the lower growth values of the AfdB projections [2015]. The lower values were chosen as in the high growth trajectory Africa approach Western European GDP values by 2060, which seems unlikely especially when compared to the GDP projection of McKinsey [2015] and the IEA [2014(I)] to 2040. Figure 4.4. gives the projected GDP for different African regions under the AfdB lower growth scenario.

Population

Population growth plays a large factor in global energy demand. Population growth in Africa is larger than any other continent [UNDP 2014]. UNEP publishes population forecasts for all countries until 2100. For Africa these forecasts indicate a tripling of the population between 2000 and 2050 with some regions like East Africa and Nigeria experiencing even more rapid growth. Expected population growth per region is shown in figure 4.3. As population currently outpaces generation capacity growth, it is expected that there will be more Africans without electricity access in 2030 than there are today [IEA 2014(I)].

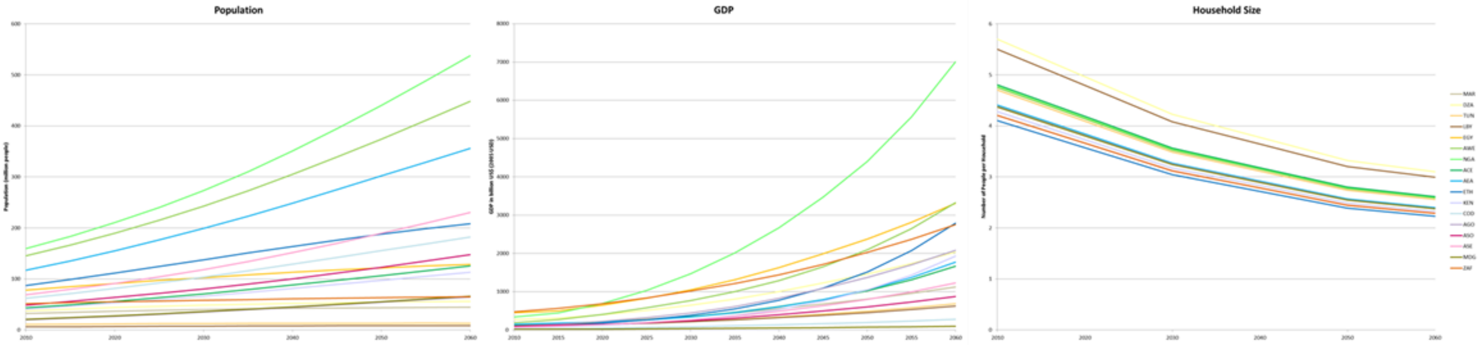
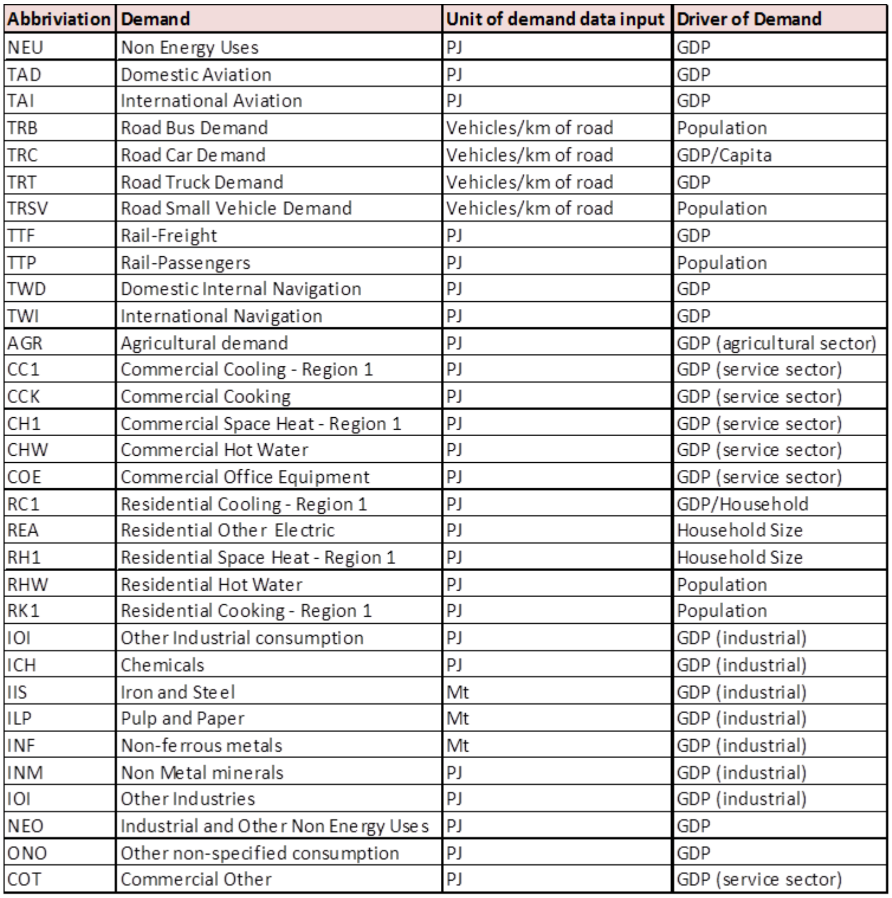


Fig. 4.4. Extrapolation of the main demand drivers per region until 2060.

Household Size

Average household size, or the amount of people that inhabit a housing unit, is of large influence on electricity demand as many electric appliances are organized in one appliance per household. Reduced household size thus leads to an increase in electricity use. In Africa, household sizes are still relatively large, varying slightly from 5 and 7 people on average per household, compared to 2.5 for European or American household [Giuliano 2007]. With increasing wealth and modernization, household size tends to decrease. This has been observed in most Western and Asian economies over the past century [Bongaarts 2001]. For the model, household size was extrapolated based on the most recent annual decrease and on historical trends observed in other regions. For Islamic countries, the decrease was slower than in other sub-regions, as they traditionally tend to have larger household sizes [Bongaarts 2001].



Abbriviation	Demand	Unit of demand data input	Driver of Demand
NEU	Non Energy Uses	PJ	GDP
TAD	Domestic Aviation	PJ	GDP
TAI	International Aviation	PJ	GDP
TRB	Road Bus Demand	Vehicles/km of road	Population
TRC	Road Car Demand	Vehicles/km of road	GDP/Capita
TRT	Road Truck Demand	Vehicles/km of road	GDP
TRSV	Road Small Vehicle Demand	Vehicles/km of road	Population
TTF	Rail-Freight	PJ	GDP
TTP	Rail-Passengers	PJ	Population
TWD	Domestic Internal Navigation	PJ	GDP
TWI	International Navigation	PJ	GDP
AGR	Agricultural demand	PJ	GDP (agricultural sector)
CC1	Commercial Cooling - Region 1	PJ	GDP (service sector)
CCK	Commercial Cooking	PJ	GDP (service sector)
CH1	Commercial Space Heat - Region 1	PJ	GDP (service sector)
CHW	Commercial Hot Water	PJ	GDP (service sector)
COE	Commercial Office Equipment	PJ	GDP (service sector)
RC1	Residential Cooling - Region 1	PJ	GDP/Household
REA	Residential Other Electric	PJ	Household Size
RH1	Residential Space Heat - Region 1	PJ	Household Size
RHW	Residential Hot Water	PJ	Population
RK1	Residential Cooking - Region 1	PJ	Population
IOI	Other Industrial consumption	PJ	GDP (industrial)
ICH	Chemicals	PJ	GDP (industrial)
IIS	Iron and Steel	Mt	GDP (industrial)
ILP	Pulp and Paper	Mt	GDP (industrial)
INF	Non-ferrous metals	Mt	GDP (industrial)
INM	Non Metal minerals	PJ	GDP (industrial)
IOI	Other Industries	PJ	GDP (industrial)
NEO	Industrial and Other Non Energy Uses	PJ	GDP
ONO	Other non-specified consumption	PJ	GDP
COT	Commercial Other	PJ	GDP (service sector)

Table 4.3. Energy Demands in the TIAM-ECN model with their units and drivers. The petro-chemical industry is included in the Chemicals demand. Non-energy uses fall, where possible to separate, under NEO.

4.3. Scenarios

Four scenarios were run for this thesis: A business as usual scenario, an emissions constraint scenario, and two carbon tax scenarios. The carbon tax is represented by attaching a universal price on the emission of CO_2 equivalent. Each scenario optimizes for the same energy demand. The scenarios are described in detail below. What is important to understand is that the TIAM-ECN is a global model, so that the scenarios will run for all 36 regions in the model and the conditions apply for every region in the model. The results for Africa will thus be influenced by the developments in the other regions through emission caps, CO_2 price and trade. In this research we will only analyze the outcomes for the African sub-regions.

It is realized that the scenario's proposed here are harsh and the implied costs would hinder African development. The high costs implied by each of these scenarios cannot be supported by developing countries alone. Funding for renewable electricity access as well as the policies required to promote renewable development likely need to be sourced from foreign sources, for example through aid foreign investment. These investments in the African electricity sector will have worldwide benefits by reducing global carbon emissions growth. The scenarios run in these thesis must therefore be seen as a theoretical exercise to gain more insight into the price elasticity of renewable generation capacity development for the African sub-regions, and if a price difference between fossil fuels and renewables could lead to a more renewable grid, and in what regions and with what technologies. This price difference can then also be achieved through removal of fossil fuel subsidies or through subsidies on renewable electricity.

The scenarios in this model are significantly different from those discussed in the original research proposal. The original variable carbon tax scenarios were replaced by a fixed carbon tax. This was done as the variable carbon tax inhibited growth of the electricity sector almost completely. The implementation of an annual increasing global emissions restraint, the original third scenario, was dropped as runs would not compute. The additional scenario of a global emissions cap was run for the 450ppm constraint (2 degrees target) only, as the 650ppm target did not differ from the base scenario. More research will need to be done to determine the influence of milder global carbon caps on the development of the African power sector, but for this thesis it was decided that the 650ppm scenario did not add value at this moment.

Although IAM's generally run to the end of the century, we focused on the medium time interval and analyzed our scenarios to 2050. This is done because 1) the uncertainty over longer time spans increases greatly due to uncertainty in the demand drivers as well as technologies and fuels available and 2) a short time span is more relevant for African policy makers. Despite this short-term focus, long-term energy system effects to 2100 are considered in the model, as the model is run with perfect foresight until the end of the century.

Baseline Scenario

Scenario 1: Core Baseline Scenario [BAU]

- This business-as-usual scenario will be used as the reference for all scenarios. It is gauged on the baseline assumptions as discussed in chapter 5 for both the regional and global level.
- Any policies (such as portfolio standards, building codes, renewable subsidies) enacted prior to the base year (2010) are included. Proposed policies, including those designed to reach a country's Copenhagen pledge[2], are not included.
- The baseline scenario is used to compare model runs with regional and global modeling groups.

Mitigation Scenarios

Scenario 2&3: Carbon Tax Scenarios [Ctax10 and Ctax50]

- Base-year assumptions are as in BAU, and global and regional economy-wide CO_2 price paths, applied to all GHG's, beginning in 2020 (for values see table below).
- The CO_2 prices will be applied to all regions and all energy and agricultural sectors.
- Carbon prices were taken from the Climacap research by ECN [Köber 2014], where it was decided to take a low and realistic carbon tax of $10 (lower than the carbon tax of European countries, but in the range of Canada, the US and New Zealand) and a stringent high carbon tax scenario at $50.

Scenario 4: Scenario with global CO_2 concentration targets [450ppm]

- Base-year assumptions are as in BAU, and a global maximum radiative forcing is established for 2100, following the definition taken from the representative concentration pathways of the ICCP [2014].

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[2] Although African countries have not made Copenhagen pledges, some of the other regions in the model have.

- The constraint will be applied to all regions and all sectors.
- For non-CO_2 greenhouse gasses we use the IPCC ARS-100-year Global Warming Coefficient to obtain the corresponding price.

Scenario		Description
1	BAU	Baseline
2	Ctax10	Carbon Price of $10/tonne CO_2e
3	Ctax50	Carbon Price of $10/tonne CO_2e
4	450ppm	Global radiative forcing kept below 2.7W/m^2 450ppmv CO_2) by 2100. Concentration can overshoot before 2100

Table 4.4. Short description of the four scenarios run for this thesis

4.4. Division of African Sub-Regions

For this thesis the original TIAM-ECN Africa region was divided into 17 sub-regions, 12 of which are separate countries and 5 that are aggregations of multiple countries. The complete division is shown in figure 4.6 and some characteristics of the sub-regions are shown in table 4.6. With the addition of these 17 sub-regions the TIAM model consists of 36 regions. It was chosen to analyze different African regions to provide greater clarity regarding future energy demand, possible generation capacity mixes and mitigation capacity. Furthermore gathering data on a more detailed level for the different African regions increases the detail of the aggregate African region, improving the quality of the model runs in the TIAM-20 model. The TIAM-36 model can be used for both analysis on by itself and for comparison with other research. The African sub-regions can be added up to be comparable to the regions in the African Energy outlook and the African Power Pools reports and in the future to the results of the studies of the GCAM and IMAGE models. The only exception is Mauritania, which in included in the North African power pool (COMELEC) but is integrated in the West African region in the TIAM-ECN model. It was decided against modelling Mauritania separately as there was little information for the region and there would be no added value.

Motivation division

The most important factor in deciding on our the division was the added value of each sub-region. A balance had to be found between improving on local details by creating smaller sub-regions and introducing additional uncertainty if reliable data for sub-regions was not available. When there was enough data available and a region could provide interesting new insights now or in the future the country was modelled separately.

Country	Motivation
Morocco	Interconnectivity with Spain and the European Electricity Network
Algeria	Interconnectivity with Europe and large fossil fuel reserves
Tunisia	Interconnectivity with Europe
Libya	Interconnectivity with Europe and large fossil fuel reserves
Egypt	Interconnectivity with Europe and the Middle East, large industry and population
Nigeria	OPEC nation, large population, growing industry
Kenya	High (sustainable) energy targets
Ethiopia	Large energy demand growth, high potential for renewables
DR Congo	Large country with substantial hydropower potential
Angola	OPEC nation with low electricity access and fast growing GDP
Madagascar	Separated for better integration with other models
South Africa	High per capita energy use, high energy intensity and high emission intensity

Table 4.5. Motivation for the choice of individual countries as sub-regions beside availability of data. More information on (renewable) electricity targets can be found in appendix 3.

Several constraints to which the division had to adhere:

[1] Firstly, it was decided that where possible under [2], countries that were deemed of significant impact on the rest of the continent and the world with regards to electricity and energy were modelled separately. For motivation for each country choice, see table 4.5.

[2] The availability of information – sufficient data needs to be available to model each sub-region, to minimize the added uncertainty arising from introducing regions. Lack of data was the reason Sudan was not modeled as a separate country, as it was impossible to separate Sudan's and South Sudan's data for the base-year in which they were not yet separate countries.

[3] Comparability with the aggregation of African regions in other Integrated Assessment Models, such as GCAM and IMAGE (fig. 4.5).

   a. In order to compare our model results with other Integrated Assessment Models that will model the African energy sector, it is important that our sub-regions are divided so that they can be compared with the regions in these other studies.

   b. These models have not produced results so far, but in the future the results from the TIAM-ECN 36 can be compared with the outcomes of these models.

[4] Comparability with the aggregation of African regions in other reports, studies and regional plans such as the IEA African Outlook [IEA 2014(I)] seen in figure 4.5. and the different regional African Power Pools, as documented by IRENA [2013(II)] (see also section 5.2.2.).

   a. In order to compare our model to other studies, it is important that our sub-regions can be compared to the regions defined in these studies. Unfortunately, the regions as defined in constraint [1] are not the same as those in [2]. Even with our separated countries that left us with Madagascar. It was therefore decided to separate Madagascar as a separate region, even though it did not adhere to constraints [1] and [2].

Sub-Region	Name	Population (Million)	GDP/Capita ($/capita)	Electrification Rate (%)			Main form of Generation	Main Resources
				Total	Urban	Rural		
MAR	Morocco	32157	4260	98.9	100	97.4	Coal, Gas, Hydropower	x
DZA	Algerica	37063	7231	99.3	99.8	97.9	Gas	Natural Gas
TUN	Tunesia	10632	8428	99.5	100	98.5	Gas	Natural Gas
LBY	Libya	6041	15926	100	100	99.1	Gas	Oil, Natural Gas
EGY	Egypt	78076	5764	99.6	100	99.3	Gas, Heavy Fuel Oil	Natural Gas
AWE	Western Africa	145376	1269	35.8	62.7	17.5	Diesel, Gas, Hydropower	x
NGA	Nigeria	159708	2123	48	79.8	34.9	Diesel, Gas, Hydropower	Oil, Natural Gas
ACE	Central Africa	43237	2669	32.0	56.1	9.6	Hydropower	Oil
AEA	East Africa	117092	1248	20.3	50.3	11.7	Hydropower	Oil
ETH	Ethiopia	87095	888	23	85	4.8	Hydropower, Geothermal	Geothermal, Hydro
KEN	Kenya	40909	1472	23	58.2	8.1	Hydropower, Geothermal	Geothermal
COD	DR Congo	62191	336	15.2	39.2	3	Hydropower	Hydro
AGO	Angola	19549	5049	34.6	82.5	5.5	Hydropower	Oil
ASE	South-East Africa	48658	1915	22.6	56.1	7.6	Gas, HFO, Hydropower, Coal	Coal, Natural Gas
ASO	Other Southern Africa	68941	1095	14.86	45.53	3.08	Hydropower	Coal
MDG	Madagascar	21080	854	14.3	61.5	9.4	Hydropower, Diesel	x
ZAF	South Africa	51452	9232	82.7	94.3	64.1	Coal	Coal

Table 4.6. Characteristics of the different African sub-regions

African Energy outlook **IMAGE & GCAM** **African Power Pools**

Fig. 4.5. African regions in other studies, compatible with the TIAM-ECN model (below)

Fig. 4.6. The African sub-regions included in the TIAM-36 model

Chapter 5: *Data Collection*

The main challenge of this thesis was the data-collection for the sub-regions, as data for most African countries is scarcely available. The TIAM-ECN model is a data-intensive model, and requires a large quantity of detailed information. In order to expand the model, extensive data on energy demands, energy supply and trade was gathered for each of the 17 new sub-regions. For sub-regions consisting of multiple countries, averages were taken. Approximations were made where data was not available on energy demands. Often these approximations were based on the demand of similar sub-regions. In other instances, data was calculated from related factors. Several examples of these approximations are given in section 5.3. For demands that are currently zero or near-zero, demand was introduced for later model periods. Sector 5.4. elaborates on the adaptions made. The model was calibrated to 2010, but data from 2005 to 2009 was also gathered as additional control value, as data for African sub-regions can vary substantially between years. For North African countries in many instances data for 2010 was often unreported due to the Arab Spring starting early 2011. Data from either 2009 or 2012 was taken as a substitute. Due to the unrest, 2011 was considered an unrepresentative year. The following is a short overview of data gathered:

- Demand
    - Total fuel demand per sector
    - Fuel share per energy demand for each sector
    - Demand drivers for each fuel use (population, GDP, household size)
    - Future projections demand drivers

- Supply
    - Resource availability and their economic and technical potential[3]
    - Current generation & planned generation for the coming years

- Trade
    - Expected trade links between African regions and all other regions in the model
    - Current and expected future trade in PJ

5.1. Data sources and data collection methods

The basis for all data collection in the TIAM-ECN model is the IEA database [IEA 2014(II)]. This database contains information on energy use for the different sectors per fuel type and per country. Not all African countries are included in this database[4]. In addition, for many of the countries that are included data is missing for certain years, fuel types or sectors. This missing data was gathered from a large variety of sources, such as government reports, non-governmental agencies, scientific literature and industry data. An overview of all sources used can be found in Appendix 2. The available IEA data was also crosschecked against these other sources where available. In figure 5.1. the general process of data-mining is described for both supply and demand data.

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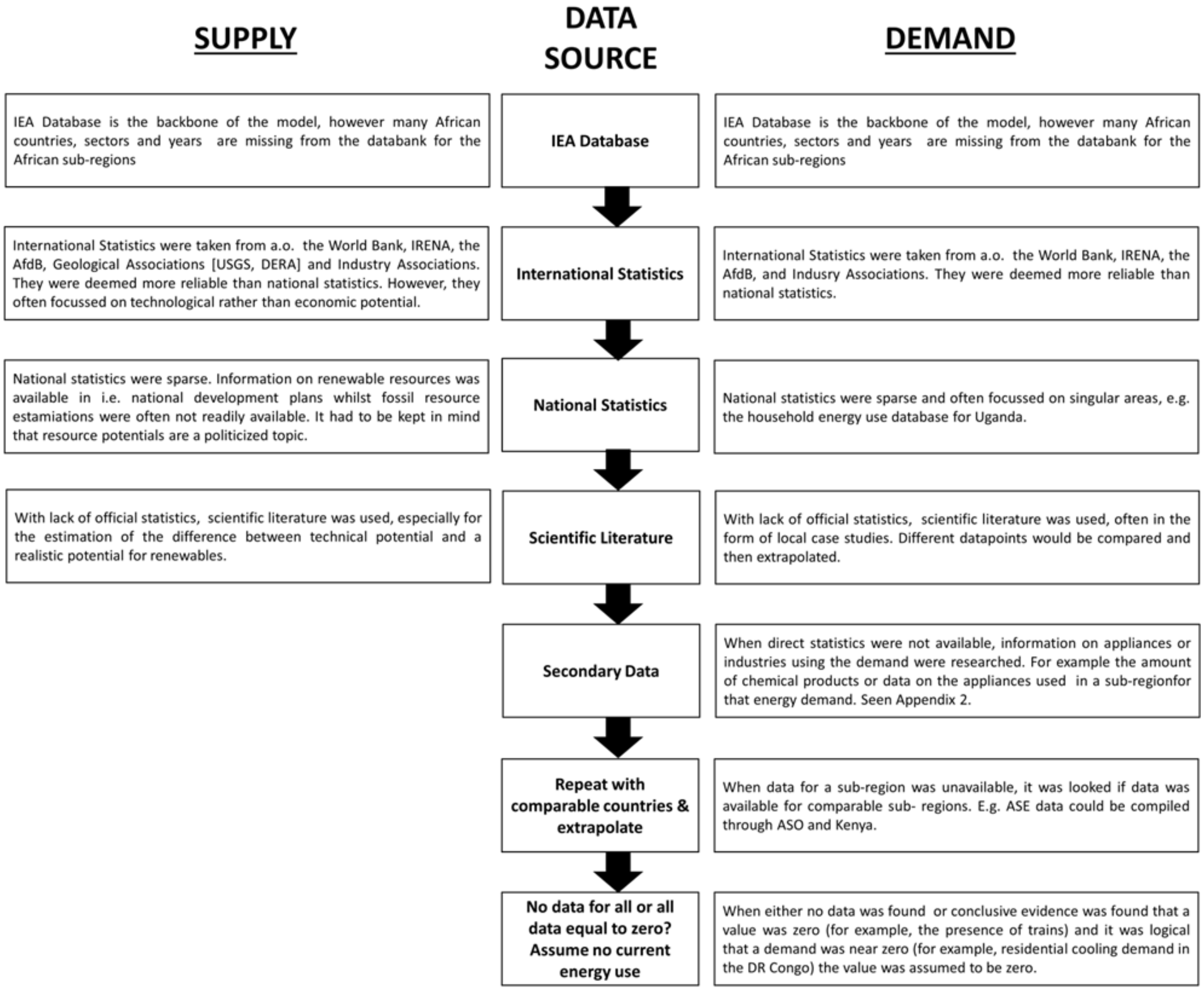
[3] For fossil fuel resources economic and technical potential were based on industry reports [e.g. BP 2014, Shell 2013]. For renewables the technical potential encompassed all the electricity that could technically be generated (based among others on IRENA [2014] and Buys [2012]. The economic potential was determined by estimating a realistic potential based on current and future prices and area used. This estimation was based on industry reports [IRENA, RES21] and consultation with experts at ECN.

