ENERGY, CLIMATE AND POPULATION: GROWTH, PEAKS, AND DECLINES

1900-2100

A Dissertation

by

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ABSTRACT

This dissertation is derived from numerical models that quantitatively examine energy, climate, and population. Future energy production in each chapter is modelled using the single-cycle Hubbert technique. Population figures are taken from United Nations projections. Per capita energy consumption is projected in each chapter either using regression modelling, or as a set of goals unique to the study. Annual energy demand is a product of per capita energy consumption and population. Renewable energy demand is defined as the total energy demand minus the projected non-renewable energy production. Emissions from energy production are calculated from global-averages for each source.

The global-scale model of energy production and consumption suggests that peaking non-renewable energy will create renewable energy demand equal to 50% of global energy by 2054 and by 2028 in order to achieve climate goals. Similar modelling of regional-scale energy consumption goals highlights specific challenges for that energy transition, including population growth, development, and dependence on imported energy. A sensitivity analysis of the global model inputs uncovers that increasing current per capita energy consumption 3% negates the total global non-hydro renewable energy contribution. Additionally, doubling fossil fuel reserves results in 32% reduction in non-hydropower renewable energy demand by 2100.

After determining the changes required to achieve certain goals in Sub-Saharan Africa, a search for a sufficient historical analogue provided evidence that the changes necessary would be globally unprecedented. Next I determine potential emissions savings in the US, EU, and Russia given a sample climate plan. The results indicate that even with total decarbonisation by 2100, the rest of the world cannot industrialise via fossil fuels. Finally, evaluation of competing goals of development and carbon emissions in China and India reiterates that developing nations will have to choose between development and realistic climate goals.

The overall conclusions of this dissertation suggest that limiting global warming is not likely. A renewable energy infrastructure will need to be built regardless of environmental concerns. Reducing the gap in global economic and social inequality world via energy availability is a potential means of reducing the influence of population growth on each of the models in this dissertation.

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NOMENCLATURE

1P	Proven Reserves (>90% assured)
2P	Probable Reserves (>50% assured)
3P	Possible Reserves (>10% assured)
AR5	Fifth Assessment Report
ASPAC	Asia Pacific
ASPO	Association for the Study of Peak Oil
BGR	Bundesanstalt für Geowissenschaften und Rohstoffe
BP	British Petroleum
BRICS	Brazil, Russia, India, China, and South Africa
CC	Climate Constrained
CHINA	China (including Mongolia, Hong Kong SAR, and Macao SAR
COP21	21st Conference of Parties
EIA	US Energy Information Administration
EJ	Exajoule (10^{18} Joules)
EROI	Energy Return On Investment
EUR	Europe
FSR	Former Soviet Union
G7	Group of Seven
G20	Group of Twenty
GDP	Gross Domestic Product

GINI	Gini coefficient
GJ	Gigajoule (10^9 Joules)
$GtCO_2$	Gigatonnes (10^9 tonnes, 10^{15} grams) of carbon dioxide equivalent
GWh	Gigawatt (10^9 Watts) hours
HDI	Human Development Index
IEA	Humane Society of the United States
INDC	Intended Nationally Determined Contribution
IPCC	Intergovernmental Panel on Climate Change
J	Joule ($1\ kg*m^2*s^{-2}$)
MENA	Middle East and North Africa
MW	Megawatt (10^6 Watts)
NCSE	National Council for Science and the Environment
NOAM	North America
NRES	Non-Renewable Energy Source(s)
NRES+H	Non-Renewable Energy Sources plus Hydropower
PCC	Per Capita energy Consumption
PV	Photovoltaic
R/P	Reserves-to-Production ratio
RCP	Representative Concentration Pathway
RES	Renewable Energy Source(s)
RF	Russian Federation
SAS	South Asia

SCAM	South and Central America
SE4ALL	Sustainable Development for All initiative
SSAF	Sub-Saharan Africa
TFR	Total Fertility Rate
TJ	Terajoule (10^{12} Joules)
TOE	Tonnes of Oil Equivalent
UC	Unconstrained
UN	United Nations
UNFCCC	United Nations Framework Convention on Climate Change
URR	Ultimate Recoverable Resource
US	United States
USD	United States Dollars
W	Watt ($1\ J*s^{-1}$)
WB	World Bank
WESP	World Economic Situation and Prospects
XNA	Xinhua News Agency
ZJ	Zetajoule (10^{21} Joules)

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CHAPTER I

INTRODUCTION

Energy statistics are published by a variety of agencies including British Petroleum (BP), the International Energy Agency (IEA) and the Energy Information Administration (EIA). Additionally, there is a large body of literature dedicated to understanding, modelling and projecting human populations. The United Nations population projections are the standard population figures used in most demographic analyses today (Lutz and KC, 2010). The most recent projections were published by the United Nations in 2015 (UN, 2015b). World population was 7.3 billion as of 2014, Gerland et al. (2014) project the population to increase to 10.9 billion by 2100, and the *United Nations World Populations Prospects 2015 Revision* (UN, 2015b) projects 11.2 billion by 2100 (7.3-16.6 range). There is, however, very little literature linking these two areas of study. I am interested in combining these two bodies of literature into a new way of examining humans in much the same way that traditional ecologists would study any other population.