[4] Countries in the IEA database: Algeria, Angola, Benin, Cameroon, Republic of Congo, Democratic Republic of Congo, Côte d'Ivoire, Egypt, Eritrea, Ethiopia, Gabon, Ghana, Kenya, Libya, Mauritius, Morocco, Mozambique, Namibia, Nigeria, Senegal, South Africa, Sudan, United Republic of Tanzania, Togo, Tunisia, Zambia, Zimbabwe



SUPPLY	DATA SOURCE	DEMAND
IEA Database is the backbone of the model, however many African countries, sectors and years are missing from the databank for the African sub-regions	**IEA Database**	IEA Database is the backbone of the model, however many African countries, sectors and years are missing from the databank for the African sub-regions
International Statistics were taken from a.o. the World Bank, IRENA, the AfdB, Geological Associations [USGS, DERA] and Industry Associations. They were deemed more reliable than national statistics. However, they often focussed on technological rather than economic potential.	**International Statistics**	International Statistics were taken from a.o. the World Bank, IRENA, the AfdB, and Indusry Associations. They were deemed more reliable than national statistics.
National statistics were sparse. Information on renewable resources was available in i.e. national development plans whilst fossil resource estamiations were often not readily available. It had to be kept in mind that resource potentials are a politicized topic.	**National Statistics**	National statistics were sparse and often focussed on singular areas, e.g. the household energy use database for Uganda.
With lack of official statistics, scientific literature was used, especially for the estimation of the difference between technical potential and a realistic potential for renewables.	**Scientific Literature**	With lack of official statistics, scientific literature was used, often in the form of local case studies. Different datapoints would be compared and then extrapolated.
	Secondary Data	When direct statistics were not available, information on appliances or industries using the demand were researched. For example the amount of chemical products or data on the appliances used in a sub-regionfor that energy demand. Seen Appendix 2.
	Repeat with comparable countries & extrapolate	When data for a sub-region was unavailable, it was looked if data was available for comparable sub- regions. E.g. ASE data could be compiled through ASO and Kenya.
	No data for all or all data equal to zero? Assume no current energy use	When either no data was found or conclusive evidence was found that a value was zero (for example, the presence of trains) and it was logical that a demand was near zero (for example, residential cooling demand in the DR Congo) the value was assumed to be zero.

Fig. 5.1. Order of data-mining for supply and demand data needed for the model

5.2. Supply: Resources & Trade

In the TIAM-ECN mode, energy resources are supplied in two ways: Through exploitation of domestic reserves and through trade with other (sub-)regions. For both resource exploitation and trade maximum constraints were established based on resource potentials and current trade links respectively. For certain trade links minima were also established. All input values were in PJ. In addition to potentials and trade, currently generation capacity was defined.

5.2.1. Resource Potentials

Both renewable and fossil fuel potentials are defined in the model for each sub-region. This section will focus on the resource potentials for electricity generation, as these were explored in most detail for this thesis. Fossil fuel reserves are defined as a finite value in PJ per fuel source while renewable potentials are defined in PJ available per year. For fossil fuels data was readily available from industry reports. For renewables assumptions had to be made to find values for the different sub-regions. For nuclear power the potential consisted of the nuclear generation capacity already planned and approved for the coming years. All the reserves and potentials were put into the model as maximum limits. In figure 5.2. an overview is given of the fossil fuel reserves and renewable potentials per sub-region.

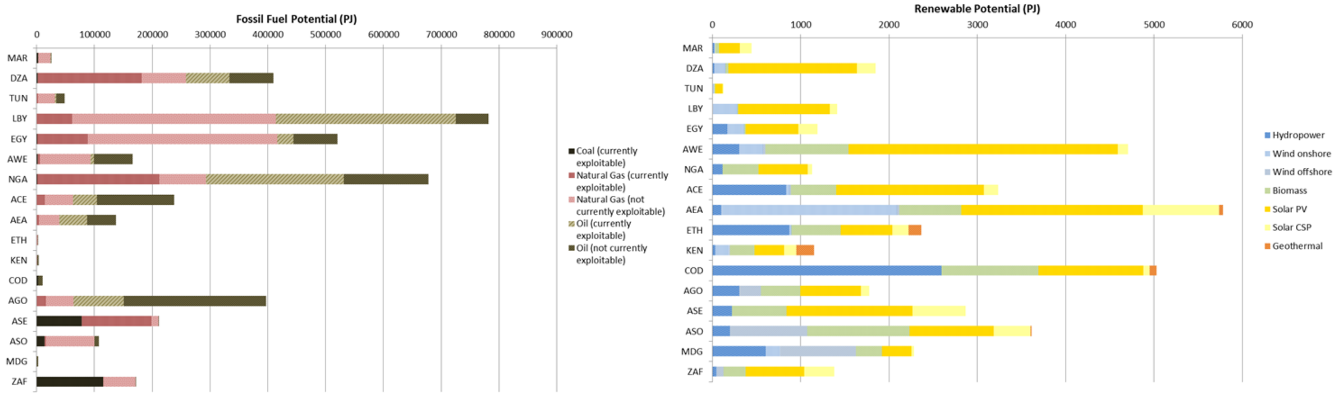


Fig. 5.2. Fossil fuel (total) and renewable potentials (per year) in PJ for the different sub-regions (2010)

Fossil Fuels

- Almost all African sub-regions possess some gas reserves, but most gas reserves are currently not exploitable for technical and/or economical regions . Significant exploitable gas resources are found in Algeria, Libya, Egypt, Nigeria and South-East Africa.
- Libya and Nigeria have the largest accessible oil reserves at 37% and 29% of total African oil reserves respectively. Significant reserves can also be found in Angola, Algeria, East Africa and Central Africa.
- Coal reserves are concentrated in 3 regions: South Africa with 53% of total coal reserves, Southern Africa with 36% and South-East Africa with 6%.

Renewables

- Solar potential is the largest renewable potential. The potential for solar capacity is especially large in Algeria, West Africa, Central Africa and South East Africa.
- Total solar potential (20630PJ or 5730TWh/year) is 9 times the current total African electricity demand of 630TWh/year. However, this number does not take into consideration land-use competition between CSP and PV capacity.
- The DR Congo contains almost half of Africa's total hydropower potential at 2591PJ or 720TWh/year. If this hydropower is realized the DR Congo could become a significant electricity exporter.
- Off-shore wind potential in Africa is low, with only Angola, Southern Africa and Madagascar possessing significant off-shore potential at 14%, 24% and 38% of total renewable potential respectively. On-shore wind potential however is large. This is mainly due to a high availability. On-shore wind potential is largest in East Africa, Egypt and West Africa.

Fossil Reserves

Fossil fuel data is based on industry, government and NGO reports, i.e. BP [BP 2012], the U.S. Energy Information Administration [EIA 2014], the German Mineral Resources Agency [DERA 2011], the American Geological Society [USGS 2012], the IEA [2012(II), the World Bank [Buys 2007], the World Energy Council [WEC 2013], the AfdB [2012] and the World Resources Institute [WRI 2011]. The model contains oil, gas and coal reserves, making no differentiation between types of coal. For oil and gas reserves differentiation was made between reserves that are currently technologically exploitable and reserves that can currently not be exploited. This differentiation was based on industry evaluations [BP 2012, DERA 2011]. For each sub-region different cost-levels for exploitation were defined. The different cost-levels were taken from the old TIAM-ECN African region, the share of resource per cost-level was estimated based on industry data [DERA 2011, EIA 2015]. To convert coal data from kg into PJ, types of coal were specified – bitumous, sub-bitumous and lignite - with different heat contents.

Studies have shown that Africa potentially has large shale gas and shale oil resources [EIA 2015, WRI 2014]. However, as these resources have not yet been proven they have not been included in the model.

Reserves (PJ) per sub-region	Oil Reserves			Gas Reserves			Coal Reserves		
	Exploitable	Currently un-exploitable	Shale	Exploitable	Currently un-exploitable	Shale	Bitumous	Sub-Bitumous	Lignite
MAR	24	2842	1.29E+06	40	21800	22640	2267	x	576
DZA	74939	75792	3.66E+07	180120	76560	800324	1631	x	x
TUN	2747	14211	9.64E+06	2600	28400	26036	x	x	x
LBY	299189	56844	1.68E+08	60880	352520	138104	x	x	x
EGY	28990	76171	2.96E+07	87400	328000	113200	442	x	x
AWE	5637	66792	6.43E+05	3760	87000	x	1936	x	x
NGA	234955	146373	x	211680	80000	x	581	3177	x
ACE	56655	141210	x	13880	48800	12760	x	x	43
AEA	48554	50212	x	4200	34800	x	x	x	x
ETH	x	947	x	1000	800	x	x	x	x
KEN	x	2369	x	x	800	x	x	x	x
COD	1137	6869	1.58E+06	40	400	x	2433	x	x
AGO	82992	246324	x	15800	48000	x	x	x	x
ASE	95	1421	x	6440	12000	x	x	77456	x
ASO	x	7579	x	2480	84000	x	19244	2	x
MDG	x	2842	x	x	200	x	x	x	x
ZAF	95	947	x	480	55296	441480	115011	x	x

Table 5.1. Fossil fuel reserves per sub-region (2010). Shale resources not included in the model

Nuclear Energy

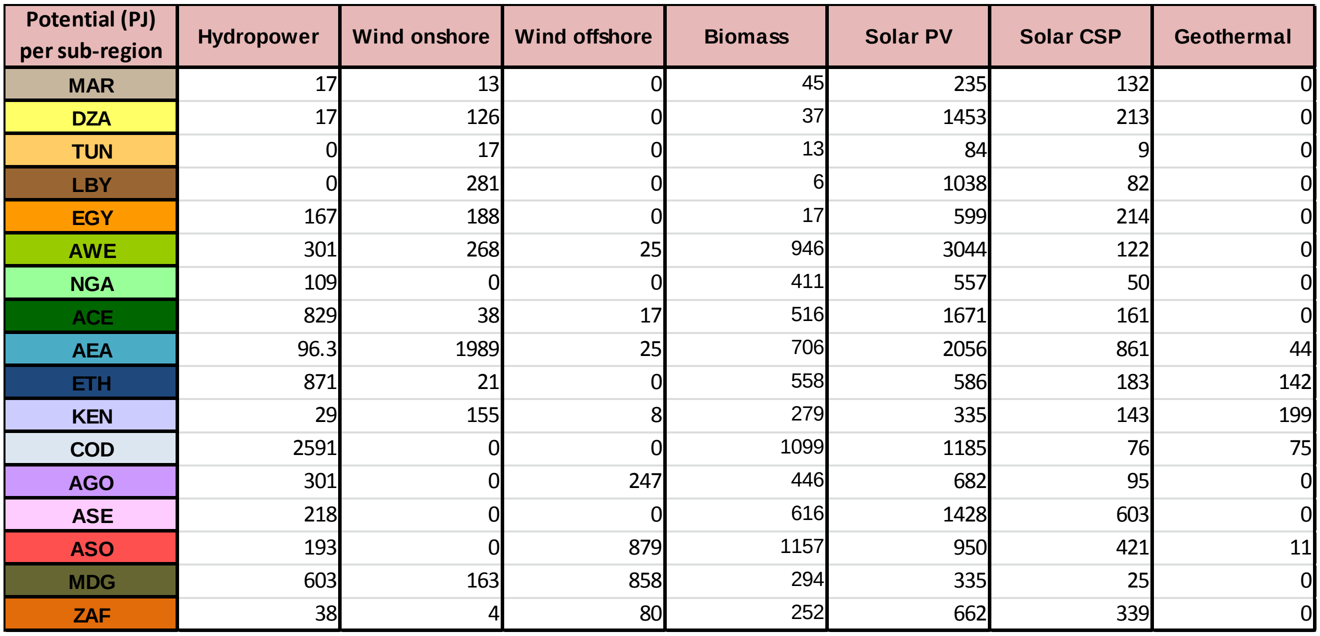
Even though many African nations have discussed the possibility of nuclear power as a solution to electricity poverty, nuclear energy in developing countries is still contested and it is not likely that developing countries currently without access to nuclear energy will gain this access in the near future [Adamantiades 2009]. It was therefore assumed that nuclear energy in Africa could only be installed in those regions that already possessed nuclear power (South Africa) or were in the far stages of installing nuclear power (Egypt) [Joskow 2012]. Both sub-region were only allowed to implement nuclear power currently planned and approved as the lead time for nuclear projects is long, especially for developing countries. This was the upper constraint for future installed nuclear capacity.

Nuclear Capacity (2050)	Upper Limit Installed Capacity
EGY	4.8GW
ZAF	6.0GW

Table 5.2. Nuclear capacity constraints. Only Egypt and South Africa have access to nuclear capacity in the model

Renewables

Renewable resource data as shown in table 5.3 was based on government, NGO and scientific reports as well as ECN expertise i.e. ARGeo [2012,2013,2014] Climatescope [2014], ECOWAS [2014], INTPOW [2013], IRENA [2012, 2014], Pollack [1993], ECOWAS [2014], SolarPACES [2015], UNIDO [2006, 2013] and USEA [2013]. All references used can be found in Appendix 2. Geothermal, wind and hydropower data were taken directly from data sources. For each technology, multiple sources were used. As the data from these sources differed significantly, averages were taken. Where possible, the Solar PV, CSP and biomass potentials were calculated from their technical potential as explained below. Land-use competition was not taken into account in the calculation of renewable potentials. As current model runs use only a small share of total renewable potential, it was decided that land-use competition was not a significant factor at this moment.

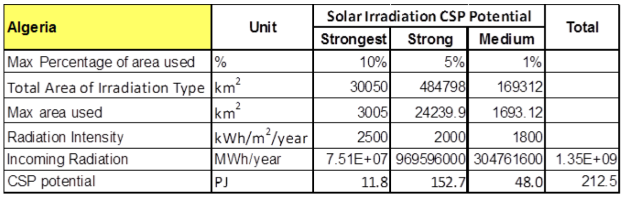


Potential (PJ) per sub-region	Hydropower	Wind onshore	Wind offshore	Biomass	Solar PV	Solar CSP	Geothermal
MAR	17	13	0	45	235	132	0
DZA	17	126	0	37	1453	213	0
TUN	0	17	0	13	84	9	0
LBY	0	281	0	6	1038	82	0
EGY	167	188	0	17	599	214	0
AWE	301	268	25	946	3044	122	0
NGA	109	0	0	411	557	50	0
ACE	829	38	17	516	1671	161	0
AEA	96.3	1989	25	706	2056	861	44
ETH	871	21	0	558	586	183	142
KEN	29	155	8	279	335	143	199
COD	2591	0	0	1099	1185	76	75
AGO	301	0	247	446	682	95	0
ASE	218	0	0	616	1428	603	0
ASO	193	0	879	1157	950	421	11
MDG	603	163	858	294	335	25	0
ZAF	38	4	80	252	662	339	0

Table 5.3. Renewable energy potentials per year per sub-region

Solar PV & CSP

For Africa technical solar potential far exceeds realistic potential, yet in literature only a technical potential is available for most sub-regions. The technical potential given in IRENA [2014] includes all unused land for calculating solar potential. As not all the area technically available for solar power will be used for generation of solar power, a further calculation was necessary to determine a realistic potential. The IRENA report divides the area technically available for solar power into 3 categories, based on solar irradiation level: Strongest, Strong and Medium (table 5.4). Based on consultation with ECN experts, it was decided to take a maximum of 10% area used for solar generation of the strongest potential sites, 5% of the strong sites, and 1% of the medium sites. From these calculations maximum CSP and PV potentials were determined. In table 5.4 the calculation for Algeria CSP is shown as an example. The values found for CSP and PV are currently not mutually exclusive. This was not deemed to be a problem for now as the model utilizes little of the available solar potential.



Algeria	Unit	Solar Irradiation CSP Potential			Total
		Strongest	Strong	Medium	
Max Percentage of area used	%	10%	5%	1%	
Total Area of Irradiation Type	km^2	30050	484798	169312	
Max area used	km^2	3005	24239.9	1693.12	
Radiation Intensity	kWh/m^2/year	2500	2000	1800	
Incoming Radiation	MWh/year	7.51E+07	969596000	304761600	1.35E+09
CSP potential	PJ	11.8	152.7	48.0	212.5

Table 5.4. Example of ***t****he CSP realistic potential from the technical potential for Algeria*

The above calculation finds a maximum potential of 1350 TWh/year for CSP in Algeria, compared to the technical potential of 26530TWh/year as defined by IRENA. These results where compared with the results of van Tuyll [2009], who calculated the CSP potential for African countries by assuming that 4.5% of the technically available land would be used for CSP. The results were mostly in agreement. However, Tuyll's calculation neglected the fact that a larger share of strongly suited land would be used for solar generation capacity than of less suited land. It was chosen to maintain our own calculations.

Biomass

Biomass data for different sub-regions was based on data from the Deutsches Biomasse Forschungs Zentrum (DBFZ) [2014], IRENA [2014] and on the expertise of the ECN bio-energy department. Data was available on the kg woody and agricultural biomass available for modern generation for the whole of Africa and total area suitable for biomass generation per sub-region. Combining the share of woody and agricultural lands respectively, every sub-region was assigned a proportional share of total kg of biomass. A standard value for the energy content of wood and agricultural biomass respectively was then taken to convert the kg values in PJ. This method gave a crude estimation of the biomass potential for different regions as shown in figure 5.5. More research is needed to identify biomass potentials and costs in detail.

Woody biomass potential	MAR	DZA	TUN	LBY	EGY	AWE	NGA	ACE	AEA	ETH	KEN	COD	AGO	ASE	ASO	MDG	ZAF	AFR
Biomass available (kg)	2000	500	500	100	500	62625	5000	23000	49966	50000	19382	84030	5971	40731	63617	9760	3400	**421082**
Share of total	0%	0%	0%	0%	0%	15%	1%	5%	12%	12%	5%	20%	1%	10%	15%	2%	1%	**100%**
Biomass available (PJ)	11.4	2.8	2.8	0.6	2.8	356.9	28.5	131.1	284.8	285.0	110.5	478.9	34.0	232.2	362.6	55.6	19.4	**2400**

Table 5.5. Example of calculation of the woody biomass potential for the different sub-regions

5.2.2. Trade

Trade data in the TIAM-ECN model consists of the current and potential future trade links between regions and the maximum and minimum quantities traded. Trade is allowed both between African sub-regions as well as between African sub-regions and other regions. Regional trade is allowed for a large range of energy commodities[5]. For the African sub-regions, Coal, Natural gas, Crude Oil and Electricity are the only commodities traded in substantial amount. Trade links can be uni-lateral or bi-lateral. As a rule trade links for pipelines and transmission lines are always bilateral whilst the other trade links can be either bi- or unilateral.

For each established link trade data for 2005 and 2010 was gathered from the US geological society (for commodities) [USGS 2015], the UN Comtrade database [UN Comtrade 2015] and the MIT Observatory of Economic Complexity [MIT 2015]. For pipelines EIA country reports [2015], BP [2012] and PWC [2014] were used. As for many more unstable regions the trade varies greatly per year, an average of several years was taken. One example is Mozambique, where the coal trade was non-existent between 2010 and 2012 due to an insurgent attack on the only coal-transporting railway line. Since trade links and capacity were available, the average trade value between 2005 and 2009 was taken for the base-year 2010. Besides base-year trade a cap on future trade was established. This cap was decided by extrapolating current trades based on industry predictions, extrapolations of historical growth and historical growth from other countries.

Current electricity data was based on reports on the African Power Pools: the West African Power Pool [IRENA 2015(II)], the East African Power Pool [AEEP 2014] and the Southern African Power Pool [IRENA 2013, 2014(II)]. North Africa has its own power pool, Comité Maghrébin de l'electricité [COMELEC 2015]. More connections are planned [AfdB 2015], AEEP [2014] Mason [2011]. The maximum capacity of transmission lines was therefore set as the maximum constrain for electricity trade, with no minimum. Electricity trade links are shown in fig. 5.3. Blue indicates current trade while red indicates future connections. WUE stands for Western Europe.

Electricity Trade	MAR	DZA	TUN	LBY	EGY	AWE	NGA	ACE	AEA	ETH	KEN	COD	AGO	ASE	ASO	MDG	ZAF	WUE
MAR	▨	🟦																🟦
DZA	🟦	▨																🟥
TUN			▨															🟥
LBY				▨	🟦													🟥
EGY				🟦	▨													
AWE						▨	🟦											
NGA						🟦	▨	🟦										
ACE							🟦	▨				🟦						
AEA									▨	🟦	🟦							
ETH									🟦	▨	🟥							
KEN									🟦	🟥	▨				🟥			
COD								🟦				▨	🟥	🟦				
AGO												🟥	▨	🟥				
ASE												🟦	🟥	▨	🟦		🟦	
ASO											🟥			🟦	▨	🟦	🟦	
MDG															🟦	▨		
ZAF														🟦	🟦		▨	
WUE	🟦	🟥	🟥	🟥														

Table 5.6. Current and future electricity trade links between sub-regions. Blue means current trade links, red future links

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[5] Coal, Natural Gas, LNG, Crude Oil, Gasoline, Heavy Fuel Oil, Diesel, Naphta, NGL, Solid Biomass, Biodiesel, N2O, CH4, Oil products, CO2, Electricity.

5.2.3. Generation Capacity

Using a combination of government sources, IRENA power pool reports, PLATTS power-plant database and industry reports, an overview of generation capacity per sub-region for the year 2005 and 2010 was constructed as seen in fig. 5.3. It was important to separate the installed capacity from the operational capacity, as in many countries a large share of capacity is (permanently) out of operation. For the electricity produced per region see figure 6.5 in section 6.1.

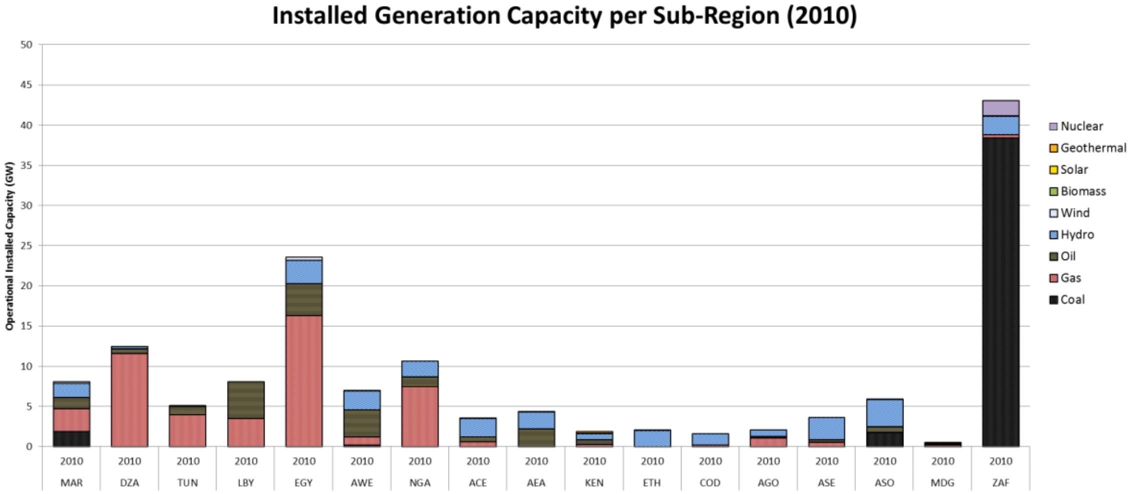


Fig. 5.3. Operational installed capacity per sub-region (2010)

5.3. Demand: Energy consumption and fuel shares

The TIAM-ECN model contains 32 energy demands as shown in figure 4.3. The model requires two types of data input for each energy demand: 1) Total current energy use for each energy demand and 2) Share of total fuel per energy demand. When direct data values were not available the needed data was derived from secondary sources. For example, for some countries energy demand for domestic aviation could be found from CO_2 emissions for aviation [Carbon Watch Market 2013, IIASA 2012, IISD 2013] and the average CO_2 emissions from kerosene [IEA 2015]. For other countries energy demand calculated using the total amounts of kilometers flown, take-off and landings, average load and occupied seats and the average fuel use for the plane type used. This data came from i.e. [IATA 2015], [Airlineleader 2015], and [MIDT 2014]. Residential electricity shares where partially calculated from the amount and type of appliances in the home, their average electricity use (for their respective African sub-regions) and whether they were in continuous (fridge) or intermittent operation (fans, lighting). This data was found i.e. from government reports [Ministere Algerién de l'Energie 2011] case studies [Attia 2012, Howells 2004] and NGO data [Gelil 2011, IRENA 2014(III)]. Full references can found in appendix 2. Some of the methods used to find data for the different sectors is shown in figure 5.4.

Industrial	Residential / Commercial	Upstream	Transport	Electricity Generation
• Industrial Association Reports • Products produced from the American Geological Society and Industry Reports • Standard efficiencies and industry application for fuel shares	• Country surveys • International NGO data • Scientific case studies on residential / commercial fuel shares and use • Appliances sold and appliances per household	• Previously determined efficiencies and fuel shares for the African continent • Divided per share of product produced	• Government census • Vehicles sold + average (African) lifetime of vehicles • Vehicles per population data (based on Worldbank and AfdB data) • Number of flights and routes	• Industry Association Reports • IRENA (powerpools), RES21 and IEA data • Local government presentations and reports on operational status • PLATTS database

Fig. 5.4. Data sources for the different sectors

The input for a demand variable is given in PJ or Mt for industries with a consistent energy use. For each fuel the share of fuel used per energy demand was defined. Figure 5.5. gives an example of Fuel Share per Energy demand input for the residential sector. In Kenya 95% of residential electricity was used for lighting, 1.8% for water heating, 2.4% for residential cooking and 0.8% for Miscellaneous Electric Energy. These fuel shares were based on local case studies The iron & steel and non-ferrous metal demands were measured in Mt instead of PJ as their energy demand is relatively uniform per Mt produced, thus taking the well reported value of Mt produced and converting this to PJ using industry standers for average energy use per Mt produced gives a more accurate value. For the transport sector we choose to use the amount of vehicles per km of road. This value was then converted to PJ. This was done as there is little uniformity in the amount of passengers per vehicle in Africa, so there is no direct correlation between total passengers and fuel use.

Fuel Share per Energy Demand (Kenya)	Space Heating	Space Cooling	Water Heating	Refrigerators and Freezers	Clothes Drying	Residential Cooking	Clothes Washers	Dishwasher	Residential Other Energy	Miscellaneous Electric Energy	Lighting	Total
Natural Gas	10.0%	0.0%	52.0%	0.0%		38.0%	0.0%	0.0%	0.0%		0.0%	100%
Distallate	10.0%	0.0%	60.0%	0.0%	0.0%	30.0%	0.0%	0.0%	0.0%		0.0%	100%
Heavy	100.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%		0.0%	100%
Kerosene	0.8%	0.0%	1.9%	0.0%	0.0%	15.9%	0.0%	0.0%	0.2%		81.2%	100%
Coal	0.0%	0.0%	10.0%	0.0%	36.0%	50.0%	0.0%	0.0%	4.0%		0.0%	100%
LPG	3.0%	0.0%	5.0%	0.0%	0.0%	12.0%	0.0%	0.0%	0.0%		80.0%	100%
Biomass	0.0%	0.0%	1.8%	0.0%	0.0%	96.6%	0.0%	0.0%	0.8%		0.8%	100%
Electricity	0.0%	0.0%	1.8%	0.0%	0.0%	2.4%	0.0%	0.0%	0.0%	0.8%	95.0%	100%
Heat	100.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%		0.0%	100%
Geothermal	100.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%		0.0%	100%
Solar	0.0%	0.0%	100.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%		0.0%	100%

Table. 5.7. Fuel shares per demand for the Residential sector. Brown indicates that the fuel is used for that energy demand

5.4. Model and Data Adaptations

Besides the lack of available data, there were several other issues with data collection caused by the current low level of electrification in Africa. First of all, growth trajectories had to be adapted to incorporated the rapid demand growth brought on by gaining modern energy access. Secondly, a way had to be found to incorporate those purposes for which the energy demand is currently zero, as the model only allows future growth for non-zero values in the baseline.

Dealing with growth

Africa is expected to undergo a rapid growth in GDP, population and modern energy access. These three factors combined will lead to near exponential growth for many energy demands in coming decades. Other developing regions such as the 'Asian tigers' have shown that rapid modernization and increase in electricity use is possible but when and if this rapid development will take off is difficult to predict. Rapid growth also needs to not be allowed to continue for the entire duration of the model – extrapolating current rapidly rising cooling demand in Libya led to a demand of several PJ for cooling in 2050 for Libya alone. In order to not overstate energy growth, expected growth in Africa was benchmarked with the historical, current and future growth of other developing regions in Latin America and Asia to ensure that the model included rapid but realistic growth. The case studies were based i.e. on McKinsey [2015], Nussbaumer 2012 and Bazilian [2013(I)].

Predicting growth from zero

For many African regions, certain modern energy demands – for example those that require electricity (cooling, heating) or those that require government investment (trains) are currently non-existent. As TIAM determines future energy demand by extrapolating current energy demand, the model extrapolate a demand from zero. As it is expected that demands for heating, cooling, etc. will develop with rising wealth, for those regions that lack demand currently this demand has to be manually introduced sometime in the future. Two methods were used to address this problem: One for train transport and one for residential and commercial demands.

1] Train Transport: looked at future plans for trains on research reports [Bullock 2009, PWC 2013] and railway associations [International Union of Railways 2015, China Railway Construction Cooperation 2015, Central East African Railways 2015], input this into the model from the year the trains would start running according to these plans. Most sub-regions would start incorporating public transport from 2030. As no train lines are currently under construction and they are only mentioned in long-term infrastructure plans, these assumptions might be overly optimistic.

2] Residential demands: Looked at the historical demand growth for other African sub-regions, and introduced a small per capita appropriate cooling and heating from 2020 (2030 for the DRC and AEA). The amount deemed appropriate was based on the experience of other African sub-regions and it was checked if the extrapolation of the demand over the 21st century was within reasonable bounds compared to other regions.

In the following sections the results from different scenarios are discussed at both the continental and sub-regional level. The baseline energy demand, electricity mix and emissions will be reviewed. The mitigation scenarios will be compared for mitigation potential and generation mix. The regions with the least – Egypt and Nigeria – and greatest – Morocco, Ethiopia and South Africa – mitigation potential are discussed in further detail. DR Congo due to its relative lack of growth. Sector 6.1 will discuss the results from the base-year. Sector 6.2 will analyze the different mitigation scenarios. Sector 6.3 reviews the results in depth for the selected regions and section 6.4 compares our baseline model runs to the studies by McKinsey [2015] and the IEA [2014(I)].

6.1. Base-line Results

The reference scenario is characterized by the lack of mitigation policies for African sub-regions. Here we will review the results of the BAU for the final energy use, electricity demand, electricity mix and CO_2 emissions for both Africa as a whole as well as the 17 sub-regions. We focus the presentation of results on the period 2010 to 2050, as longer term predictions are very uncertain for developing countries. In addition, longer term predictions are less relevant for African policy makers and global donors. Despite this short-term focus, long-term energy system effects to 2100 are considered in the model, as it runs with perfect foresight until the end of the century.

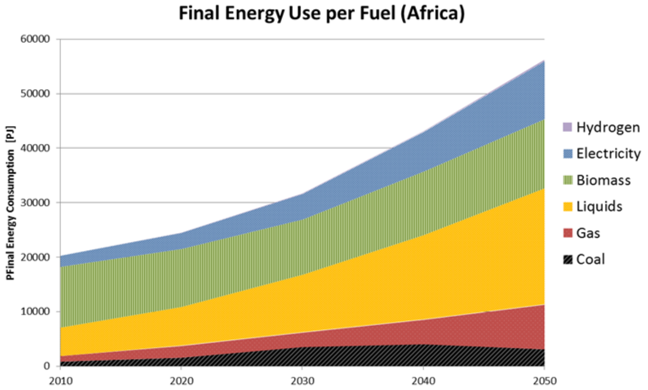


Fig. 6.1. Final energy use per fuel (PJ) for total Africa until 2050. Baseline Scenario.

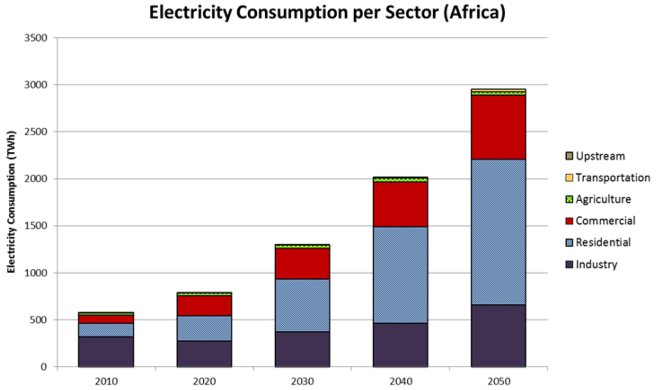


Fig. 6.2. Electricity consumption (TWh) per sector for total Africa until 2050 in the Baseline Scenario.

Energy Demand

Future energy demand is the same for all four scenarios and follows from the demand drivers and base-year data as specified in section 4.2.2. Energy demand in Africa is rapidly rising for all fuels as shown in figure 6.1. Total final energy demand is expected to almost triple by 2050 following a doubling of population as well as increased energy use per capita. Electricity has the second highest demand growth after liquid fuels, with gas consumption also increasing rapidly. Biomass use remains roughly equal between 2010 and 2050, as also predicted by the African Energy Outlook [IEA 2014(I)]. A decline of coal in the final energy demand is expected after 2030. This is mainly cause by the incorporation into the model of South Africa's current climate pledges.

Electricity Demand

Electricity demand is the second-fastest growing fuel demand behind liquid fuels and is increasing for all sub-regions (fig. 6.5). Ethiopia and Nigeria have the fastest electricity demand growth with a 32-fold and 18-fold increase in demand respectively. These nations are also expecting the largest GDP and population growth (sector 4.4). The electricity demand is fastest growing in the residential sector with an 10-fold increase (1053%) in electricity demand by 2050, with the commercial sector showing a growth of 815% over the same time period (fig. 6.2). Agricultural and industrial demand growth are relatively small, with the electricity demand in industry expected to even fall steeply between 2010 and 2020. As shown in figure 6.4, this drop is caused by fuel substitution in the model of electricity by other fuels, with the total energy demand in industry increasing from 700PJ to 1650PJ. The substitution of liquids in the industrial sector is even larger than that of electricity. These high level of substitution might indicate that the fuel elasticity of the industry demand uses is too large. The industry and upstream sectors fuel shares are the only part of the model completely not adapted for the African sub-regions. More research is needed into the different fuel shares in the industrial sector. Due to the industry substitution the model likely underestimates total electricity demand.

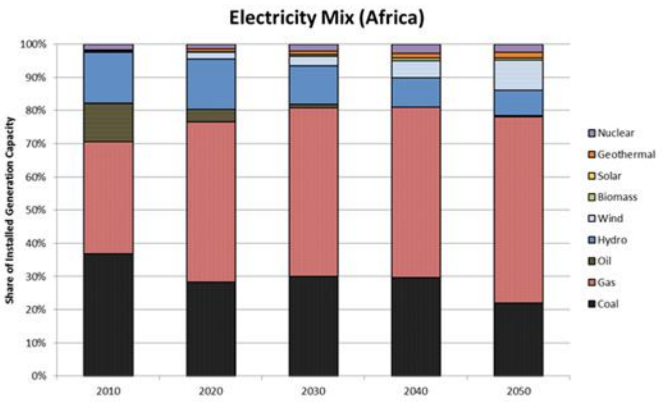


Fig. 6.3. Share of electricity production per generation technology until 2050. Baseline Scenario.

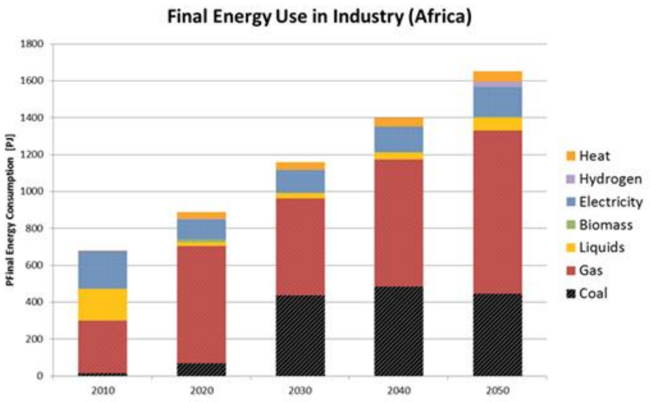


Fig. 6.4. Final energy use per fuel (PJ) for the industry sector until 2050 in the Baseline Scenario.

Electricity Mix

The current electricity mix is predominantly fossil fuel based, and it is projected to remain so in 2050. Figure 6.3 gives an overview of the shares of different technologies in the electricity mix. The electricity mix diversifies in all regions, except for Libya and Tunisia that remain almost completely depended on natural gas and the DR Congo that remains almost completely reliant on hydropower. Diversification plays an important role in energy security. A diverse power supply is more resistant against temporary shocks such as low water levels or insufficient gas supplies, and can help reducing the economically damaging black-outs prevalent in many African sub-regions.

Gas dominates the projected electricity mix, growing from 50GW installed in 2010 to 443GW in 2050. Every sub-region except for the DR Congo and Madagascar will have installed significant gas-fired generation capacity by 2050 (figure 6.8). This capacity will be fueled by the gas currently flared in oil producing sub-regions, the gas already produced in North African countries, and the new gas fields discovered of the coast of Mozambique and Tanzania. Growth of gas-fired power plants is largest in those sub-regions that have substantial domestic gas reserves – North Africa, Nigeria and Angola. A notable exception to this is the South-Eastern African region, where hydropower is preferred over gas capacity. The growth of gas in the electricity mix of Africa is consistent with the findings of McKinsey [2015] and the IEA [2014(I)] as shown in section 6.4. Although the relative share of coal in the electricity mix decreases from 37% to 22%, absolute coal capacity is more than doubling. Coal capacity is also present in countries without sizable domestic coal reserves such as Egypt, Morocco and Ethiopia. Oil capacity is nearly phased out by 2050.

By 2050, total low-emission capacity is expected to increase from 19% (28GW) to 23% (170GW) through market forces alone. The renewable power in commission also diversifies from 97% hydropower to a mixture of hydropower (58GW), wind (99GW) and geothermal (7GW), where geothermal capacity is almost exclusively limited to Kenya (figure 6.5). All wind capacity installed is on-shore wind power, which has a high load factor and small LCEO for the coastal areas of Egypt, West Africa and East Africa. Small amounts of biomass capacity can be found in multiple regions, most notably in Ethiopia and Southern Africa. Development of solar capacity is notably absent in the base-year scenario, even in the high potential sub-regions of North Africa. The absence of solar power was unexpected, as the incorporated solar technologies had higher availabilities than were deemed feasible for most of Africa (section 4.1.1). The LCEO of solar however, is still relatively high, especially for CSP, making solar capacity a costly form of generation. From our model it seems unlikely that solar will be a cost-effective form of generation capacity in any sub-region without subsidies or other policy support.

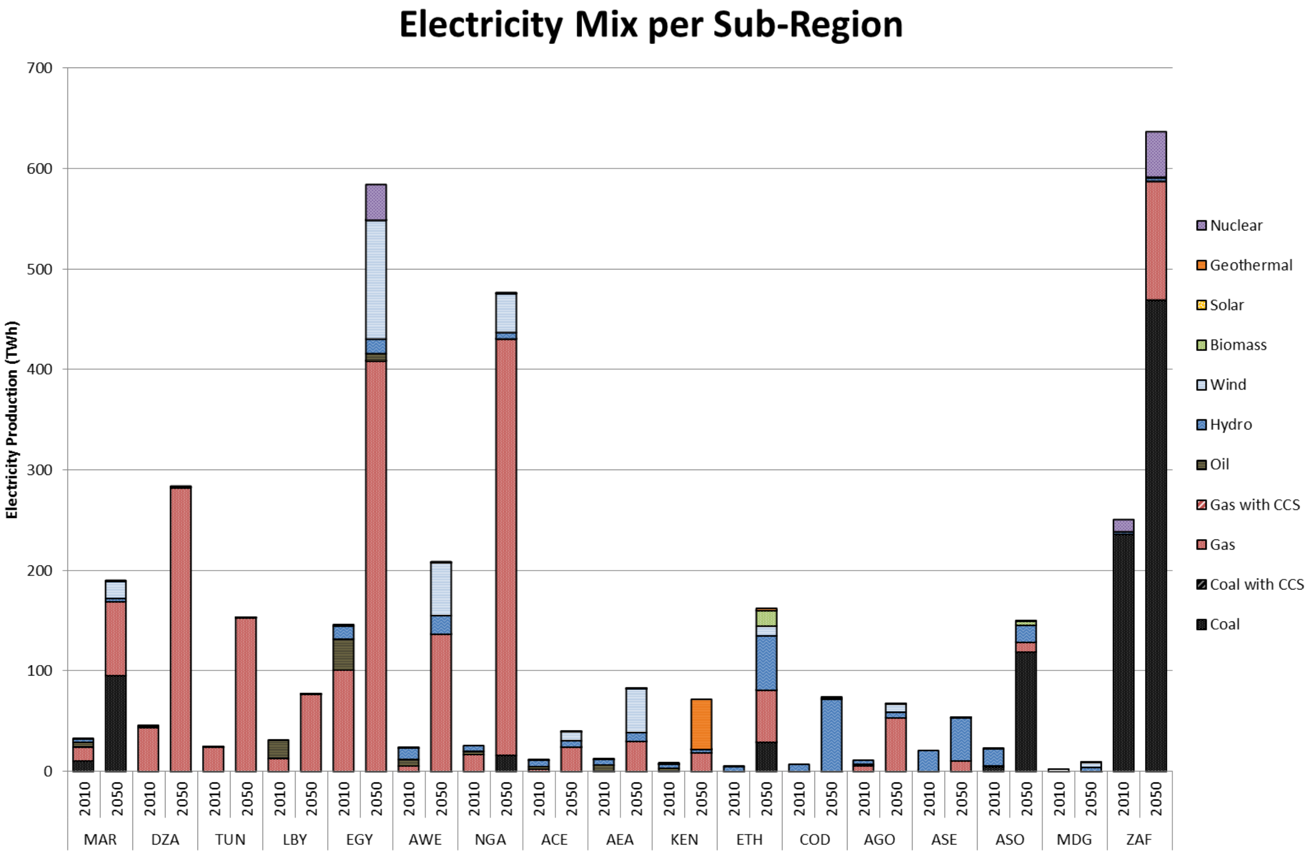
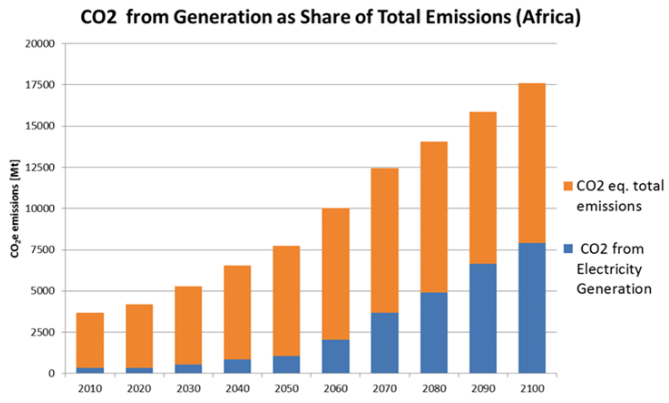


Fig. 6.5. Electricity production (TWh) per sub-region until 2050. Baseline Scenario

CO2 emissions

Resulting from the high share of fossil fuels in the generation mix in the baseline scenario are rapidly rising CO_2 emissions from electricity generation. By 2050 CO_2 emissions from electricity generation will have tripled from the base-year, while total GHG emissions have doubled. Considering growth until 2050, growth comes mostly from developing Sub-Saharan sub-regions as seen in figure 6.7 that currently have little CO_2 emission. The model accounts for CO_2 emissions from industry, residential and commercial use, agriculture, transport, upstream, land-use and electricity generation. By 2060 CO_2 emissions from electricity generation will have become the largest source of CO_2 emissions (fig 6.6). CO_2 emissions from electricity generation therefore also constitute the main driver of emissions growth. From the electricity mix and CO_2 generation forecasts it can be deduced that according to our model most African sub-regions are unlikely to develop a low-emission electricity system without policy interventions.



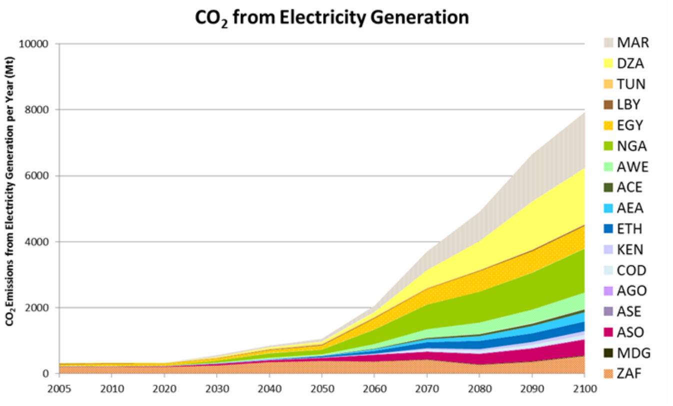


Fig. 6.6. CO_2e total and CO_2 from electricity generation (Mt) for total Africa until 2050. Baseline Scenario.