The goal of this dissertation is not to advocate specific policies in reference to future population growth and/or energy consumption. Rather, I will combine what the UN projects for 21st century global population with what energy production trends indicate in order to answer my research question: Given the published energy trends and reserves, one can question the future of the energy demand and source mixture (oil, coal, natural gas, nuclear, hydro, wind, solar, and biofuels percentages) that the population projections will require throughout the remainder of the 21st century.

This dissertation consists of eight chapters. The second chapter lays out the theoretical framework for the remaining chapters. Chapter II presents the global model of energy production, consumption and population from 1900-2100. This is a global model that does not take international borders or energy type/interchangeability into account. This style model is used for establishing model protocol and gaining a generalized idea of the impacts each of the variables forces within the model. The primary research focus of this chapter is to determine global peak production dates for the non-renewable energy sources and project the growth of renewable energy demand necessary to ensure a global energy supply in both a climate constrained and an unconstrained 21st century.

Chapter III models the world as a set of nine world regions. Economic development is a concern for all nations. There is a great range of per capita energy consumption around the world. Both population growth and economic development are going to be dependent on the availability of energy (Mohammed et al., 2013). Lambert et al. (2014) found that per capita energy consumption was directly associated with several quality of life indices including human development index, female literacy, and improved rural water sources. Chapter III is an evaluation of per capita energy and the resultant total energy demand of each region. The primary research focus of this chapter is to examine the global model from chapter II to identify and quantify the issues facing each of the nine world regions with respect to changes in per capita energy consumption.

The models used in chapters II and III are improved versions of those used in my previous master's thesis (Warner, 2012). The models have been altered from that previous state in that the original models were heavily assumption-dependent and attempted to project population from the energy availability portion of the model. Both the original models and the models presented in my dissertation are three body models. Population projections, energy availability projection and per capita energy consumption projections are necessary to each model. The master's version of the models used model-derived projections of energy availability and per capita consumption in order to derive a population projection. While not necessarily invalid, the model contained one irreconcilable flaw: how could we accurately project the growth of the renewable energy sources? It was decided that the models had to be rebuilt from the ground up with renewable energy production as the unknown variable.

The models that constitute these chapters of my dissertation are less dependent on assumptions than the original models from which they are derived. The focus is no longer to try and predict the human population of the future. Population projections are instead now taken directly from the latest United Nations projections. From a modelling point of view, this allows me to now dictate the terms by which these UN projections can come to fruition. It is well established that non-renewable resources will peak and the availability of these energy sources will decline. I have projected the timing of these peaks and declines. The only way to make up a deficit of energy demand is via renewable energy sources. I can now step back and say, 'If the world population is to follow the three UN projections, this will have to be the future energy mix.'

Chapter IV serves as a sensitivity analysis and an official documentation that the theoretical concerns have been tested. The most intriguing aspect of this chapter will be the section associated with potential criticism 2 as outlined above. Though hydraulic fracturing has, for the moment, eased whatever notions of oil insecurity that existed after the 2008 economic depression, it is yet to be seen whether or not the boom is sustainable (Murray and Hansen, 2013). There are still lingering energy return on energy investment (EROI) issues associated with unconventional fossil fuel resources (Hall et al., 2009). The primary research focus of this chapter is to determine the effect of varying per capita energy consumption and fossil fuel reserves on the outputs of the model from chapter II.

Chapters V, VI & VII are a critical evaluation of the results from chapter III. I have integrated the findings of the earlier chapters of my dissertation with the latest findings and reports of the United Nations, the World Bank and other institutions around the world in an attempt to augment those reports to include the energy *and* the population issues going into the future. These chapters are necessary in order to identify and project the ways in which major players will shape the global energy and population mixes throughout the 21st century.