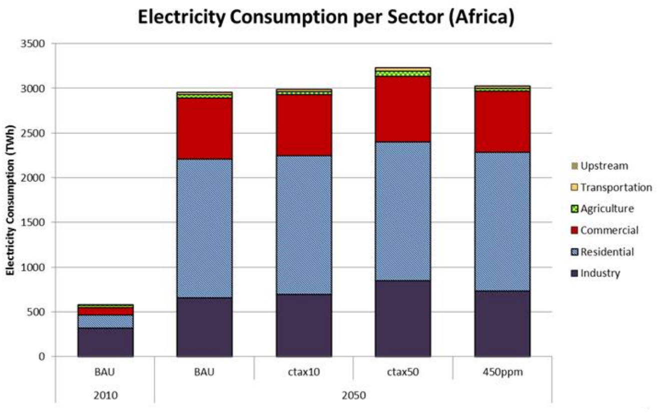
Fig. 6.7. CO_2 from electricity generation (Mt) per region until 2050. Baseline Scenario.

6.2. Scenario Results

The results of the three different mitigation scenarios as defined in section 4.3 will be compared to the base-year scenario. The scenarios will be compared based on the resulting capacity mix and their mitigation potential. The mitigation scenarios have a large effect on the electricity mix and CO_2 emissions. Even the least stringent mitigation scenario reduces carbon emissions by 45% by 2050. This shows the African electricity might be able to leapfrog into a greener electricity system with outside support and investments.

Substitution

Despite total energy demand for all scenarios being equal, electricity demand is higher in the in the mitigation scenarios, especially in the ctax50 scenario (figure 6.8). This is due to the substitution of higher emission fuels by electricity in the mitigation scenarios. The highest substitution is in the industry sector, which has a degree of substitution in all mitigation scenarios. In the Ctax50 scenario substitution in the transport, agriculture and commercial sectors also occurs.



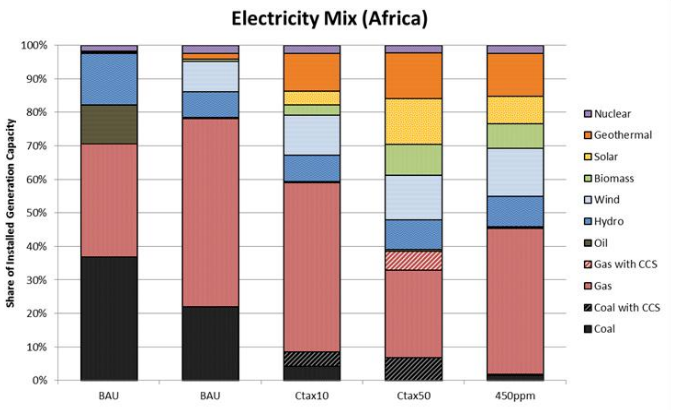


Fig. 6.8. Electricity Consumption (TWh) per sector for total Africa in 2010 & 2050. Comparing Scenarios.

Fig. 6.9. Share of electricity production per technology for total Africa in 2010 & 2050. Comparing Scenarios.

Electricity Mix

All mitigation policies lead to a higher share of low-emission generation capacity, increasing to 45% for the ctax10 scenario, 73% for ctax50 and 55% for the 450ppm scenario from 26% in the BAU (figure 6.9). Coal power is strongly reduced in all three mitigation scenarios, and non-CCS coal capacity is no longer deployed in the ctax50 scenario. In all three scenarios geothermal, hydropower and wind power are roughly equally deployed. In the more stringent ctax50 and 450ppm scenario biomass, solar power and CCS become more prominent in the electricity mix. The share and absolute amount of hydropower in the electricity mix is smaller in the mitigation scenarios than in the baseline scenario.

The mitigation scenarios not only promote a less emission intensive grid, but also a greater diversity in generation capacity. Except for Libya (natural gas), Tunisia (natural gas) and DR Congo (hydropower), no sub-region has a dependence of more than 60% on a single fuel source. Furthermore, as more renewables are introduced into the electricity grid, sub-regions become less dependent on importing fossil fuels. Countries that produce fossil fuels can export more of their product. This creates greater energy security and has economic benefits. However, as wind and solar capacity are intermittent and have small load hours, an increase in these renewables leads to a larger generation capacity to be needed to meet the same electricity demand. This, in combination with the increased demand for electricity due to substitution effects, leads to more generation capacity installed in the mitigation scenarios than in the baseline to ensure security of supply – 1042GW in the Ctax50 scenario compared to 906GW in the baseline.

CO_2 Emissions

CO_2 emissions continue to rise in the electricity sector in the baseline scenario and in at a faster pace than total GHG emissions, as also seen in sector 6.1. All mitigation scenarios reduce emissions compared to the baseline scenario both in CO_2 from electricity generation and total GHG emissions. See figure 6.10 and 6.11 for an overview until 2050 of CO_2 emissions from electricity generation and total emissions.

- The ctax10 scenario increases CO_2 by 40% in 2050 compared to 2010, which is a reduction of 50% when compared to the BAU scenario in 2050.
- The stringent ctax50 scenario has the largest effect on the reduction of CO_2 emissions by electricity generation, reducing emissions by 73% in 2050 from the base-year. In this scenario the CO_2 emitted in 2050 is 96Mt, only 8% of the CO_2 emitted in the BAU in the same year.
- The 450ppm scenario reduces CO_2 emissions in 2050 by 12% from the base-year, or 30% of the CO_2 that would be emitted in the same year in the BAU scenario.
- CO_2 emissions are reduced for all scenarios and in all regions, but reduction potential differs significantly per region (fig. 6.13) with most reductions reached in South Africa, Ethiopia and Morocco and the least in Nigeria and Egypt. These countries with the addition of DR Congo will be reviewed in more detail in section 6.4.
- The effect of all mitigation policies on CO_2 emissions in the electricity sector is both earlier (fig 6.11 and 6.12) and relatively larger compared to their effect on GHG emission reductions from other sectors (fig. 6.14). Land-use emissions decrease for all scenarios and transport increases greatly for all scenarios.
- This suggests that the electricity sector is the most cost-effective sector for reducing CO_2e emissions

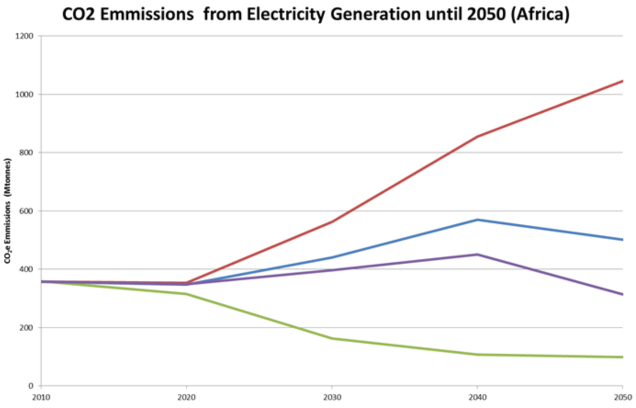


Fig. 6.10. CO_2 emissions (Mt) from electricity generation for total Africa until 2050. Comparing Scenarios.

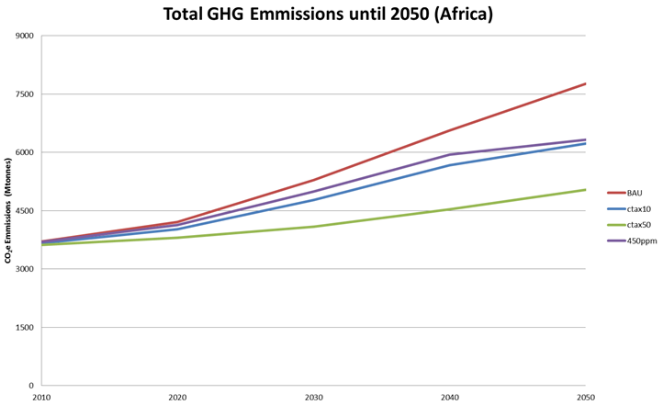


Fig. 6.11. Total GHG emissions (Mt) for total Africa until 2050. Comparing Scenarios.

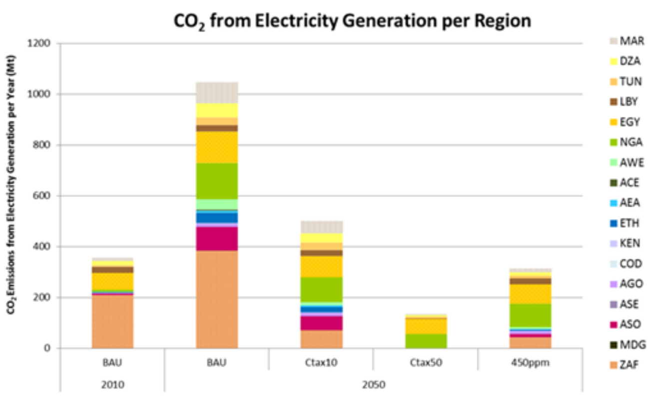


Fig. 6.12. CO$_2$ emissions from electricity generation (Mt) per region in 2010 & 2050. Comparing Scenarios.

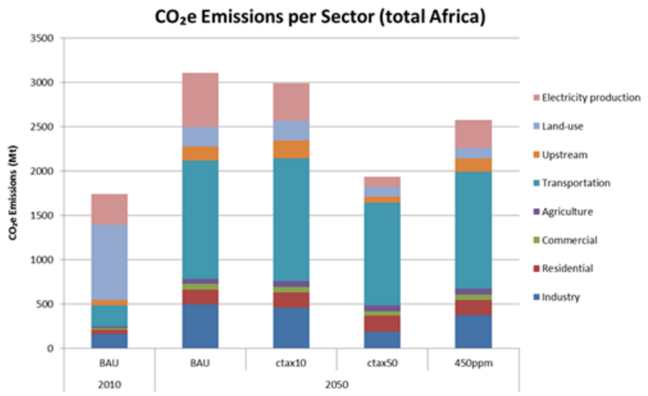


Fig. 6.13. CO$_2$e emissions (Mt) per sector for total Africa in 2010 & 2050. Comparing Scenarios.

Costs of Mitigation Scenarios

Below an over view of the cost of the different mitigation systems is given as well as the total GHG emissions mitigated. As an representation of costs the total undiscounted system costs between the BAU and each mitigation scenario is given, from now on referred to as the Climate Policy Cost. As the model was not updated for costs, these costs should be given as an indication of relative cost differences and not as an absolute value. It can be deduced that the ctax10 scenario is the most cost-effective at reducing emissions while the 450ppm scenario is especially expensive in 2020 and 2030. When considering the entire Africa region, it seems as if the ctax50 scenario is needed in order to achieve a tipping point into a renewable grid. However, as will be discussed in section 6.3. and in Chapter 8, for some regions it is possible to achieve a relatively 'leapfrogged' grid with less stringent policies such as the ctax10 scenario.

It was expected that the costs of the ctax10 would be lower than that of the other scenarios, as the cheapest CO$_2$ is mitigated first. However, the cost difference between the mitigation scenarios was significant – with the ctax50 scenario having an added system cost 7.5x higher than that of the ctax10 scenario, while only mitigating 2.5x as much CO$_2$ by 2050. The 450ppm scenario is the most expensive per tonne of CO$_2$ mitigated. This is due to a high rise in two costs compared to the ctax10 scenario: Firstly, the investment costs are increased. As the model has perfect foresight to the end of the century, this could be due to investment decisions to reduce costs later on. Secondly, trade is reduced. As the 450ppm scenario requires stringent emission reduction from most world regions, trade of fossil fuels is likely reduced, decreasing revenue and increasing system costs.

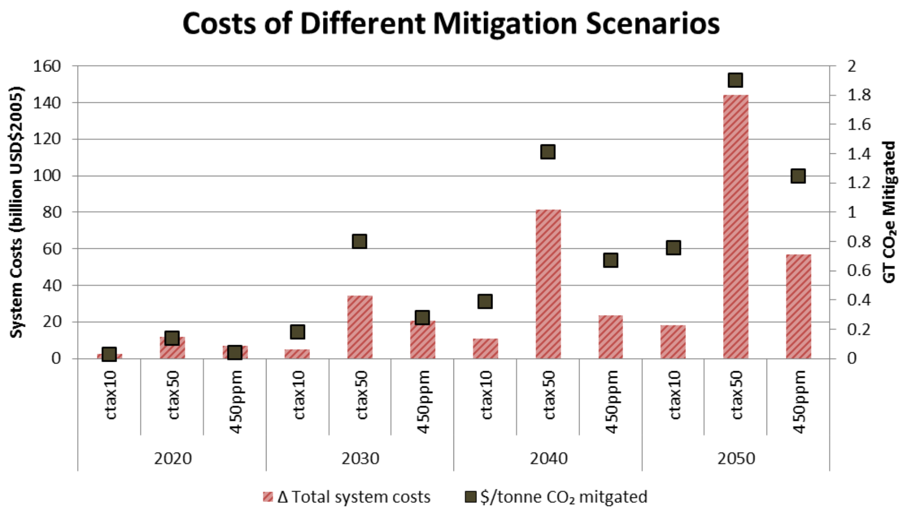


Fig. 6.14. Comparison between the mitigation scenarios of the additional total system costs (billion USD$2005) and the total GHG mitigated (GT) for total Africa to 2050 compared to the baseline

6.3. Regional Focus

It has been shown that there is a large potential for lower CO2 emission generation capacity to be installed in Africa with the help of financial incentives. All regions have lower emissions in the mitigation scenarios than in the baseline scenario, but as can be seen from figure 6.13, this mitigation potential varies considerably per sub-region. North African regions and Nigeria show the least mitigation potential, with South Africa and Ethiopia having the relatively largest mitigation potential. Mitigation potential depends both on the available renewable potential and the amount of the emission intensive coal capacity in the baseline scenario that can be negated. The sub-regions Egypt, Morocco, Nigeria, Ethiopia, the Democratic Republic of Congo and South Africa will be review here in more detail. Egypt and Nigeria due to their large demand growth and small mitigation potential, Morocco, Ethiopia and South Africa due to their large mitigation potential, and the DR Congo due to its hydropower development.

Egypt: As seen in figure 6.5, Egypt has one of the largest demand growths in Africa, mainly due to its predicted fast economic growth. It is expected that most of this increased demand will be met by domestic and imported natural gas. Egypt also has a high on-shore wind potential with high availabilities, and almost all low-cost wind potential will already be installed in the baseline. Outside of the most stringent scenario, where CCS becomes cost-effective, Egypt has one of the lowest emission reduction potentials. The main reasons for this are:

- Continued dependence on domestic fossil resources that are widely available and relatively cheap
- Potential nuclear power is already fully utilized in the base-line
- Wind power potential is cost-competitive with fossil fuels and already fully utilized in the base-line
- The high potential of solar power is not explored in less stringent scenarios because it is relatively too expensive at current predicted costs to compete with fossil fuels and other renewables. Even in the high-CO_2 cost Ctax50 scenario only a small percentage of available solar potential is utilized.

In other words, all low-cost low-emission potential is already utilized in the BAU scenario, with more expensive technologies such as solar and imported biomass being installed in the more stringent mitigation scenarios.

Morocco: In contrast to other North African countries, Morocco has no domestic gas and oil resources. In addition, the country has relatively low renewable potentials (fig. 5.2). Morocco is therefore for a large part dependent on fuel imports. In the business as usual scenario Morocco develops an emission intensive grid, with 50% of generation capacity in the form of coal power plants. In the Ctax10 scenario, more wind-power is used as well as CCS technology for half of the coal generation capacity. In the more stringent scenarios, coal generation is party replaced by biomass and solar, although coal power plays a role in all four scenarios. This is in line with current planned generation increases, which focus for a large part on coal capacity. Reduced CO_2 emissions in the mitigation scenarios are cause by avoiding this coal development or implementing it in combination with CCS. Imposing renewable electricity policies could strongly benefit Morocco in reducing future coal dependence.

Nigeria: Nigeria has the second fastest growing electricity demand in Africa (fig. 6.5). It also has access to a abundance of natural gas to satisfy this demand – natural gas that is currently flared. This makes natural gas competitive even in the more stringent climate scenarios. In the mitigation scenarios, more of the domestically available solar, wind and biomass potential are used, but it is expected that domestic gas will still be the dominant fuel. What is surprising is the share of coal power, with or without CCS, present in all scenarios. Despite Nigeria having some coal reserves (table 5.1), these are generally considered too expensive compared to gas and renewable reserves to explore in the coming decades.

Ethiopia: With a large and diverse renewable reserves (fig. 5.2) Ethiopia has a large potential for leapfrogging. Ethiopia has the fastest predicted demand growth in Africa, with demand increasing more than 30-fold from the baseline. Depending on the mitigation scenario this demand is met by a significantly different generation capacity mix. In the baseline and Ctax10 scenario this demand is met by in part by imported coal and natural gas capacity, at 45% and 30% respectively. In the more stringent climate scenarios all of the coal and most of the gas capacity installed Ethiopia in the baseline is replaced by biomass and solar capacity. This shows that adequate policies for renewables can indeed help Ethiopia to leapfrog into an almost exclusively renewable grid.

DR Congo: Of all sub-regions in the model, the DR Congo has the lowest demand growth and the lowest carbon emissions both currently and in the future. This low demand growth is mainly due to low GDP growth estimations and low current energy use. Carbon reduction policies in the DRC would not only not significantly reduce the – practically non-existent – carbon emissions from electricity generation, but could also be damaging to the development of generation capacity in the country. The DR Congo has one of the highest hydropower potentials in the world, as mentioned in section 5.2.1. This hydropower is more than abundant enough and the most cost-effective way to meet the slow-growing electricity demand to 2050. The model gives a residual amount of biomass and biomass with CCS generation capacity, but in all scenarios more than 98% of total electricity generated will come from biomass. In the 450ppm scenario the total electricity produced is lower than in the other scenarios. This is due to the fact that traditional biomass continues to play a larger role in this scenario. Since the transition from traditional biomass to electricity has many developmental benefits as discussed in section 3.3, any policies that limit this transition should be avoided.

South Africa: Of all sub-regions in the model, South Africa has the greatest mitigation potential. This is mainly due to the current and future emission-intensive coal based grid. Demand growth in South Africa is modest compared to most other African sub-regions, with demand only increasing by 240% by 2050. In the BAU scenario, most of this increased demand would be met through domestic coal generation, with coal capacity doubling by 2050, with the rest of demand met by nuclear capacity and imported gas. However, even with a relatively mild carbon tax most of the coal in the South-African baseline capacity is replaced by gas capacity or coal with CCS. In a more stringent scenario renewable technologies are also explored. In all mitigation scenarios there is less electricity generated in South Africa than in the baseline, as in the mitigation scenarios a significant quantity of electricity is imported from ASE and ASO. Although the model results clearly indicate that South Africa will not leapfrog to a renewable grid with mitigation policies, and that it is likely that fossil fuels remain dominant, South Africa does have the potential to reduce its CO_2 emissions by 98% with a stringent carbon tax and by 63% with a mild carbon tax through use of natural gas and CCS.

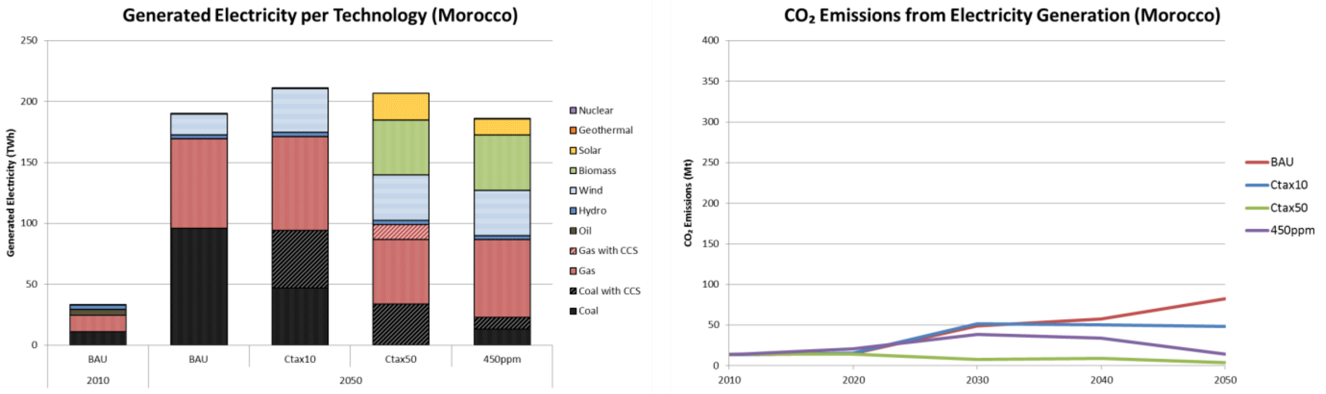


Fig. 6.15a. Generated Electricity (TWh) and CO_2 emissions from Electricity Generation (Mt) to 2050 for the different Scenarios for Morocco

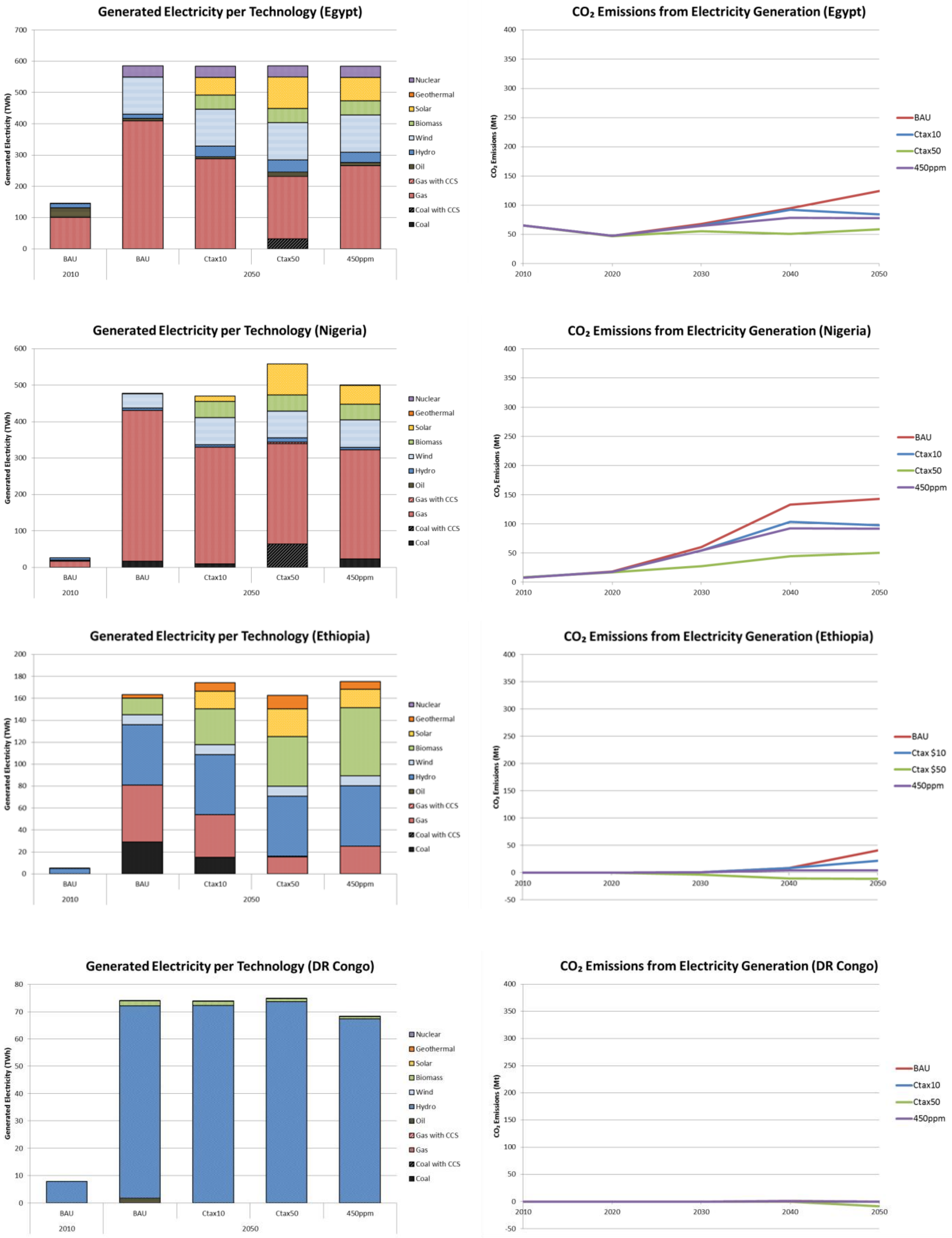


Fig. 6.15b-e. Generated Electricity (TWh) and CO_2 emissions from Electricity Generation (Mt) to 2050 for the different Scenarios for b) Egypt c) Nigeria d) Ethiopia and e) DR Congo