Chapter V is an in-depth examination of the population-driven prospects of Sub-Saharan Africa. This region is home to many of the world's least developed nations (UN, 2016). The population of the region is also projected to grow to nearly four billion by 2100 CE (UN, 2015b). I examine several potential development scenarios for the region as a whole and determine the energy mix necessary to allow Sub-Saharan Africa to achieve higher levels of development. Energy availability is also linked to education and lowering fertility rates. The results suggest that the population projection of four billion people in 2100 is likely to occur without significant investment into the energy infrastructure of Sub-Saharan Africa. The primary research focus of this chapter is to quantify some of the efforts needed for development goals in the region and to determine if any suitable analogue can be found in the past 50 years to use as an example for Sub-Saharan Africa going forward.

Chapters VI and VII reintroduce the ‘coal question’ from (Jevons, 1865). Chapter VI suggests that the ‘coal question’ of the 21st century is one of climate change. I focus on the United States, the European Union, and the Russian Federation. These countries have high populations exhibiting below replacement fertility (UN, 2015b), relatively high per capita energy consumption (BP, 2015; UN, 2015b), and over half of the world’s proven coal reserves (BP, 2015). Chapter V tests potential coal exploitation tracks in these countries to determine the possible effect of recent climate negotiations on the fossil fuel availability for the other 87% of the world that does not live in these countries. The primary research focus of this chapter is to quantify the difference in carbon emissions projected in these 30 countries in a future unconstrained by climate concerns versus one of more ambitious climate change agreements.

Chapter VII compares and contrast the projected future of China and India in light of the ‘21st century coal question’. These nations have been chosen for comparison because combined they are 37% of the global population (UN, 2015b), but only consume 27.3% of global primary energy (BP, 2015). These two countries are among the most rapidly developing nations in the world. Recently India announced that a move away from coal was unrealistic (Harris, 2014). China has announced plans to move away from coal (Landler, 2014), though the motivation behind this move is suspect. These developing nations will almost certainly not be able to skip from low-consuming nations to high-consuming RES dominant nations without significantly leaning on a fossil fuel crutch to bridge any energy profile throughout the 21st century. It becomes apparent throughout this dissertation that these large and relatively undeveloped populations will, as the goal of development is pursued, have the most significant impact on the definition of the 21st century global energy profile. The primary research focus of this chapter is to model and identify the challenges of concurrently developing highly populated countries and achieving global climate goals.

To address the issue that approximately 1.2 billion people had no access to modern energy supplies (those energy sources not derived from the burning of traditional biomass) in 2012, the World Bank and the International Energy Agency developed the Sustainable Energy for All (SE4ALL) initiative and set three goals for the year 2030: to provide universal access to electricity and safe cooking fuels, a doubled rate of improvement in energy efficiency, and the doubling of renewable energy production (Banerjee et al., 2013). In a world where 91% of the 548 exajoules (10^{18} Joules, EJ) of energy production is derived from non-renewable fuels, energy access and economic development come with the cost of carbon emissions. In addition to energy access goals, the G7 countries announced a goal in June of 2015 to reduce global carbon emissions to one-half of 2010 levels by 2050 and to be 100% renewable by 2100. The Intergovernmental Panel on Climate Change's *Fifth Assessment Report* (Pachauri et al., 2014) estimates that in order to prevent >2°C warming, total carbon emissions from 1870 through 2100 should not exceed 2900 gigatonnes of carbon dioxide equivalent ($GtCO_2$). At the 2014 global emission of 35.5 $GtCO_2$ (BP, 2015), the world would surpass the 2˚C goal by 2038.

In 1968, Ludwig von Bertalanffy synthesized the systems approach to science (von Bertalanffy, 1968). The general systems theory presents two main hypotheses: First, any component of the observable world exists within a system of other components and that all disciplines are not only interrelated but necessary for complete understanding of the system and its components. Second, that there are underlying principles that can be universally or near universally applied to all systems. It is perhaps all too common for humans to create a false dichotomy that separates civilization and our species above the laws of the natural world. This dissertation is an attempt to reconcile that dichotomy in order to examine the difficulties associated with a post-peak energy world.

This problem is particularly important because it has been recently suggested that not only is energy availability perhaps the greatest of global concerns, but that it may in fact be the key to working around most all of the world's other major issues (Smalley, 2005). This is especially true as population projections suggest increasing population throughout the 21st century (UN, 2015b) while non-renewable energy sources are projected to peak by mid-century (Jones and Warner, 2016; Maggio and Cacciola, 2012; Mohr et al., 2015). Figure 1 demonstrates the tight energy production and global population are highly correlated (Pearson correlation coefficient of 0.9955).

A Granger causation analysis of temporal trends as described in Reynolds and Kolodziej (2008) and performed using R software, implies that there is strong evidence that energy production causes population change and there is no significant evidence that population change causes energy production ($\alpha = 0.05$). To reconcile the counter-trending trajectories of population increase (Gerland et al., 2014; UN, 2015b) and non-renewable energy decrease (Maggio and Cacciola, 2012; Mediavilla et al., 2013; Mohr et al., 2015), my dissertation will begin by examining the rates of increase necessary from the renewable energy sources in order to satisfy 21st century energy demand.

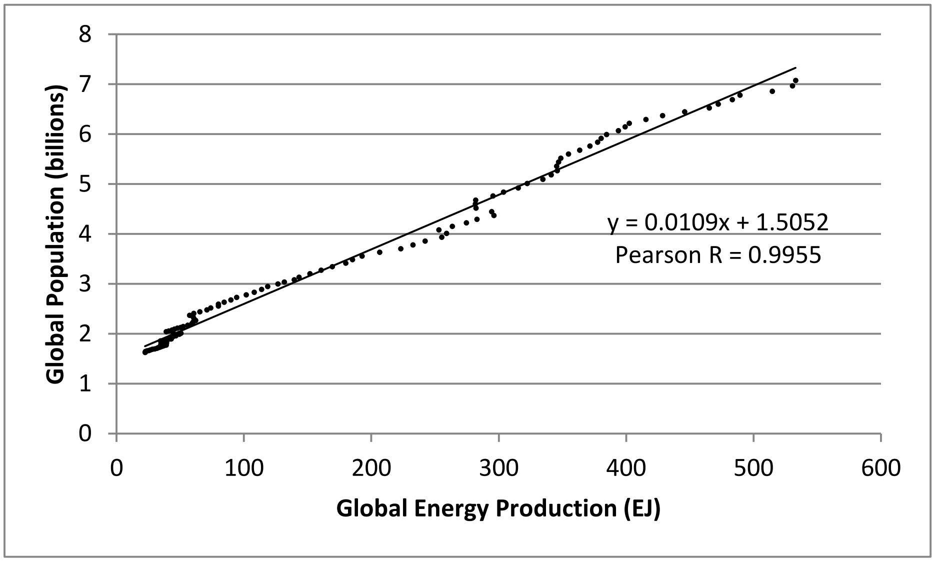

Figure 1: Global energy production and global population, 1900-2013. The intercept on the fit line suggests that in the absence of energy production, approximately 1.5 billion people can be supported. This number is in close agreement with other independently-derived estimates, such as (Pimentel et al., 2010). Data from (BP, 2015; UN, 2015b).

The third aspect of this dissertation is a practical evaluation of climate change as a function of population growth and development. Atmospheric carbon dioxide concentration is the number one concern in current sustainability and anthro-ecological studies, with many calls for switching from fossil fuels to renewable energy sources (RES) (e.g., Hansen et al. (2013)). Though I do not believe that global warming will be the main concern of the 21st century, carbon emissions will play a very important role in the future energy infrastructure. I believe that climate change concerns will develop a limitation on fossil fuel use. There are wide ranging estimates of fossil fuel reserves. Some studies consider only proven reserves that are both technically and economically feasible, whereas others cite resources that are likely to be viable based on future technologies or scarcity-driven market prices. The problem of energy scarcity in the face of growing populations and developing economies will ultimately be defined by a combination of geological, economic, and environmental limitations.

Overall, this research is necessary for two reasons: First, there is an extremely limited body of literature that explicitly bridges the gap between future energy availability and future global population. Second, research of this nature is very limited in the United States. The majority of the works cited in this dissertation originate from research groups in Europe, China, and Australia. Without speculating on the reasons for this, it is my hope that events such as the NCSE Energy & Climate Change conference in Washington (January, 2015) and the publication of these chapters will have some meaning for a country in which nominally 4.5% of the world's population (UN, 2015b) consumes about 18% of the world's total energy production (BP, 2015).

The methods of my dissertation are based within the theoretical framework of systems ecology. First - any component of the observable world exists within a system of other components and that all disciplines are not only interrelated but necessary for complete understanding of the system and its components. In this case, the human population exists within the natural laws that govern any other animal population. It is necessary to examine energetic costs and captures into the human population. Second - that there are underlying principles that can be universally or near universally applied to all systems. The metabolic functions that govern animal behaviour (e.g., maintenance, growth, reproduction) require energy. The same holds true for humans (though we may also consider disposable energy consumption (discretionary metabolism) for non-essential/biological functions (i.e., social and economic development). This enables me to remove the social biases that seemingly distinguish civilization and our species from the laws of the natural world and examine the difficulties associated with a post-peak energy world.