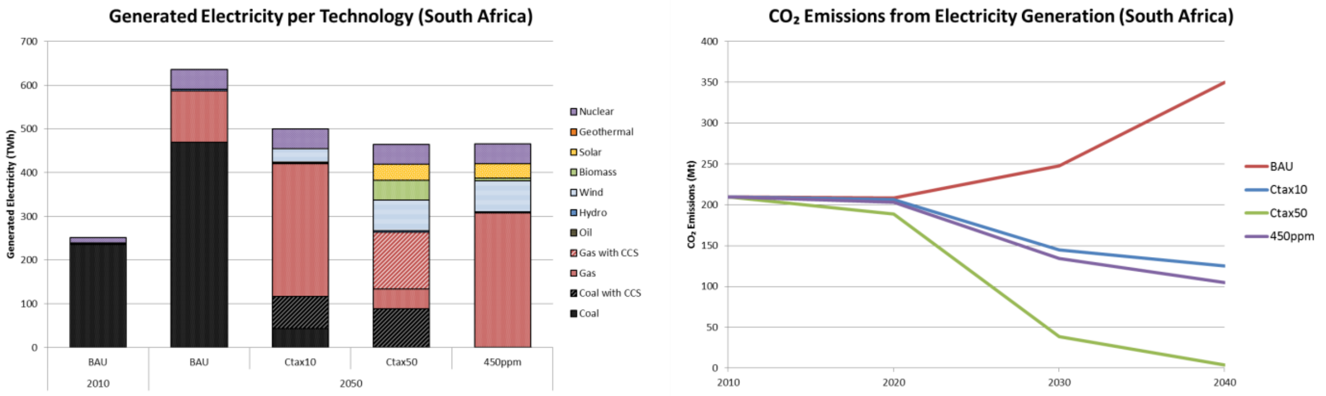


Fig. 6.15f. Generated Electricity (TWh) and CO_2 emissions from Electricity Generation (Mt) to 2050 for the different Scenarios for South Africa

6.4. Baseline comparison with other studies

We compared our results to two other reports recently published on the African electricity sector: The McKinsey report 'Brighter Africa – the growth potential of the Sub-Saharan electricity sector' and the International Energy Agency publication 'Africa Energy Outlook – A focus on Energy Prospects on Sub-Saharan Africa'. The International Energy Agency is a clean energy research organization with great influence with governments. McKinsey is an international consulting agency whose advice is hugely influential for businesses. Both of these reports focus on Sub-Saharan Africa and both run to 2040. To compare our results we only used the outcomes of the 12 Sub-Saharan sub-regions. Instead of using an optimization model to determine future capacity mix the IEA and McKinsey report made use of accounting framework. It is shown that although energy demand and pricing predictions are relatively similar for all three studies, the resulting generation mix without mitigation interventions differs. This is mainly due to large differences in the predicted load hours of wind energy and the trust put into unconditional renewable electricity targets. In order to accurately determine the mitigation potential of different African regions more research into the following areas: 1) the renewable potentials for different regions, as especially for solar, wind and hydropower price is large related to availability. This will be especially difficult for the latter, as it also means taking into account future climate change and droughts 2) the reliability of future conditional renewable electricity targets, to have a better oversight into developing regions strategy for future electricity generation. This issue is likely to also be addressed at the 2015 Paris COP.

Electricity Demand

Electricity demand in Africa is expected to increase Both the IEA and McKinsey assume less-than universal electricity access by 2040, although this number is not further specified. This is in agreement with the findings of Bazilian et al. [2013] and this study as elaborated on in section 7.3. Although the total energy demand has been calculated in different ways, the answer is comparable. The TIAM-ECN has the most conservative estimate, which is mainly caused by a lower amount of electricity used in the industrial sector as described in section 6.1.

Baseline Scenarios

Although overall demand is similar for the three studies, there are significant differences between the three studies regarding electricity generation capacity in 2040 (fig x).

- Coal: The TIAM-ECN model still has significant quantities of coal-generated electricity in 2040 compared to the two other studies. This is due to the fact that both the IEA and the McKinsey study take into consideration new and unconditional pledges by South Africa to reduce its dependence on coal capacity, that are not included in the TIAM-ECN model.

- Wind Power: Although the TIAM-ECN model predicts a significant capacity of wind power to be built (, the IEA report does not contain wind power separately (it is contained under others) while the McKinsey predicts a maximum of 8 GW to be built some of which was already constructed by 2015. The cost of wind power in the McKinsey model is higher than our estimates due to a lack of differentiation between off-shore and on-shore wind. The higher costs end up making wind power uncompetitive.
- Solar power is almost absent in the TIAM-36 baseline scenario, while both the IEA and McKinsey report indicate the utilization of 5-10% solar power. This is due to a much steeper learning curve and slightly lower costs of solar power in the McKinsey model - $725/kWh for McKinsey compared to $800/kWh for TIAM-36 in 2040. THE IEA report does not indicate future prices. However, it is expected that the difference mainly arises due to the inclusion of unconditional pledges in both reports.
- The TIAM-36 model has lower hydro-power capacity than the comparison reports, despite having higher availability (60% for TIAM-ECN compared to 45% for McKinsey and IEA). The difference lies in the fact that the ECN model (and to a lesser extend the McKinsey report) have different cost levels build in for hydropower generation – this makes hydropower increasingly expensive and limits the amount of hydropower in the model. It was decided to build these cost levels as there are only a few river basins in Africa with high hydropower potential, and many with more difficult access. In addition, climate change, droughts and population pressure are expected to add additional pressure on hydropower basins in the future.
- Gas power is lower in the IEA as it competes directly with hydropower in West and Central Africa.
- Finally, the ECN and IEA report allow South African and Egyptian planned nuclear power, while the McKinsey report only allows for South African planned capacity.

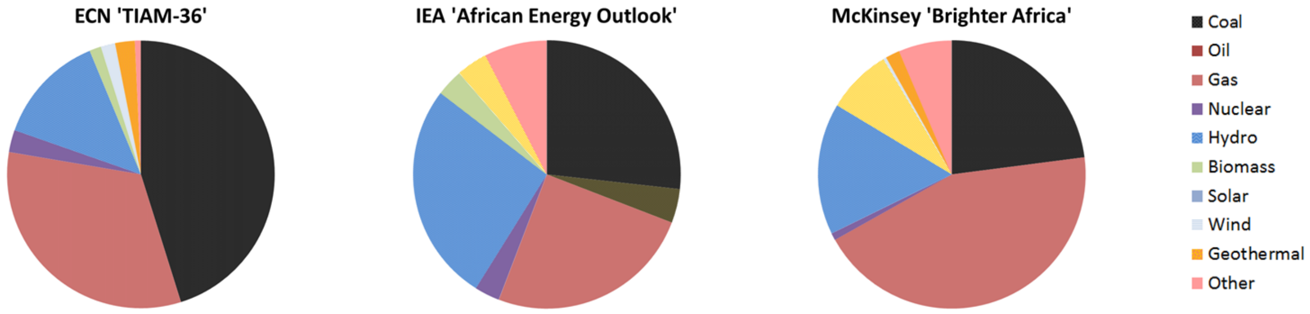


Fig. 6.16. Generated Electricity (TWh) per technology in 2040 for Sub-Saharan Africa in the Baseline Scenarios for the different models.

When looking at the different predictions it can be said that renewables are likely to be market competitive for around a quarter of the market, but the main developments will still be in fossil fuels in Business as Usual Scenarios – or close to Business as Usual in the IEA report. Most of the newly installed renewable capacity will be in hydropower, with the amount of wind and solar capacity very dependent on load hours. Load hours and investment costs in developing countries now have a wide range and need to be further specified for regions to be able to define realistic renewable electricity targets. Gas power is likely to become the dominant form of generation capacity in Africa over the coming decades.

Chapter 7: *Discussion*

This model is only an initial step toward a more specified model for Africa. It still has a number of limitations and shortcomings. Data can be expanded and improved, especially in the industry sector. The model structure can be further updated to suit developing regions even better, especially with respect to traditional biomass. It is the hope that this model can be as a start for further research into Africa, both within ECN and outside of ECN. It is also intended as a first step in further work regarding regional African electricity policy, and only addresses part of the discussion. Here we will discuss several other aspects of the electricity sector in Africa, as well policy options that could be applied to reach leapfrogging. Section 7.1 discusses model shortcomings, while section 7.2 addresses model uncertainty and improvements made. Based on the base-year inputs, section 7.3 covers several insights about planned capacity and section 7.4 discusses the implications on reaching electricity targets. Finally, section 7.5 reviews different electricity policy options for the African power sector.

7.1. Model shortcomings

This model is intended as an initial step toward a better representation of Africa. Several areas of the model can therefore be adapted in the future to improve the results both in data input, where additional data is needed and in the model structure, where some model features can be further adapted to be better suited to describe the African sub-regions and to . The most important are listed below.

Data

For this model many hours of data-searching has been put in. The amount of data in the TIAM-ECN model for Africa has been greatly improved. However, there are still large gaps and some unproved assumptions in the model.

- *Renewable load hours:* Little research has been done into the load hours of renewable capacity for different African regions. Load hours were only found for a small number of regions (table 4.1). Differences between high and medium load hour regions are expected to make a large difference in LCEO for renewable. McKinsey [2015] reported a difference up to $40/MWh in costs by 2040 for wind power depending on load hour estimates. To correctly judge the costs and competitiveness of renewables it is important to define load hours for different regions through local measurements.
- *Industry & Upstream fuel-share data:* Although the total energy demand was specified for the different industrial and upstream sectors, the share of fuel used for each process was not updated, but instead taken from the previous Africa model.
- *Energy demands (general):* Energy demands came from a variety of sources, with different methods and definitions. This increases the uncertainty in the model. Further work and fieldwork would be necessary to define these demands further and according to the same methods.

Model Structure

- *Biomass substitution:* The use of traditional biomass in Africa is large, representing up to 95% of all energy use in certain regions and used everywhere extensively except for the North African countries [IEA2014(I)]. It is expected that following access to modern fuels , traditional biomass will be rapidly replaced by modern fuels. Currently the model directly substitutes fuels. Traditional biomass is however not only used for a single purpose: For example, using biomass for cooking also has the secondary benefits of heating and lighting. In order to model the substitution of traditional biomass correctly, substitution of biomass will to be replaced by fuels for cooking, lighting and heating. More research needs to into traditional biomass substitution and how to substitute this substitution into models and policy recommendations.

- *Industry sector fuel substitution:* As seen in figure 6.4. the model currently substitutes electricity for other fuels in the industry sector. This results in the electricity demand for the industry sector being lower in 2050 than in 2010 in the baseline scenario. This could be adapted by reviewing the fuel elasticity for the industry sector, by reviewing the fuel share per industrial demand (see 'data') and gathering more data on industrial fuels used and fuel costs.
- *Industrial energy demands:* The current industrial energy demands division as shown in table 4.3 was taken from the previous TIAM-ECN model. In this division, the petro-chemical sector falls under the chemical sector. As the petro-chemical industry is one of the largest users of energy and non-energy fuel in Africa, identifying energy demands and fuel shares for the petro-chemical industry sector could improve the accuracy of the model.
- *Size added capacity:* Currently the minimum size of added is not restricted. A possible future addition to the model could be the restriction of a unit of generation capacity. As the amount of generation capacity for African regions is generally low, a certain technology is sometimes deployed in a smaller volume than a minimum plant size. Adding a minimum capacity size would however introduce many complications into the model such as the decreasing LCEO of a plant with more electricity produced and the investment barrier to adding a new plant, as well as the distinction between macro and micro generation capacities. This might be too intricate for an integrated assessment model covering the entire energy system.

Scenarios

It is also realized that more scenarios need to be tested to accurately reflect the costs of renewable generation capacity, and to research which policies – tax, subsidies, foreign technology investments – would be most appropriate for different African sub-regions. With the carbon tax scenarios in this thesis the sub-regions were identified that were most susceptible to leapfrogging. Further research most now be conducted for these regions to identify the mitigation measures most appropriate, and to identify means of funding for these mitigation measures.

7.2. Uncertainty

When dealing with data-intensive model, uncertainty in data is always an issue. This issue becomes more serious when dealing with a model where much of the data comes from different sources and many estimations have to be made. For many of the African sub-regions data is unavailable or unreliable because research into the topics have never been done, much of the trade and industry is done in the informal sector, and much information is politically sensitive and biased. Even the IEA data, the backbone of the TIAM-ECN model, lacks data for certain countries and years, and clearly over and understated values – influenced by the fact that this data is also based on government reports [IEA 2014(I)].

For most values in the model alternative sources had to be found or assumptions were made. Although it can be argued that these estimations increase uncertainty, it should not be overlooked that 1) much of the data estimated was data that before was not included in the model at all, and the model was therefore underestimating the African electricity sector and 2) the model was before based mainly on IEA data which had obvious flaws. It can be stated that the model before contained 'unknown unknowns' – it was not clear which data was missing and which data was flawed. The TIAM-36 still contains many uncertainties and approximations, but it is clearer which data is unknown and which data might be flawed. In essence, the model now contains 'known unknowns'. These known unknowns can now be tackled in further research to improve the model. Below this argument is demonstrated by reviewing several residential energy demands.

Energy Demands

Due to the unknown unknowns energy use for Africa was underestimated for certain demands and underestimated for others. In the previous TIAM model, fuel shares per energy use for the whole African region were divided according to the known South African shares. For regions were not even a South-African average was known, Latin American shares were used. This led to flaws in the energy demand projections. For example, due to different climates and cultures using South African averages led to a significant overestimating of the energy used in heat and hot water and a underestimation of the energy used in cooling as shown in table 8.1. Having more detailed values for the different African regions will also benefit the certainty of results when the aggregated African region is used.

Energy Use in Africa in 2010 (PJ)	TIAM-ECN 20	TIAM-ECN36	Difference
Residential Heating	322	152	-170
Residential Hot Water	655	330	-325
Residential Cooling	31	81	50

It is clear that the data uncertainty increased due to the use of the many different sources. However, the uncertainty is also reduced because the model is now a more accurate representation of the continent. As it were, the unknown unknowns – or unknown uncertainties – were replaced by known unknowns – or known uncertainties. By aggregating the data again a new Africa region would be formed that could be used for global energy studies that do not need sub-regional detail, and this new aggregated Africa region would be more accurate in its representation of the continent.

Regions

The availability of data differed significantly between the regions. As expected, data was relatively available for South Africa and the North African countries. For much of Sub-Saharan Africa data was lacking, especially concerning the industry and transport sector. Data was especially scarce for the Central Africa, East Africa and Madagascar sub-regions. These regions also currently lacked many electricity demands, and thus required assumptions on when these demands would arise and how they would develop. Although the assumptions made will provide reasonable estimates for the sub-regions, especially when used for a new aggregated African region as mentioned above, if a study would be undertaken for one of these regions specifically, it would be imperative that more data was gathered. As much of this data is not yet available, extensive field studies are likely required to gather this data.

7.3. Planned Capacity Insights

Few comprehensive data overviews of African energy statistics exist, especially that compare data on the regional scale. The database gathered for this thesis provided several key insights in its own right. Here we will review the 2010 capacity installed, current (2015) capacity and planned capacity for 2020. From this we find that for most African countries no significant namely the 2010, current (2015) and planned generation capacity for 2020, and what the trend in installed capacity means for 2020 and later electricity availability in African sub-regions. Planned generation capacity also gives an indication of countries environmental commitments.

Current and Planned Generation Capacity

Using 2010 installed capacity (as described in section 5.2) in combination with government pledges, reports from investors and additional news articles were used to construct an overview of the current capacity (2015) and planned capacity to 2020. This 2020 overview was used to check and calibrate the model – the planned capacity for 2020 was the maximum capacity that could be constructed. In this section the data on planned capacity will be used to deduce information about the electricity availability in the African sub-regions in 2020. This information will then be compared to targets for the year 2020 and 2030, and a short review will be given on the changes needed to reed 2030 targets.

In table 7.2. an overview of baseline, current and planned capacity is given for each African sub-region. In the bottom part of the table, the planned doubling and % of targets reached are given. It is important to realize here that countries have very widely varying targets, with Ethiopia hoping to increase its installed capacity 20-fold, whilst most countries have planned a 2 or 3 fold increase. It must also be realized that an increase installed capacity does not have to have a linear relation to electricity produced. Firstly, many countries also have targets to increase power plant efficiencies and reduce losses, which will also lead to increases in available electricity [Climatescope 2014]. Secondly, as wind, solar and hydropower have a significantly lower availability more generation capacity is needed to produce the same amount of electricity.

2010 capacity	MAR	DZA	TUN	LBY	EGY	AWE	NGA	ACE	AEA	ETH	KEN	COD	AGO	ASE	ASO	MDG	ZAF	AFR
Coal	1885	0	0	0	0	152	0	26	100	0	0	0	0	1733	16	29	38375	42316
Gas	2828	11555	3946	3503	16288	956	7453	542	5	0	268	191	1022	25	532	87	412	49613
Oil	1376	640	1039	4564	4096	3319	1197	607	2108	148	617	53	228	745	287	153	25	21202
Hydro	1486	276	61	0	2846	2374	1979	2299	1578	1391	750	1800	802	3355	2749	122	2267	26135
Wind	243	0	70	0	415	17	0	4	15	0	5	0	0	12	0	5	10	796
Biomas	0	0	0	0	0	27	0	12	0	0	60	2	0	0	0	0	46	147
Solar	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	3
Geothermal	0	0	0	0	0	0	0	0	0	8	204	0	0	0	0	0	0	212
Nuclear	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1930	1930
Total	7818	12471	5116	8067	23645	6845	10629	3490	3806	1547	1904	2046	2052	5870	3584	396	43068	142354

Capacity Installed between 2010 & 2015	MAR	DZA	TUN	LBY	EGY	AWE	NGA	ACE	AEA	ETH	KEN	COD	AGO	ASE	ASO	MDG	ZAF	AFR
Coal	0	0	0	0	0	0	300	0	0	0	0	0	0	600	0	0	5200	6100
Gas	500	2845	0	0	5980	311	774	0	262	0	0	0	0	90	0	0	444	11206
Oil	0	0	0	0	1382	0	0	0	0	220	0	0	0	0	0	0	0	1602
Hydro	0	0	0	0	0	62	0	0	120	4169	766	24	0	0	0	0	1133	6274
Wind	16	0	20	0	155	0	0	0	0	0	0	0	0	0	0	0	459	650
Biomas	0	0	0	0	0	-27	0	37	0	0	0	0	0	0	0	0	0	10
Solar	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	75	75
Geothermal	0	0	0	0	0	0	0	110	0	0	400	0	0	0	0	0	0	510
Nuclear	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Total	516	2845	20	0	7517	346	1074	147	382	4389	1166	24	0	690	0	0	7311	26427
																		0.28451962

2020 Planned Additional Capacity	MAR	DZA	TUN	LBY	EGY	AWE	NGA	ACE	AEA	ETH	KEN	COD	AGO	ASE	ASO	MDG	ZAF	AFR
Coal	2676	0	0	0	4000	586	1200	26	660	0	0	0	0	4783	4520	29	8290	26660
Gas	1126	6200	778	3620	19000	2621	7251	149	249	149	782	145	188	1749	1040	87	2102	46764
Oil	88	1164	1879	3242	952	1470	823	109	824	13836	565	25	224	890	118	210	6991	31506
Hydro	1312	0	2	0	93	4314	1857	4508	2778	1020	335	349	2597	2842	4401	458	898	25724
Wind	1498	50	194	50	2508	411	710	296	1036	90	480	0	50	339	400	45	1250	9407
Biomas	201	10	120	0	267	190	34	12	164	100	507	0	0	481	110	0	754	2926
Solar	2160	1275	60	100	100	196	1136	0	0	1238	0	0	0	50	0	0	352	6667
Geothermal	160	0	0	0	100	0	0	0	950	8	2998	0	0	0	0	0	343	4543
Nuclear	0	0	0	0	2400	0	0	0	0	0	0	0	0	0	0	0	3200	5600
Total	9221	8699	3033	7012	27516	9940	19356	4726	6661	14385	4582	519	3059	11134	10589	597	24180	165209
																		0.298210146

Targets	MAR	DZA	TUN	LBY	EGY	AWE	NGA	ACE	AEA	ETH	KEN	COD	AGO	ASE	ASO	MDG	ZAF	AFR
Planned Share of Renewables in 2020	41%	8%	6%	1%	12%	45%	24%	87%	62%	11%	71%	84%	67%	42%	54%	63%	9%	25%
Planned doubling 2010-2020	2.18	1.70	1.59	1.87	2.16	2.43	2.22	2.35	2.75	10.30	3.98	1.25	2.49	2.90	3.95	2.51	1.56	2.12
% of 2020 target reached in 2015	6%	33%	1%	0%	27%	3%	6%	3%	6%	31%	25%	5%	0%	6%	0%	0%	30%	16%

Table 7.2. Overview of 2010 capacity, 2020 additional planned capacity and progress made toward target for each sub-region and each technology

From table 6.1. several initial conclusions can be drawn. Firstly, most countries have ambitious plans for installed capacity development toward 2020, but targets vary strongly between sub-regions from a 125% in DR Congo to a 1030% increase in Ethiopia. Only few sub-regions are approaching their targets – only Algeria, Egypt, Ethiopia, Kenya and South Africa have taken made meaningful progress. Of these countries only Ethiopia and Kenya are currently suffering from severe electricity poverty, with 23% electricity access in both countries [World Bank

Database]. Most impressive is Ethiopia, that has already tripled its installed capacity in the past 5 years by exploiting its hydropower potential. However, they are planning to triple their current capacity again by 2020, which would turn them from one of the most electricity poor countries to a significant electricity exporter. Several sub-regions have not or barely added capacity in the past 5 years. This will have a large influence on achieving electricity access targets and economic development. For these sub-regions our model projects of capacity installed in 2020 is likely to be an overestimation. More policy, funding and technical support is nessecary to reach generation capacity goals.

Secondly, the share of renewables is 25% in 2020, up from 19% in 2010. Almost a third of all new installed capacity is renewable, higher than predicted in the BAU model scenario. This would indicate that renewable electricity generation is a priority of African governments. However, it is especially this renewable generation capacity – and in particular non-hydro capacity – that has not yet been constructed by 2015. This shows that liability and policy support are necessary for renewable capacity to succeed. In addition, 35% of planned capacity is the form of high-emission heavy fuel oil plants and coal fired power plants. This shows that if no mitigation intervention is taken, a more emission intensive grid will develop.

7.4. Reaching Electrification Targets in Developing Sub-Saharan Africa

Electrification targets have long been part of African development policy. In 2001, the New Partnership for African Development (NEPAD) set the objective: ‘‘to increase from 10% to 35% or more, access to reliable and affordable commercial energy supply by Africa’s population in 20 years’’ [EU Commission 2008]. This objective was soon followed by more ambitious targets set by the Regional Economic Communities (REC’s), aiming for between 50-100% access by 2015 [Brew-Hammond 2009, CEMAC 2006; ECOWAS, 2006; FEMA, 2006]. These objectives have turned out to be overly optimistic, especially as expected investments failed to materialize. Already in 2005 the World Bank and Fall [2005] stated that the target of 50% access to electricity by 2015 was unlikely to be achieved, and that a more realistic target would be 35% by 2015 and 48% by 2030, taking into account the difficulties of expanding access to rural areas [World Bank 2006]. The original goal of 50% electricity access in Sub-Saharan Africa in 2015 is indeed far from a reality - by 2014, only 32% of SSA’s population had access to electricity.

More recently the international community has had increased attention to the developments of electricity poverty in Africa, and new targets have been set both by international organizations and local governments. On the 30th of June 2013, President Obama of the United States announced the ‘Power Africa’ Initiative – a cooperation between the US Agency for Development, African governments and the power sector aimed at installing an additional 30GW of generation capacity across the continent [USAID 2015]. The most prominent target set by the development community is the UN initiative SE4ALL. Their objective is to reach universal access to electricity by 2030 primarily through renewable electricity. Energy access is here defined as defined as an access of 50KWh (rural) to 100KWh (urban) per person per year [SE4ALL 2015]. Several African countries have stated their own targets next to the 2030 timeline, with Kenya hoping to achieve a 100% grid connectivity by 2020 and Nigeria aiming at 75% electricity access to be achieved through expansion of current grid capacity to rural areas and the utilization of local renewable potentials [Climatescope]. For a full overview of African countries electricity target see appendix 3.

In order to obtain the SE4ALL objective an annual growth rate of 13% in installed capacity would be required from 2015 until 2030 – which sounds ambitious, especially when considering capacity is currently being added at 1.7% per annum [Bazilian 2011]. Generation capacity in Africa has increased by 43% in the period 2000-2014 [IEA 2014(I)] , and most countries have barely added generation capacity since 2010 (section 7.2). In addition, most of the added capacity has been in the form of fossil fuel plants, although there has been some investment in (large-scale) hydropower, geothermal and solar generation. Experience has shown that rapid electrification is possible. Thailand recently managed to upscale from a 25% to a 100% electrification rate in less than a decade [Bazilian 2013]. However, current African actions to reach their electrification targets are lacking in both scale and pace. At present African countries on average spend less than 3% of their GDP on their power sector, with operating costs absorbing 75% of the total spending [Eberhard et al., 2008]. This means less than 0.5% of GDP is devoted for public investment in the electricity sector, which is woefully low when compared to Western economies that spend an average of 5 of their GDP on more established grids [CASE 2008]. In order to achieve universal electrification, especially using renewables, large scale investments will be necessary in the power sector throughout Sub-Saharan Africa.

Electricity access and our model results

Electricity generation increases more than 4-fold between 2010 and 2050 in the TIAM-ECN model. However, due to increasing population and increased energy access this does not mean that the electricity generated per capita will increase. The SE4ALL target, which is also the target for most African countries, is universal electricity access by 2030. Research say this target is more likely to be reached around 2050 [World Bank 2011]. In our model the kWh/capita available per capita in developing Sub-Saharan Africa, assuming 100% electricity access by 2050, decreases between 2010 and 2050 for most regions and remains equal for others. Only Nigeria and Ethiopia show an increase in electricity/capita available. This is in accordance with the predictions from the African Energy Outlook (IEA 2014(I)].

Since the SE4ALL target is only 250kWh per year per person with electricity access, all regions in our model except for MDG (172kWh/capita) will reach this target – with East Africa just making the target at 280kWh per capita. In order for African regions to reach meaningful energy access as defined by Bazilian [2013] installed capacity in Sub-Saharan Africa will need to be of an order of magnitude larger than follows from energy demand in our current model. In order to not decrease the electricity available per capita with current electricity access targets and predicted population growth, almost double the generation capacity projected by this model will need to be installed. This would have a large effect on potential mitigation and the costs of different technologies. It could therefore be valuable to run a scenario with higher energy demands based on not only reaching modern energy access, but meaningful energy access. This option is currently explored by ECN.

Finally, when comparing the SE4ALL targets with the current electricity use of other countries (fig 7.1), it is clear how low the 100kWh/person/year target actually is. This is further shown by the fact that 100kWh/year would be enough power to light a single lightbulb for just a few hours a day. It has been argued that the SE4ALL targets are aimed more at poverty management than at the transformational change needed for poverty alleviation [Bazilian 2013, Collier 2013]. Current electrification targets are severely underestimating the ambition of Africa's economic development.

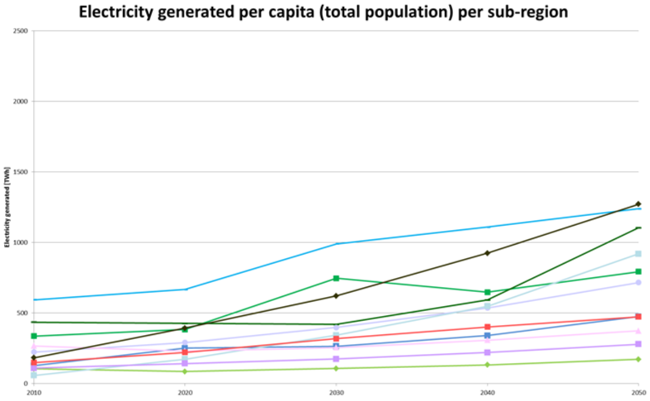


Fig. 7.1. Electricity per Capita per sub-region SSA until 2050 in BAU.

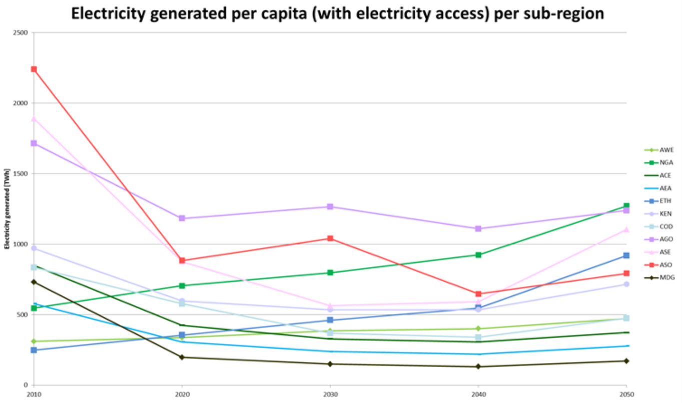


Fig. 7.2. Electricity Available per Capita with Electricity Access per sub-region for SSA until 2050 in BAU

7.5. Implications and Policy Recommendations

In this thesis we have shown that it is possible for some African sub-regions – in particular those regions with little fossil resources and South Africa – to develop an electricity grid focused around low-emission capacity with the support of mitigation scenarios. A combination of domestic policy and international funding could support this development. Currently there are few international incentives that promote African renewable electricity on a policy scale. Most actions undertaken to promote clean development have a limited development focus as the SE4ALL and Power Africa are project based, instead of providing a long-term policy focus.

There are three main options to promote renewable electricity in African regions: 1) International Assistance such as Development Aid and Clean Development Mechanisms (CDM's) 2) policies to promote renewable generation capacity and 3) policies to disincentivize high-emission generation capacity. This thesis reviewed the latter, which although highly effective in reducing emissions, are likely to be too costly for African regions to implement. Several African countries are already demonstrating leadership in mitigation actions, instating feed-in tariffs and tax exemptions for renewable generation capacity (appendix 3). Due to lack of financing and ineffective governance these incentives are however difficult to enforce and implementation of these policies is lacking [IEA2014(I), Africa Progress Panel 2015]. Development assistance has often focused on single projects and temporary change. Three reduction policy options will be shortly reviewed here for their application in Africa: CDM, reform of fossil fuel subsidies, and carbon tax.

Clean Development Mechanism

The CDM is based on the fact that emissions need to be reduced globally, and that developing regions have a greater potential to reduce emissions that developed regions. It is more cost-effective to construct a clean-energy plant in Africa than to retro-fit a European or American plant – and even more so considering that the fossil fuel plant otherwise constructed in Africa will also need to be retro-fitted in several decades. In the CDM, developed nations fund sustainable development projects in developing regions aimed at reducing emissions. The uptake of CDM's in Africa has been extremely low, with only 2% of all CDM project located in Africa [UNEP 2012]. This is caused due to the fact that CDM projects require intensive local monitoring and technical support, for which the capacity is lacking in most African regions. In addition, development of projects is often too costly for African countries, especially with the current low carbon price. In order for the Clean Development Mechanism to make a significant difference in Africa, it would have to be reformed to suit the needs of African regions. In addition, NGO's and foreign governments could provide training to African countries to develop CDM projects.

Reform of fossil fuel subsidies

One of the most important steps to promoting renewables is the abolishment of extensive subsidies on fossil fuel capacity, which are prevalent throughout Africa. These policies both reduce the competitiveness of renewables and curtail electricity investments in general by lowering the electricity price. They also put a burden on national governments and increase the risk for foreign investors. The money saved from these subsidies could be used to directly invest in new generation capacity, to increase electricity access or to subsidize renewables [Africa Progress Panel 2015, AfdB 2010].

Carbon Tax

One of the instruments used in this thesis to achieve emission reduction were the carbon tax scenarios. Carbon taxes have been shown to reduce Sub-Saharan growth by several percent even with a carbon tax as low as \$1/tonne of CO_2. Carbon taxes are therefore unlikely to be implemented in Sub-Saharan Africa in the coming decades. For North African countries, reducing or abolishing fossil fuel subsidies is will likely be a better alternative to carbon tax in the coming years [AfdB 2010]. South Africa has however been reviewing the implementation of a carbon tax for 2016, and research by Winkler [2005, 2007, 2009] and Alton [2014] have shown that the implementation of a carbon tax could reduce carbon emissions at a low socio-economic cost, due to most savings being made by increasing energy efficiency and reducing energy intensity.

Chapter 8: *Conclusion & Final Thoughts*

The aim of this thesis was to research the effects of different mitigation scenarios on the African electricity sector and see if there were possibilities for leap-frogging in the different scenarios. Furthermore, it was aimed at further exploring the benefits of these mitigation pathways and the benefits and constraints of a regional African electricity model. A number of conclusions can be drawn from our results: 1) African energy and electricity demands are rapidly growing 2) without mitigation scenarios the development of the African electricity sector will be mostly fossil fuel based 3) generation capacity is elastic with mitigation scenarios and leapfrogging is possible in certain regions 4) even relatively mild mitigation scenarios have large effects on CO_2 mitigated and diversification of the generation capacity 5) The electricity sector shows the largest reduction between mitigation scenarios 6) The 450ppm scenario would achieve significant carbon reductions in Africa, but is less stringent for Africa than for other world regions. These six conclusions are discussed in more detail below. Finally, it is concluded that the different African regions have different generation capacity development over the coming decades. In order to gain an accurate insight into the effect of any climate policy on Africa, this diversity should be taken into account.

1. Energy demand for Africa will increase nearly 3-fold from 2010 to 2050. Electricity demand will be the fastest growing demand after liquid fuels and will increase 5-fold in the same time period from 680 TWh to 3500 TWh. This will require at least an equal growth in generation capacity although decreases in transmission losses can also contribute toward increasing electricity supply. The demand as predicted in the model will achieve similar per capita electricity consumption for those with electricity access in 2050 as in 2010 for developing Sub-Saharan Africa. To achieve the meaningful electricity needed for economic and social development an even greater increase in capacity is needed. Installation of new capacity in recent years have been below planned capacity and far below what is needed to meet electricity demand.

2. In a business as usual scenario the development of the African electricity sector will be largely – around 80% - fossil fuel based. The majority (60%) of newly installed generation capacity will be gas powered, which is in agreement with other studies such as the McKinsey 'Brighter Africa' report and the African Energy Outlook. Gas power will be installed in all regions except for the DR Congo and Madagascar. The increased gas capacity will require increase exploitation of African natural gas and utilization of currently flared gas. The increase of fossil capacity will cause a tripling of CO_2 emissions by 2050 to 1.1Gt, with a possible 2000% increase by the end of the century. Electricity generation is likely to become the biggest emitter of CO_2 in Africa by the middle of the century.

3. In order to research the potential of different African regions to develop a less emission intensive generation grid and 'leapfrog' fossil fuel generation capacity, we ran three different mitigation scenarios: A \$10/tonne carbon tax, a \$50/tonne carbon tax, and a global 450ppm emission cap. All mitigation scenarios resulted in an increase of renewable capacity and a reduction of CO_2 emissions. The extend of possible emission reductions differed per sub-region. Ethiopia, Morocco and South Africa can achieve the most reductions; South Africa by reducing its reliance on high-emission coal plants, and Ethiopia and Morocco through the construction of large-scale renewable capacity. Gas and oil producing regions such as Nigeria and Libya show the least reduction potential. However, the majority of the generation capacity in these sub-regions are gas-fired power plants using gas that would otherwise be flared.

4. When reviewing the different scenarios in this model, it is clear that the least stringent mitigation scenario – ctax10 – already has a large positive effect on the installment of renewable capacity. In addition, it limits the construction of coal capacity in much regions in favor of gas-fueled power plants. Finally, the carbon tax helps diversify the electricity grid by leading to more generation types installed per region. Although carbon taxation is an expensive option for most African regions, similar effects could likely be achieved by abolishing fossil fuel subsidies and increasing foreign renewable investment. Although African sub-regions likely do not possess the funds to introduce mitigation scenarios, development aid, foreign investment and global carbon trade could result in a significantly greener African grid and perhaps even lead the power sector to leap-frog in certain sub-regions.

5. Under all mitigation scenarios, most of the GHG emissions are achieved by reducing the CO_2 from electricity generation. This indicates that when the aim is to mitigate African carbon emissions, the electricity sector would be the most cost-effective to achieve this target.

6. Finally, in this thesis both carbon tax and a 450ppm scenario were used. The 450ppm scenario is generally the most stringent carbon reduction scenario used in developed nations. Although this scenario achieves significant CO_2 reduction for Africa, the effect is less stringent than shown for developed nations, for example in Gunnar [2012]. This shows that in a global carbon cap scenario Africa will not leapfrog into an entirely clean power sector – and that it is thus not the cheapest option to mitigate all African carbon emissions. More research is needed on the relative effect between African and other World regions.

Final thoughts

It has been shown that African regions can leap frog – especially non-oil producing developing Sub-Saharan Africa and Morocco – and that they need relatively little funding to achieve significant green development. This indicated that renewables are near-competitive with fossil fuels. Renewables can be further promoted in different ways: Through carbon tax, foreign investment, development aid and removal of fossil fuel subsidies. Assistance with regards to clean electricity would be best focused on those countries and regions where the most benefit can be reached at the least cost. Not only will promoting clean development in Africa be beneficial worldwide because of lower emissions, it will also benefit electricity security by diversifying generation sources and will help prevent leakage through energy intensive industries when developed countries install more stringent measures.

Africa's primary focus for the coming decades however should be promoting electricity access in general. Current efforts to increase capacity are far below what is needed to reach electricity access targets, let alone to reach the level of electricity consumption necessary for economic growth. The development of a clean electricity grid in Africa should be a global priority, not an African priority. The reform of incentive mechanisms such as the CDM as well as the promotion of foreign investments can help reach electrification targets.

It is hoped that this thesis and work by institutes such as ECN and the Cape Town Energy Research Centre can help spark further discussion about the development of generation capacity in Africa. Africa is a diverse continent, and each region has different opportunities for development. With adequate financial and policy support, different regions could indeed leapfrog toward a green electricity grid.

Appendix 1: Thesis References

Acker, Richard H., and Daniel M. Kammen. "The quiet (energy) revolution: analysing the dissemination of photovoltaic power systems in Kenya." Energy Policy 24.1 (1996): 81-111.

Adamantiades, Achilles, and I. Kessides. "Nuclear power for sustainable development: current status and future prospects." Energy Policy 37.12 (2009): 5149-5166.

AfdB. "The Arab Republic of Egypt: The Power Sector in Brief: AfdB: Abidjan (2010) < http://www.afdb.org/fileadmin/uploads/afdb/Documents/Publications/ENERGY%20mpa%20ENG%20Power%20Sector%20Emer.pdf>

AfdB. "African Economic Outlook 2015" (2015) http://www.africaneconomicoutlook.org/fileadmin/uploads/aeo/2015/PDF_Chapters/Overview_AEO2015_EN-web.pdf

Africa Progress Panel. "People, Planet, Power: Seizing Africa's Energy and Climate Opportunities". *Africa Progress Report.* 2015.

Aker, Jenny C., and Isaac M. Mbiti. "Mobile phones and economic development in Africa." Center for Global Development Working Paper 211 (2010)

Akinlo, Anthony Enisan. "Electricity consumption and economic growth in Nigeria: evidence from cointegration and co-feature analysis." Journal of Policy Modeling 31.5 (2009): 681-693.

Anandarajah, Gabrial, Olivier Dessens, and Christophe McGlade. "Modelling of global energy scenarios under CO2 emissions pathways with TIAM-UCL." (2013).

Apergis, Nicholas, and James E. Payne. "A dynamic panel study of economic development and the electricity consumption-growth nexus." Energy Economics 33.5 (2011): 770-781.

Attia, Shady, Arnaud Evrard, and Elisabeth Gratia. "Development of benchmark models for the Egyptian residential buildings sector." Applied Energy 94 (2012): 270-284.

Azoumah, Yao, D. Yamegueu et al. "Sustainable electricity generation for rural and peri-urban populations of sub-Saharan Africa: the "flexy-energy" concept." Energy Policy 39 (2011)

Baker-McKenzie. The Future for Clean Energy in Africa. *Clean Energy Pipeline Report.* (2013)

Barnes, D.F., Fitzgerald, K.B. and Peskin, H.M. "The Benefits of Rural Electrification in India: Implications for Education, Household Lighting and Irrigation". *Background Study for India Rural Energy Access Strategy*. Washington D.C.: World Bank (2002)

Barnes, D.F., Krutilla, K. "The Urban Household Energy Transition". *World Bank Research Report*. World Bank: Washington DC. (2004)

Bazilian, Morgan, et al. "Measuring energy access: Supporting a global target." Earth Institute, Columbia University, New York (2010).

Bazilian, Morgan, et al. "Energy access scenarios to 2030 for the power sector in Sub-Saharan Africa." (2013(I)).

Bazilian, Morgan, et al. "Re-considering the economics of photovoltaic power." Renewable Energy 53 (2013(II)): 329-338.

Beck, Thorsten, and Robert Cull. "Banking in Africa." World Bank Policy Research Working Paper 6684 (2013)

Bhattacharyya, S. "Rural Electrification Through Decentralised Off-grid Systems in Developing Countries". London: Springer (2013)

Birol, Fatih. "Energy economics: a place for energy poverty in the agenda?." The Energy Journal (2007): 1-6.

Birol, Fatih. "Energy for all: the next challenge." Global Policy 3.2 (2012): 184-186.

Bongaarts, John. "Household size and composition in the developing world in the 1990s." Population studies 55.3 (2001): 263-279.

Brand, Bernhard, and Jonas Zingerle. "The renewable energy targets of the Maghreb countries: Impact on electricity supply and conventional power markets." Energy Policy 39.8 (2011): 4411-4419.

Brew-Hammond, Abeeku, and Francis Kemausuor. "Energy for all in Africa—to be or not to be?!." Current Opinion in Environmental Sustainability 1.1 (2009): 83-88.

van den Broek, Machteld, et al. "Impact of international climate policies on CO 2 capture and storage deployment: illustrated in the Dutch energy system." Energy Policy 39.4 (2011): 2000-2019.

Brown, David S., and Ahmed Mushfiq Mobarak. "The transforming power of democracy: regime type and the distribution of electricity." American Political Science Review 103.02 (2009): 193-213.

Bugaje, I. M. "Renewable energy for sustainable development in Africa: a review." Renewable and Sustainable Energy Reviews 10.6 (2006): 603-612.

Casillas, Christian E., and Daniel M. Kammen. "The energy-poverty-climate nexus." Renewable energy 300 (2010)

De Castro, Carlos, et al. "Global wind power potential: Physical and technological limits." Energy Policy 39.10 (2011): 6677-6682.

Cecelski, Elizabeth. "Rethinking gender and energy: Old and new directions." ENERGIA/EASE (2004): 41-49.

Chandran, V. G. R., Susan Sharma, and Karunagaran Madhavan. "Electricity consumption–growth nexus: the case of Malaysia." Energy Policy 38.1 (2010): 606-612.

Chineke, Theo Chidiezie, and Fabian M. Ezike. "Political will and collaboration for electric power reform through renewable energy in Africa." Energy Policy 38.1 (2010): 678-684.

Clancy, Joy S., Margaret Skutsch, and Simon Batchelor. "The Gender-Energy-Poverty Nexus: Finding the energy to address gender concerns in development." University of Twente (2002).

Climate Action Tracker. < http://climateactiontracker.org/> Accessed March 2015.

Climatescope. "Climatescope 2014: Mapping the Global Frontiers for Clean Energy Development". *Bloomberg New Energy Finance Report.* BNEF: London (2014)

Collier, Paul, and Anthony J. Venables. "Greening Africa? Technologies, endowments and the latecomer effect." Energy Economics 34 (2012): S75-S84.

Cook, Paul. "Infrastructure, rural electrification and development." Energy for Sustainable Development 15.3 (2011): 304-313.

Davidson, Ogunlade, et al. "The development and climate nexus: the case of sub-Saharan Africa." Climate Policy 3.1 (2003): S97-S113.

Deichmann, Uwe, C. Meisner, S. Murray, D. Wheeler. "The economics of renewable energy expansion in rural Sub-Saharan Africa." Energy Policy 39.1 (2011)

Dincer, Ibrahim. "Renewable energy and sustainable development: a crucial review." Renewable and Sustainable Energy Reviews 4.2 (2000): 157-175.

Eastern Africa Power Pool and East African Community. "Regional Power Systems Master Plan" (2011) <www.eac.int>

Eberhard, Anton, and Maria Shkaratan. "Powering Africa: Meeting the financing and reform challenges." Energy Policy 42 (2012): 9-18.

Ebohon, Obas John. "Energy, economic growth and causality in developing countries: a case study of Tanzania and Nigeria." Energy policy 24.5 (1996): 447-453.

Economist. “Eastern El Dorado?” 7th April 2012. <http://www.economist.com/node/21552265>

Economist. “Lighting a dark continent”. 27th September 2014 < http://www.economist.com/news/middle-east-and-africa/21620245-power-shortages-have-been-holding-africa-back-are-last-easing-lighting>

Economist. “A Brightening Continent”.17th January 2015. http://www.economist.com/news/middle-east-and-africa/21620245-power-shortages-have-been-holding-africa-back-are-last-easing-lighting

ECOWAPP. “West African Power Pool Master Plan” (2011) www.ecowapp.org

ECOWAS. “Renewable Energy and Efficiency”. *Status Report*. (2014)

Energy+. *Norwegian Climate and Energy Initiative.* < https://www.regjeringen.no/en/topics/foreign-affairs/development-cooperation/energy_plus/id672635/> Last accessed April 2015.

ESKOM. < www.eskom.co.za/> Accessed March 2015.

Fall, Latsoucabe. "Energy Access: illusion or reality for the poor?." Energy & Environment 16.5 (2005): 743-762.

FAO. “Woodfuels and Climate Change Mitigation”. *Forest and Climate Change Working Paper*. (2010)

Fang, Guochang, et al. "The impacts of carbon tax on energy intensity and economic growth–A dynamic evolution analysis on the case of China." Applied Energy 110 (2013): 17-28.

Fatona, Pius, et al. Viewing Energy, Poverty and Sustainability in Developing Countries Through a Gender Lens. INTECH Open Access Publisher (2013)

Federal Ministry of Environment for Nigeria. “National Environmental, Economic and Development Study for Climate Change in Nigeria”. September (2010).

Ferguson, Ross, William Wilkinson, and Robert Hill. "Electricity use and economic development." Energy policy 28.13 (2000): 923-934.

Fig, David. "Reluctant Embrace: South Africa and Renewable Energy." Emerging Economies. Springer India, 2015. 239-261.

Foster, Vivien, and Jevgenijs Steinbuks. "Paying the price for unreliable power supplies: in-house generation of electricity by firms in Africa." World Bank Policy Research Working Paper Series. Vol 2 (2009).

Giuliano, Paola. "Living arrangements in western europe: Does cultural origin matter?". Journal of the European Economic Association 5.5 (2007): 927-952.

Luderer, Gunnar, et al. "The economics of decarbonizing the energy system—results and insights from the RECIPE model intercomparison." Climatic Change 114.1 (2012): 9-37.

Haines, Andy, et al. "Policies for accelerating access to clean energy, improving health, advancing development, and mitigating climate change." The Lancet 370.9594 (2007): 1264-1281.

Halsnæs, Kirsten, and Jan Verhagen. "Development based climate change adaptation and mitigation—conceptual issues and lessons learned in studies in developing countries." Mitigation and Adaptation Strategies for Global Change 12.5 (2007): 665-684.

Heffner, Grayson, et al. "Minding the gap: World Bank's assistance to power shortage mitigation in the developing world." Energy 35.4 (2010): 1584-1591.

Hermann, Sebastian, Asami Miketa, Nicolas Fichaux. “Estimating the Renewable Energy Potential in Africa” IRENA-KTH working paper. *International Renewable Energy Agency*: Abu Dhabi (2014).

Helio International. “Energy and Sustainable Development in Tanzania”. *Sustainable Energy Watch.* 2005.

Hiemstra-Van der Horst, Greg, and Alice J. Hovorka. "Reassessing the “energy ladder”: household energy use in Maun, Botswana." Energy Policy 36.9 (2008): 3333-3344.

Howells, Mark I., et al. "A model of household energy services in a low-income rural African village." Energy Policy 33.14 (2005): 1833-1851.

IEA. “World Energy Investment Outlook”. *Special Report.*(2012(I))

IEA. “Transition to Sustainable Buildings. *Research Report.* IEA: Paris (2013)

IEA. Africa Energy Outlook: A Focus on Energy Prospects in Africa. *World Energy Outlook Special Report*. Paris (2014(I))

INTPOW. “World Hydro Potential and Development. http://www.intpow.com/index.php?id=487&download=1. Accessed February 2015.

IPCC. “Summary for Policymakers. In: IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation”. Cambridge: Cambridge (2011)

IPCC. Climate Change 2014: Impacts, Adaptation and Mitigation. *Fifth Assessment Report.* Cambridge University Press, Cambridge, United Kingdom (2014)

IRENA. “Prospects for the African Power Sector”. IRENA: Abu Dhabi (2012)

IRENA. “Africa’s Renewable Energy Future”. IRENA: Abu Dhabi (2013(I))

IRENA. “East and Southern African Clean Energy Corridor”. IRENA: Abu Dhabi (2013(II))

IRENA. “Estimating the Renewable Energy Potential in Africa”. IRENA: Abu Dhabi (2014)

IRENA: “Renewable Power Generation Costs in 2014”. IRENA: Abu Dhabi (2015(I))

IRENA: “Africa Power Sector: Planning and Prospects for Renewable Energy”. IRENA: Abu Dhabi (2015(II))

Johnson, K. “Dirty South, Clean It Up”. Foreign Policy: March-April (2014)

Joskow, Paul L., and John E. Parsons. "The future of nuclear power after Fukushima." (2012).

Jumbe, Charles BL. "Cointegration and causality between electricity consumption and GDP: empirical evidence from Malawi." Energy economics 26.1 (2004): 61-68.

Kanagawa, Makoto, and Toshihiko Nakata. "Assessment of access to electricity and the socio-economic impacts in rural areas of developing countries." Energy Policy 36.6 (2008): 2016-2029.

Karekezi, Stephen, Kusum Lata, and Suani Teixeira Coelho. "Traditional biomass energy: Improving its use and moving to modern energy use." Renewable Energy—A Global Review of Technologies, Policies and Markets 1.1 (2006): 231-261.

Karekezi, Stephen, and John Kimani. "Status of power sector reform in Africa: impact on the poor." *Energy Policy* 30.11 (2002): 923-945.

Karekezi, Stephen. "Renewables in Africa—meeting the energy needs of the poor." *Energy Policy* 30.11 (2002): 1059-1069.

Karekezi, Stephen, Waeni Kithyoma, and Energy Initiative. "Renewable energy development." *workshop on African Energy Experts on Operationalizing the NEPAD Energy Initiative: June* (2003)

Karekezi, S., S. McDade, B. Boardman, J. Kimani. “Energy, Poverty, and Development”. Chapter 2 in Global Energy Assessment – Toward a Sustainable Future. Cambridge University Press: Cambridge (2002)

Kaygusuz, Kamil. "Energy for sustainable development: A case of developing countries." Renewable and Sustainable Energy Reviews 16.2 (2012): 1116-1126.

Kebede, Ellene, John Kagochi, and Curtis M. Jolly. "Energy consumption and economic development in Sub-Sahara Africa." Energy economics 32.3 (2010): 532-537.

Kelly, David L., and Charles D. Kolstad. "Integrated assessment models for climate change control." International yearbook of environmental and resource economics 2000 (1999): 171-97.

Keppo, Ilkka, and Bob van der Zwaan. "The impact of uncertainty in climate targets and CO2 storage availability on long-term emissions abatement." Environmental Modeling & Assessment 17.1-2 (2012): 177-191.

Kirubi, Charles, et al. "Community-based electric micro-grids can contribute to rural development: evidence from Kenya." World development 37.7 (2009): 1208-1221.

Khandker, S. R., Barnes, D. F., & Samad, H. A. "Energy Poverty in Rural and Urban India. Are the energy poor also income poor?" *Policy Research Working Paper 5463*. Washington, DC: World Bank (2012)

Kober, Tom, B. van der Zwaan, and Hilke Rösler. "Emission Certificate Trade and Costs under Regional Burden-Sharing Regimes for a 2 C Climate Change Control Target." Climate Change Economics (2013).

Kober, Tom, Bob van der Zwaan, and Hilke Rösler. "Schemes for the Regional Allocation of Emission Allowances under Stringent Global Climate Policy." *Informing Energy and Climate Policies Using Energy Systems Models*. Springer International Publishing (2015): 93-110.

Köhlin, Gunnar, et al. "Energy, gender and development: what are the linkages? where is the evidence?" *Policy Research paper.* Washington DC: World Bank (2011).

Kok, Marcel, et al. "Integrating development and climate policies: national and international benefits." Climate Policy 8.2 (2008): 103-118.

Komendantova, Nadejda, et al. "Perception of risks in renewable energy projects: The case of concentrated solar power in North Africa." Energy Policy 40 (2012): 103-109.

Komor, Paul, and Morgan Bazilian. "Renewable energy policy goals, programs, and technologies." Energy Policy 33.14 (2005): 1873-1881.

Krupa, Joel, and Sarah Burch. "A new energy future for South Africa: The political ecology of South African renewable energy." Energy Policy 39.10 (2011): 6254-6261.

Lee, Chien-Chiang. "Energy consumption and GDP in developing countries: a cointegrated panel analysis." Energy economics 27.3 (2005): 415-427.

Lomofsky, Lilian, and Sandy Lazarus. "South Africa: First steps in the development of an inclusive education system." Cambridge Journal of education 31.3 (2001): 303-317.

Loulou, Richard, et al. "Documentation for the TIMES Model Part II." Energy Technology Systems Analysis Programme (ETSAP),[available at: http://www. etsap. org/documentation. asp] (2005).

Loulou, Richard, and Maryse Labriet. "ETSAP-TIAM: the TIMES integrated assessment model Part I: Model structure." Computational Management Science 5.1-2 (2008(I)): 7-40.

Loulou, Richard. "ETSAP-TIAM: the TIMES integrated assessment model. Part II: mathematical formulation." Computational Management Science 5.1-2 (2008(II)): 41-66.

Lu, Xi, Michael B. McElroy, and Juha Kiviluoma. "Global potential for wind-generated electricity." Proceedings of the National Academy of Sciences 106.27 (2009): 10933-10938.

Mandelli, Stefano, et al. "Sustainable energy in Africa: A comprehensive data and policies review." Renewable and Sustainable Energy Reviews 37 (2014): 656-686.

Mason, Michael, and Dennis Kumetat. "At the crossroads: energy futures for North Africa." Energy Policy 39.8 (2011): 4407-4410.

Massetti, Emanuele. "Carbon tax scenarios for China and India: exploring politically feasible mitigation goals." International Environmental Agreements: Politics, Law and Economics 11.3 (2011): 209-227.

Martinsen, Thomas. "Introducing technology learning for energy technologies in a national CGE model through soft links to global and national energy models." Energy Policy 39.6 (2011): 3327-3336.

Masud, Jamil, Diwesh Sharan, and Bindu N. Lohani. "Energy for all: addressing the energy, environment, and poverty nexus in Asia." (2007).

McCollum, David, Yu Nagai et al. "Energy investments under climate policy: a comparison of global models." Climate Change Economics 4.04 (2013)

McDonald, David, ed. Electric capitalism: Recolonizing Africa on the power grid. London: Routledge (2012).

McKinsey. “Brighter Africa: the Growth Potential of the Sub-Saharan Electricity Sector”. Mckinsey: Washington DC (2015) < http://www.mckinsey.com/insights/energy_resources_materials/powering_africa>

Merven, B., Gielen, D. “Southern African and Western African Power Pool Models for Capacity Building and Preliminary Analysis of the role of Renewable Electricity” *IEW Report*. (2012)

MIT. “Energy and Climate Outlook 2014”. MIT: Cambridge (2014). http://globalchange.mit.edu/research/publications/other/special/2014Outlook

MIT. *The Observatory of Economic Complexity*. < https://atlas.media.mit.edu/en/> . Accessed May 2015.

Modi, Vijay, et al. "Energy services for the millennium development goals." Energy services for the Millennium Development Goals (2005).

Moussa, Omar Ahmed, and Hamoud Souleiman. "Country Report, Geothermal Development in Djibouti Republic." Proceedings World Geothermal Congress 2015. 2015.

Nussbaumer, Patrick, Morgan Bazilian, and Vijay Modi. "Measuring energy poverty: Focusing on what matters." Renewable and Sustainable Energy Reviews 16.1 (2012): 231-243.

Nyakabwa-Atwoki, Ralph K.B. “Challenges in Developing Katwe Geothermal Power Project in Kikorongo-Bunyampaka, Kasese District, Western Uganda.” *Proceedings, 38th Workshop on Geothermal Reservoir Engineering*. Stanford (2013) <www.geothermal-energy.org/pdf/IGAstandard/SGW/2013/Nyakabwaatwoki.pdf>

Odhiambo, Nicholas M. "Energy consumption and economic growth nexus in Tanzania: an ARDL bounds testing approach." Energy Policy 37.2 (2009): 617-622.

OFID. “Energy Poverty in Africa. *OFID Pamphlet Series.* (2008)

Onyeji, Ijeoma. "Harnessing and Integrating Africa’s Renewable Energy Resources." (2014).

Owen, Matthew, Robert van der Plas, and Steve Sepp. "Can there be energy policy in Sub-Saharan Africa without biomass?." Energy for sustainable development 17.2 (2013): 146-152.

Pachauri, Shonali, and Daniel Spreng. "Energy use and energy access in relation to poverty." Economic and Political weekly (2004): 271-278.

Parshall, Lily, et al. "National electricity planning in settings with low pre-existing grid coverage: Development of a spatial model and case study of Kenya." Energy Policy 37.6 (2009): 2395-2410.

Payne, James E. "A survey of the electricity consumption-growth literature." Applied energy 87.3 (2010): 723-731.

Pegels, Anna. "Renewable energy in South Africa: Potentials, barriers and options for support." Energy policy 38.9 (2010): 4945-4954.

Pereira, Marcio Giannini, J.A. Sena, M.A.V. Freitas, N.F. Silva. "Evaluation of the impact of access to electricity: A comparative analysis of South Africa, China, India and Brazil." Renewable and Sustainable Energy Reviews 15.3 (2011)

Pfeiffer, Birte, and Peter Mulder. "Explaining the diffusion of renewable energy technology in developing countries." Energy Economics 40 (2013): 285-296.

Practical Action. Poor people’s energy outlook 2014: Key messages on energy for poverty alleviation, Rugby, UK: Practical Action Publishing (2014)

REEEP. “Sustainable Energy Regulation and Policymaking for Africa. *Research Module*. REEEP: Vienna (2008)

Republic of South Africa. “Integrated Resource Plan (2010–30)” (2013) <energy.gov.za>

van Ruijven, Bastiaan Johannes. Energy and development: A modelling approach. Utrecht University, 2008.

Rosenberg, Nathan. "The role of electricity in industrial development." The Energy Journal (1998): 7-24.

Rösler H, Bruggink JJC, Keppo IJ. “Design of a European sustainable hydrogen model”. *Report ECN-E–11-041*, Petten, The Netherlands: ECN (2011).

Rösler, Hilke, Bob Van Der Zwaan, Ilkka Keppo, and Jos Bruggink. "Electricity versus Hydrogen for Passenger Cars under Stringent Climate Change Control." Sustainable Energy Technologies and Assessments 5 (2014)

Rosnes, Orvika, and Haakon Vennemo. "The cost of providing electricity to Africa." Energy Economics 34.5 (2012): 1318-1328.

Sathaye, Jayant, et al. "Renewable energy in the context of sustainable development." Renewable Energy Sources and Climate Change Mitigation (2011).

Saveyn, Bert, Leonidas Paroussos, and Juan-Carlos Ciscar. "Economic analysis of a low carbon path to 2050: A case for China, India and Japan." Energy Economics 34 (2012): S451-S458.

Sebitosi, A. B., P. Pillay, and M. A. Khan. "An analysis of off grid electrical systems in rural Sub-Saharan Africa." Energy Conversion and Management 47.9 (2006): 1113-1123.

Sebitosi, A. B., and R. Okou. "Re-thinking the power transmission model for sub-Saharan Africa." Energy Policy 38.3 (2010): 1448-1454.

SE4ALL. < http://www.se4all.org/> Last accessed July 2015.

SEI. “Sustainable Energy Markets in Tanzania. *SEI research report.* September 2011.

Senfuka, Christopher, J. Kirabira, and J. Byaruhanga. "Options for Improvement of the Ugandan Iron and Steel Industry." Proceedings of the Second Interentionl Conference on Advances in Engineering and Tenchnology, Entebbe, Uganda, Jan. Vol. 31. 2011.

Shukla, P.R., Tudela, F., Davidson, O., Mwakasonda, S. et al. “Climate Change Mitigation in Developing Countries: Brazil, China, India, Mexico, South Africa, and Turkey”. Washington DC: Pew Center on Global Climate Change (2002)

Simiyu, Silas M. "Status of geothermal exploration in Kenya and future plans for its development." Proceedings world geothermal congress. 2010.

Van der Sluijs, Jeroen, et al. "Anchoring Devices in Science for Policy The Case of Consensus around Climate Sensitivity." Social Studies of Science 28.2 (1998): 291-323.

Smith, Kirk R., and Kalpana Balakrishnan. "Mitigating climate, meeting MDGs, and moderating chronic disease: the health co-benefits landscape." *Commonwealth Health Ministers’ Update* (2009): 59-65.

Sokona, Youba, Yacob Mulugetta, and Haruna Gujba. "Widening energy access in Africa: Towards energy transition." Energy Policy 47 (2012): 3-10.

Sovacool, Benjamin K. "Conceptualizing urban household energy use: Climbing the “Energy Services Ladder”." Energy Policy 39.3 (2011): 1659-1668.

Stambouli, Amine Boudghene. "Promotion of renewable energies in Algeria: Strategies and perspectives." Renewable and Sustainable Energy Reviews 15.2 (2011): 1169-1181.

Sustainable Development Solutions Network. “Potential for Regional Use of East Africa’s Natural Gas. *Briefing Paper.* May 2014

Syri, Sanna, H. Holttinen, E. Peltolaet et al. "Global energy and emissions scenarios for effective climate change mitigation—Deterministic and stochastic scenarios with the TIAM model." International Journal of Greenhouse Gas Control 2.2 (2008)

Thiam, Djiby Racine. "An energy pricing scheme for the diffusion of decentralized renewable technology investment in developing countries."*Energy Policy* 39.7 (2011): 4284-4297.

Trieb, Franz, et al. "Solar electricity imports from the Middle East and North Africa to Europe." Energy Policy 42 (2012): 341-353.Turkson, John, and Norbert Wohlgemuth. "Power sector reform and distributed generation in sub-Saharan Africa." Energy Policy 29.2 (2001): 135-145.

Turkson, John, and Norbert Wohlgemuth. "Power sector reform and distributed generation in sub-Saharan Africa." Energy Policy 29.2 (2001): 135-145.

WEC. World Energy Resources: Geothermal. *World Economic Council Strategic Insight.* 2013(I) < http://www.worldenergy.org/wp-content/uploads/2013/09/WER_2013_9_Geothermal.pdf>

Ummel, Kevin, and David Wheeler. "Desert power: the economics of solar thermal electricity for Europe, North Africa, and the Middle East." Center for Global Development Working Paper 156 (2008).

UNDESA. "Sustainable Energy Consumption in Africa". *African Energy Policy Research*. Nairobi, Kenya (2004)

UNDP. Energizing the Millennium Development Goals: A guide to energy's role in reducing poverty. New York, NY: United Nations Development Programme. (2005)

UNEP. "Financing renewable energy in developing countries" *Survey Study.* September 2012

USAID. *Power Africa Initiative.* < http://www.usaid.gov/powerafrica> Accessed April 2015.

US International Trade Commission. "Sub-Saharan Africa: Effects of Infrastructure Conditions on Export Competitiveness". *3rd annual report*. Washington DC (2009)

WEC. World Energy Resouces 2013 Survey. October 2013(II), <www.worldenergy.org>

Winkler, Harald. "Renewable energy policy in South Africa: policy options for renewable electricity." Energy Policy 33.1 (2005): 27-38.

Winkler, Harald. "Energy policies for sustainable development in South Africa: Options for the future." (2006).

Winkler, Harald. "Energy policies for sustainable development in South Africa." Energy for sustainable development 11.1 (2007): 26-34.

Winkler, Harald, and Andrew Marquand. "Changing development paths: From an energy-intensive to low-carbon economy in South Africa." Climate and Development 1.1 (2009): 47-65.

Wolde-Rufael, Yemane. "Energy demand and economic growth: the African experience." Journal of Policy Modeling 27.8 (2005): 891-903.

Wolde-Rufael, Yemane. "Electricity consumption and economic growth: a time series experience for 17 African countries." *Energy Policy* 34.10 (2006): 1106-1114.

World Bank. "Rural Access to Electricity: Strategy Options for India. Discussion Paper, South Asia Energy and Infrastructure Unit". Washington D.C: World Bank (2004)

World Bank. "An Investment Framework for Clean Energy and Development: A Progress Report". Washington, DC: World Bank (2006)

World Bank. "The welfare impact of rural electrification: a reassessment of the costs and benefits". *An IEG impact evaluation.* Washington DC: World Bank (2008)

World Bank. *World Bank Database* (2015) < http://data.worldbank.org/>

WRI. “Global Coal Risk Assessment”. *Working Paper.* WRI: Washington DC (2011)

WRI: “Global Shale Gas Development: Water Availability & Business Risks” < http://www.wri.org/publication/global-shale-gas-development-water-availability-business-risks> September 2014

van der Zwaan, Bob, Lachlan Cameron, and Tom Kober. "Potential for Renewable Energy Jobs in the Middle East." Energy Policy 60 (2013(I))

van der Zwaan, Bob, Ilkka Keppo, and Filip Johnsson. "How to Decarbonize the Transport Sector?" Energy Policy 61 (2013(II))

van der Zwaan, Bob, Hilke Rösler, and Tom Kober et al. "A cross-model comparison of global long-term technology diffusion under a 2 C climate change control target." Climate Change Economics (2013(III)).

Zvoleff, Alex, et al. "The impact of geography on energy infrastructure costs." Energy Policy 37.10 (2009): 4066-4078

Appendix 2: Model Input References

Acker, Richard H., and Daniel M. Kammen. "The quiet (energy) revolution: analysing the dissemination of photovoltaic power systems in Kenya." Energy Policy 24.1 (1996): 81-111.

Adamantiades, Achilles, and I. Kessides. "Nuclear power for sustainable development: current status and future prospects." Energy Policy 37.12 (2009): 5149-5166.

AEEP. “Africa EU Energy PartnerShip Status Report”. (2014) < http://www.crossborderinformation.com/sites/default/files/AEEP%20Status%20Report_2014_en_web.pdf>

AfdB. “The Arab Republic of Egypt: The Power Sector in Brief: AfdB: Abidjan (2010) < http://www.afdb.org/fileadmin/uploads/afdb/Documents/Publications/ENERGY%20mpa%20ENG%20Power%20Sector%20Emer.pdf>

Airbus. “Sustainable Aviation – Aviation environmental roadmap.” (2013)

AirlineLeader. “Strategy Journal for Airline CEO’s”. *Issue 20,21 & 29.* < http://www.airlineleader.com/> Accessed May 2015.

Anandarajah, Gabrial, Olivier Dessens, and Christophe McGlade. "Modelling of global energy scenarios under CO2 emissions pathways with TIAM-UCL." (2013).

Archer, C. and M. Jacobson. “Evaluation of global wind power”. Journal of Geophysical Research, Vol. 110 (2005)

ARGeo. *African Rift Geothermal Development Facility*. < http://theargeo.org/> Last accessed July 2015.

Attia, Shady, Arnaud Evrard, and Elisabeth Gratia. "Development of benchmark models for the Egyptian residential buildings sector." Applied Energy 94 (2012): 270-284.

Baker-McKenzie. The Future for Clean Energy in Africa. Clean Energy Pipeline Report. (2013)

Barnes, D.F., Krutilla, K. “The Urban Household Energy Transition”. *World Bank Research Report*. World Bank: Washington DC. (2004)

Bentsen, N., Felby, C. “Technical potentials of biomass for energy services from current agriculture and forestry on selected countries in Europe, the Americas and Asia”. *Forest & Landscape Working Paper University of Copenhagen.* (2010)

Bongaarts, John. "Household size and composition in the developing world in the 1990s." Population studies 55.3 (2001): 263-279.

BP. “Statistical Review of World Energy” (2006) <http://www.bp.com/productlanding.do?categoryId=91&contentId=7017990>

BP. “Statistical Review of World Energy” (2012) <http://www.bp.com/productlanding.do?categoryId=91&contentId=7017990>

British Geological Survey. *African Mineral Production*. (2006)

Bullock, Richard. "Off Track: Sub-Saharan African Railways." Africa Infrastructure Country Diagnostic Background Paper 17 (2009).

Carbon Watch Market. “Turbulences Ahead: Market Based Measures to reduce Aviation Emissions” *Policy Brief*. 2013.

de Castro, Carlos, et al. "Global wind power potential: Physical and technological limits." Energy Policy 39.10 (2011): 6677-6682.

Central East African Railways. < http://www.cear.mw/> Last accessed May 2015.

Chinese Railway Construction Cooperation. < http://english.crcc.cn/> Last Accessed May 2015.

Climate Action Tracker. < http://climateactiontracker.org/> Accessed March 2015.

Climatescope. "Climatescope 2014: Mapping the Global Frontiers for Clean Energy Development". *Bloomberg New Energy Finance Report.* BNEF: London (2014)

COMELEC. < http://comelec-net.org/> Accessed French version. Last accessed July 2015.

De la Rue du Can, S. Virginie Letschert. Energy Efficiency Country Study: Republic of South Africa. Berkeley National Laboratory. (2013)

DERA. "Rohstoffinformationen" *Annual Report*. (2012) < http://www.bgr.bund.de/DE/Gemeinsames/Produkte/Downloads/DERA_Rohstoffinformationen/rohstoffinformationen-15.pdf?__blob=publicationFile>

DFBZ. "Global and Regional Spatial Distribution of Biomass Potentials". *7th Report.* (2011)

DFBZ-IRENA. "Biomass Potentials in Africa". (2013) < https://www.irena.org/DocumentDownloads/Publications/IRENA-DBFZ_Biomass%20Potential%20in%20Africa.pdf>

Eastern Africa Power Pool and East African Community. "Regional Power Systems Master Plan" (2011) www.eac.int

ECOWAPP. "West African Power Pool Master Plan" (2011) www.ecowapp.org

Energy+. Norwegian Climate and Energy Initiative. < https://www.regjeringen.no/en/topics/foreign-affairs/development-cooperation/energy_plus/id672635/> Last accessed April 2015.

ESKOM. < www.eskom.co.za/> Accessed March 2015.

EIA. *US Energy Information Administration Statistics.* < http://www.eia.gov/>

Frankfurt School of Management. "Global Trends in Renewable Energy Investment 2014"(2014) http://www.fs-unep-centre.org

French Global Environmental Facility. 'Decentralized rural electrification in Morocco'. 2008.

Gelil, I.A., Regional Report on Efficient Lighting in the Middle East and North Africa. En.Lighten GEF Report. (2011)

Hanna, G. Sustainable Energy Potential in the Egyptian Residential Sector. Journal of Environmental Science and Engineering B 2 (2013) 374-382

Helio International. "Energy and Sustainable Development in Tanzania". *Sustainable Energy Watch.* 2005.

Hermann, Sebastian, Asami Miketa, Nicolas Fichaux. Estimating the Renewable Energy Potential in Africa, IRENA-KTH working paper. International Renewable Energy Agency: Abu Dhabi. (2014).

Hoogwijk, Monique, Bert de Vries, and Wim Turkenburg. "Assessment of the global and regional geographical, technical and economic potential of onshore wind energy." Energy Economics 26.5 (2004): 889-919.

Howells, Mark I., et al. "A model of household energy services in a low-income rural African village." Energy Policy 33.14 (2005): 1833-1851.

IATA. *International Air Transport Association Statistics.* < http://www.iata.org/Pages/default.aspx> . Accessed March 2015.

ICAO. "Offsets for Aviation Emissions". www.icao.int (2012)

IEA. "World Energy Trade Statistics" (2010)

IEA. "World Energy Investment Outlook". *Special Report.*(2012(I))

IEA. "World Energy Trade Statistics" (2012(II))

IEA. “Transition to Sustainable Buildings. *Research Report.* IEA: Paris (2013)

IEA. Africa Energy Outlook: A Focus on Energy Prospects in Africa. *World Energy Outlook Special Report*. Paris (2014(I))

IEA. “World Energy Statistics”. *IEA Database.* (2014)

IEA. “World Energy Investment Outlook”. *Special Report.*(2014(III))

IEA. “Energy Technology Perspectives. *Special Report.* (2014(VI))

IIASA. “Global Energy Assessment”. (2012) < http://www.globalenergyassessment.org/>

International Union of Railways. < http://www.uic.org/> Last accessed May 2015

IRENA. “Prospects for the African Power Sector”. IRENA: Abu Dhabi (2012)

IRENA. “Africa’s Renewable Energy Future”. IRENA: Abu Dhabi (2013(I))

IRENA. “East and Southern African Clean Energy Corridor”. IRENA: Abu Dhabi (2013(II))

IRENA. “Estimating the Renewable Energy Potential in Africa”. IRENA: Abu Dhabi (2014)

IRENA: “Renewable Power Generation Costs in 2014”. IRENA: Abu Dhabi (2015(I))

IRENA: “Africa Power Sector: Planning and Prospects for Renewable Energy”. IRENA: Abu Dhabi (2015(II))

Karekezi, Stephen, Waeni Kithyoma, and Energy Initiative. "Renewable energy development." *workshop on African Energy Experts on Operationalizing the NEPAD Energy Initiative, June*. 2003.

Khaireh, Abdoulkader, Abdou Mohamed Houmed et al. “Geothermal Development in Republic of Djibouti A Country Update Report” Proceedings 5th African Rift Geothermal Conference. Arusha (2014) < http://abstracts.theargeo.org/fullpaper/Argeo%20C5%20_Djibouti-country_update_final_20140.pdf>

Lightning Africa. Lightning Fuel Costs in Kenya. Market Intelligence Note. (2012)

Lu, Xi, Michael B. McElroy, and Juha Kiviluoma. "Global potential for wind-generated electricity." Proceedings of the National Academy of Sciences 106.27 (2009): 10933-10938.

MATEK, Benjamin. 2013 GEOTHERMAL POWER: INTERNATIONAL MARKET OVERVIEW. Eothermal Energy Association. Washington: 2013.

McKinsey. “Brighter Africa: the Growth Potential of the Sub-Saharan Electricity Sector”. Mckinsey: Washington DC (2015) < http://www.mckinsey.com/insights/energy_resources_materials/powering_africa>

Merven, B., Gielen, D. “Southern African and Western African Power Pool Models for Capacity Building and Preliminary Analysis of the role of Renewable Electricity” *IEW Report*. (2012)

MIDT. *Amadeus Airline Booking data*. < http://www.amadeus.com/businessintelligence/sales-marketing/midt-overview/> Last accessed June 2015.

Ministere Algerién de l’Energie . “Definition of the key sectors and technology needs”. 2011.

MIT. “Energy and Climate Outlook 2014”. MIT: Cambridge (2014). http://globalchange.mit.edu/research/publications/other/special/2014Outlook

MIT. *The Observatory of Economic Complexity*. < https://atlas.media.mit.edu/en/> . Accessed May 2015.

Moussa, Omar Ahmed, and Hamoud Souleiman. "Country Report, Geothermal Development in Djibouti Republic." Proceedings World Geothermal Congress 2015. 2015

Mnjokava, Taramaeli. Geothermal Development in Tanzania – A Country Update. Proceedings of the 4th African Rift Geothermal Conference Nairobi: 2012. http://theargeo.org/home/files/Tanzania/Geothermal%20Development%20in%20Tanzania_A%20country%20Update_Mnjokava.pdf

Nyakabwa-Atwoki, Ralph K.B. "Challenges in Developing Katwe Geothermal Power Project in Kikorongo-Bunyampaka, Kasese District, Western Uganda." Proceedings, 38th Workshop on Geothermal Reservoir Engineering. Stanford (2013) www.geothermal-energy.org/pdf/IGAstandard/SGW/2013/Nyakabwaatwoki.pdf

OECD. "African Economic Outlook 2014". (2014) < www.africaneconomicoutlook.org/en>

Onacha, Stephen. "RWANDA GEOTHERMAL RESOURCES DEVELOPMENT COUNTRY UPDATE" proceedings Kenya Geothermal Conference . Nairobi: 2011 <http://www.gak.co.ke/nibs/web_resources/RWANDA%20GEOTHERMAL%20RESOURCES%20DEVELOPMENT%20COUNTRY%20UPDATE.pdf>

Parikka, Matti. "Global biomass fuel resources." Biomass and Bioenergy 27.6 (2004): 613-620.

PBL. "Global Trends in Carbon Emissions". (2013)

Pegels, Anna. "Renewable energy in South Africa: Potentials, barriers and options for support." Energy policy 38.9 (2010): 4945-4954.

Pfeiffer, Birte, and Peter Mulder. "Explaining the diffusion of renewable energy technology in developing countries." Energy Economics 40 (2013): 285-296.

PLATTS. World Electric Power Plants Database. < http://www.platts.com/products/world-electric-power-plants-database> (2015)

Pollack, Henry N.; Hurter, Suzanne J.; Johnson, Jeffrey R. 1993. "Heat flow from the earth's interior - Analysis of the global data set." Reviews of Geophysics. vol. 31, no. 3, p. 267-280.

PWC. "Africa Gearing Up". *African Infrastructure report.* (2013) http://www.pwc.com/en_M1/m1/publications/africa_gearing_up_-_transport_and_logistics_industry-web.pdf

PWC. "Africa Oil and Gas Review". < http://download.pwc.com/ie/pubs/2014-pwc-africa-oil-and-gas-review-25-07-2014.pdf> (2014)

REEEP. "Sustainable Energy Regulation and Policymaking for Africa. *Research Module*. REEEP: Vienna (2008)

Remme, U. "Global Resources and Energy Trade". *Forschungsbericht.* (2007)

Republic of South Africa. "Integrated Resource Plan (2010–30)" (2013) <energy.gov.za>

SE4ALL. < http://www.se4all.org/> Last accessed July 2015.

SEI. "Sustainable Energy Markets in Tanzania. *SEI research report.* September 2011.

Senfuka, Christopher, J. Kirabira, and J. Byaruhanga. "Options for Improvement of the Ugandan Iron and Steel Industry." Proceedings of the Second Interentionl Conference on Advances in Engineering and Tenchnology, Entebbe, Uganda, Jan. Vol. 31. 2011.

Simiyu, Silas M. "Status of geothermal exploration in Kenya and future plans for its development." Proceedings world geothermal congress. 2010.

SolarPACES. *Solar Power and Chemical Energy Systems Conference Reports*. < http://www.solarpaces.org/> (2015)

Sovacool, Benjamin K. "Conceptualizing urban household energy use: Climbing the "Energy Services Ladder"." Energy Policy 39.3 (2011): 1659-1668.

Thiam, Djiby Racine. "An energy pricing scheme for the diffusion of decentralized renewable technology investment in developing countries."*Energy Policy* 39.7 (2011): 4284-4297.

Trieb, Franz, et al. "Solar electricity imports from the Middle East and North Africa to Europe." Energy Policy 42 (2012): 341-353.Turkson, John, and Norbert Wohlgemuth. "Power sector reform and distributed generation in sub-Saharan Africa." Energy Policy 29.2 (2001): 135-145.

Ugandan National Household Survey 2005/2006. Chpt. 9: Housing & Household conditions. (2008) <www.ubos.org>

Ummel, Kevin, and David Wheeler. "Desert power: the economics of solar thermal electricity for Europe, North Africa, and the Middle East." Center for Global Development Working Paper 156 (2008).

UN Comtrade. *International Trade Statistics Database*. <comtrade.un.org/> Accessed May 2015.

UNDESA. “Sustainable Energy Consumption in Africa”. *African Energy Policy Research*. Nairobi, Kenya (2004)

UNDESA. “Sustainable Energy Consumption in Africa”. African Energy Policy Research. Nairobi, Kenya (2004)

UNDP (2005). Energizing the Millennium Development Goals: A guide to energy’s role in reducing poverty. New York, NY: United Nations Development Programme.

UNDP. World Population Prospects. http://www.un.org/en/development/desa/population/ Accessed March 2015.

UNEP. Presentation on Market Development of Compact Fluorescent Lamps in Egypt. (2004)

UNIDO. “Fostering Industrial Development in Africa in the New Global Envrionment”. *United Nations Special Issue.* (2011)

UNIDO. World Small Hydropower Development Report 2013: Egypt. (2013) < www.smallhydroworld.org/fileadmin/user_upload/pdf/Africa_Northern/WSHPDR_2013_Egypt.pdf>

Ürge-Vorsatz, Diana, et al. "Heating and cooling energy trends and drivers in buildings." Renewable and Sustainable Energy Reviews 41 (2015): 85-98.

USAID. Power Africa Initiative. < http://www.usaid.gov/powerafrica> Accessed April 2015.

USGS. “Minerals Yearbook Africa and the Middle East”. < http://minerals.usgs.gov/minerals/pubs/country/africa.html> (2012)

US International Trade Commission. “Sub-Saharan Africa: Effects of Infrastructure Conditions on Export Competitiveness”. 3rd annual report. Washington DC (2009)

WEC. World Energy Resources: Geothermal. World Economic Council Strategic Insight. 2013(I) < http://www.worldenergy.org/wp-content/uploads/2013/09/WER_2013_9_Geothermal.pdf>

WEC. World Energy Resouces 2013 Survey. October 2013(II), www.worldenergy.org

Wolde-Rufael, Yemane. "Energy demand and economic growth: the African experience." Journal of Policy Modeling 27.8 (2005): 891-903.

Wolde-Rufael, Yemane. "Electricity consumption and economic growth: a time series experience for 17 African countries." *Energy Policy* 34.10 (2006): 1106-1114.

World Bank. World Bank Database (2015) < http://data.worldbank.org/>

Worldsteel Association. “Steel demand in Sub-Saharan Africa. *Regional Seminar on International Trade Statistics Presentation*. 13th May 2014.

WRI. “Global Coal Risk Assessment”. Working Paper. WRI: Washington DC (2011)

WRI: “Global Shale Gas Development: Water Availability & Business Risks” < http://www.wri.org/publication/global-shale-gas-development-water-availability-business-risks> September 2014

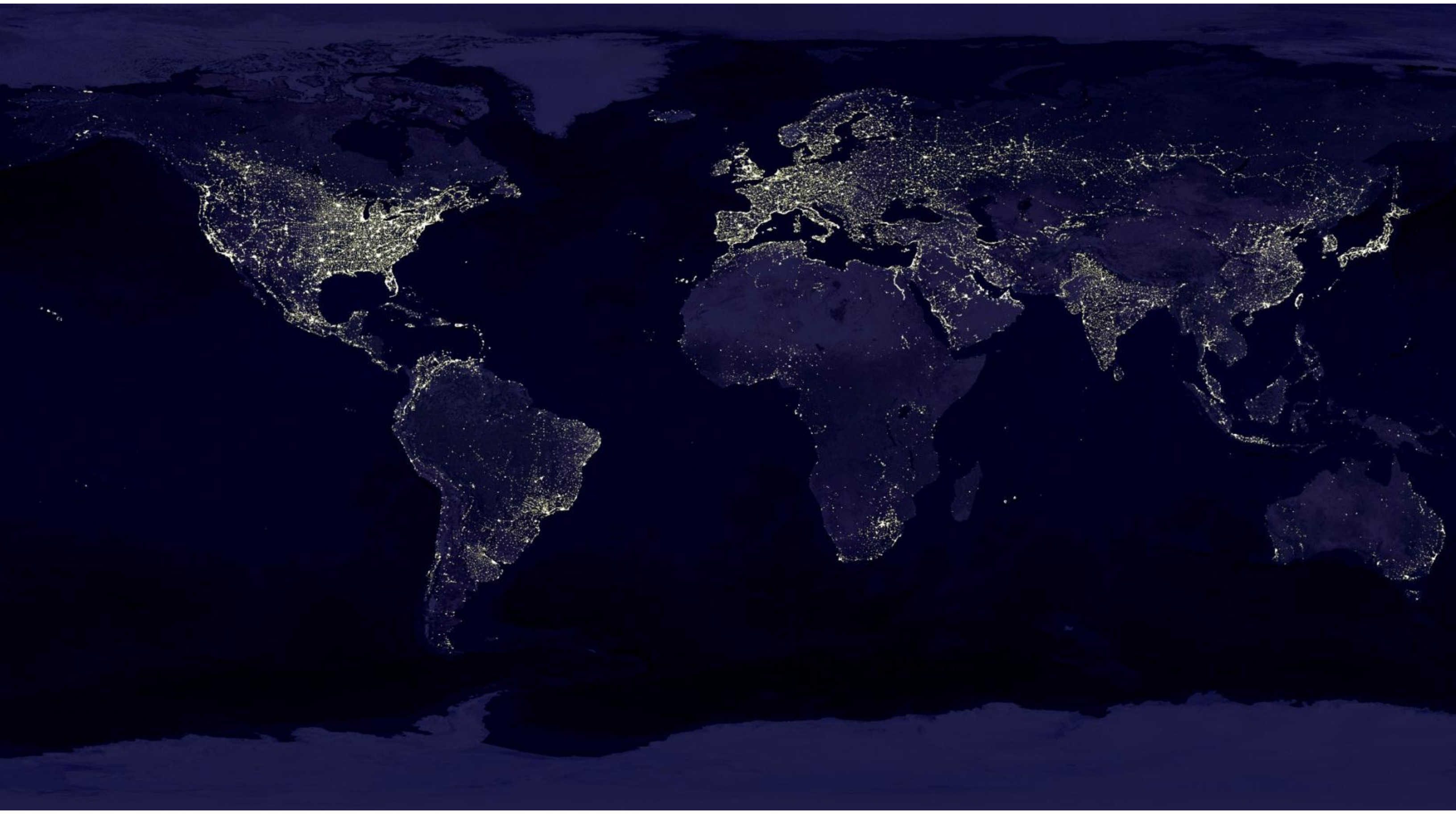
Zarma, Ismaila Haliru. HYDRO POWER RESOURCES IN NIGERIA. Energy Commision of Nigeria. International Centre on Small Hydro Power (IC-SHP) , Hangzhou, China 2006.
<http://www.unido.org/fileadmin/import/52413_Mr._Ismaila_Haliru_Zarma.pdf>

Appendix 3: Electricity Targets & Incentives

Both tables ased on ClimateScope [2014], IEA [2014(I)], Brand [2011]

Electricity Targets	**Renewables**	**Access**
Algeria	22GW by 2030	
Angola		Electricity access 60% by 2025
Tunesia	2GW renewables by 2020	
Libya	20% renewable electricity by 2020	
Egypt	20% renewable electricity by 2020	
Cote d'Ivoire	20% renewable electricity by 2020	
DR Congo		Electricity Access 26% by 2020
Ethiopia	12GW renewable elctricity by 2025, mainly Hydropower	Electricity Access 80% by 2030
Ghana	500MW installed by 2020	
Kenya	Plans for over 2500MW of renewable capacity by 2030	Electricity Access of 100% by 2020
Morocco	42% renewables by 2020	
Mozambique	Focus on 10 000 off-grid solar installations by 2025 and 125MW of small hydropower	Electricity Access 85% by 2035
Nigeria	10% renewable electricity by 2020	Electricity Access 100% by 2030
Rwanda		Electricity Access 60% by 2020; 563MW installed by 2018 (from 141MW in 2014)
Tanzania	100MW solar, 200MW wind and 200MW geothermal by 2025	Electricity Access of 22% by 2020
Senegal	20% of total electricity from renewables	
South Africa	Diversify Electricity Mix	
Uganda	61% of total energy from renewables by 2017	
Zambia		Electricity Access 51% by 2030
Malawi	10% renewable electricity by 2050	
South Africa	42% emission reduction compared to BAU in 2025	

Incentives for Renewables	
Liberia	• 100% exemption from import duty for equipment for Renewables • 100% exemption from property taxes for renewables projects
Cote d'Ivoire	• Reduced VAT rate from 18% to 9%
Ghana	• Renewable Energy Purchase Obligation • Feed-In Tariffs for Renewables
Nigeria	• Waiver of VAT for Renewables • Feed-In Tariffs for Renewables
Kenya	• Industry must realize at least 50% of maximal energy efficiency imporovement by 2020 • Feed-In Tariffs for Renewables
Tanzania	• Feed-In Tariffs for Renewables
Uganda	• Credit Enhancement for Renewables • Feed-In Tariffs for Renewables
Rwanda	• Waiver of VAT for Renewables • Feed-In Tariffs for Small Scale Hydro and Solar
Mozambique	• Waiver of VAT for Renewables • Feed-In Tariffs for Renewables
Malawi	• Feed-In Tariffs for Renewables
Zambia	• Carbon tax for motor vehicles • Feed-In Tariffs for Renewables
Zimbabwe	• Carbon tax for motor vehicles • Feed-In Tariffs for Renewables
South Africa	• Due to implement carbon tax at €12/tonne CO_2 in 2016 • Feed-In Tariffs for Renewables



Energy is the golden thread that connects economic growth, increased social equity, and an environment that allows the world to thrive.”

– UN Secretary-General Ban Ki-moon