The basic model upon which this work is built is the single-cycle Hubbert curve (Hubbert, 1982). The single-cycle Hubbert curve is an asymptotic cosine curve that is dependent on three statistics:

1. The ultimate recoverable resource, URR (the economically viable resource total);
2. The projected maximum production of the resource;
3. The estimated year in which the maximum production of the resource occurs.

Hubbert's (1956) original peak curve is an asymptotic cosine function (Equation 1) henceforth referred to as the logistic equation. The result is a bell-shaped normal distribution curve, "Hubbert's Peak". The function uses the estimated value of the Ultimate Recoverable Resource (URR), historical production and (projected) maximum production. The URR is in effect the total exploitable quantity of a resource. It is assumed that when approximately one half of the URR has been extracted, the resource will peak in production. From this point on the production will begin an inexorable decline that approximately mirrors the pre-peak production increase rate. This creates a mirror-image normal distribution of production from discovery to depletion. The end result of Equation 1 is a year-by-year curve-fit of the production of the resource in question.

$$P(Y) = 2 * \frac{Pmax}{1 + COSH[b * (Y - Ypeak)]}$$

Equation 1. Hubbert's Equation. P equals production, Pmax equals the production at the peak year, Y equals the year, Ypeak equals the peak year and b is a coefficient equal to four times the maximum production divided by the URR.

Using basic extrapolation techniques, future production of each of the non-renewable energy sources (NRES), i.e., oil, coal, natural gas, and uranium can be projected into the 21st century. It is important that the total production of any source cannot be greater than its URR. It is assumed that the peak of any non-renewable resource will occur at or around one half of the estimated URR and the decay in yearly production values after the peak will follow a logistic decay curve. To date, this projection technique has proven successful and the results (from different datasets) are comparable with recent published projections (Brandt, 2007).

I also assume that the energy that each of these sources provides is interchangeable with any of the others at 100% efficiency and that the energy will be allocated as needed (as is appropriate to the scenario), regardless of political borders. This assumption is not realistic; however, it provides an optimistic bound on the use of global energy.

While the likelihood of major NRES discoveries is decreasing, this model assumes only what is considered to be economically viable at present, and that the energy return on investment of current and/or undiscovered energy sources must be favourable enough for economically viable exploitation (Hall et al., 2009). Despite recent advances in oil sands, tight oil, and shale gas recovery, serious questions pertain to their long-term viability and ultimate recoverable resources (Murray and Hansen, 2013). I acknowledge that future technological advances may allow for the growth of the NRES used within these models. As such, this model represents a minimum estimate of future recoverable NRES. Again, this research project is necessary for two reasons. First, there does not exist within the literature any attempt to bridge the gap between the future of energy availability and the future of human populations. Second, research of this nature is very limited in the United States.

It seems only natural that humans would question our own population potential. Perhaps most famously, Thomas Malthus in *An Essay on the Principle of Population* (Malthus, 1798) questioned the Earth's ability to support an exponentially growing population. Preindustrial populations were limited by resource scarcity (Wood, 1998). Industrial, or post-industrial, societies are likewise constrained by natural limitations (Peura, 2013). Though traditional agricultural techniques may have been the limiting factor checking population growth in the time of Malthus, the Haber-Bosch process, the Green Revolution, etc. have allowed humans to artificially concentrate fossil fuel energy into agricultural production (Hall and Day, 2009; Kendall and Pimentel, 1994; Smil, 1997). As a result, the world population has increased from around 1 billion in the time of

Malthus to over 7 billion today. An alternative view has been theorized that population is the independent variable and that food production will always rise to the demand of the population (Boserup, 1965). In either case, the 21st century is expected to witness this population growing to 11.2 billion by 2100 (UN, 2015b).

Just after the American oil industry emerged in the mid-19th century, Eaton (1866) made claim that God provided oil to man and that a just and loving god would not give oil to man only to limit its availability, so the permanence of oil supply need not be questioned. The year before, William Stanley Jevons (1865) published *The Coal Question*. Despite being famous for the so-called “Jevons’ Paradox”, the book was intended as a wakeup call pertaining to the United Kingdom’s dependence on a non-renewable resource. Britain’s coal production would go on to peak in the 1920s and today’s production is about one sixth that of peak production (Höök et al., 2010). In 2014, 91% of global energy consumption was derived from non-renewable sources, 7% from hydropower, and 2% from other renewables (BP, 2015).

M. King Hubbert (1949, 1956) investigated the limits to non-renewable energy, providing the first quantitative estimates to previously theorized limits to energy resources (e.g., Jevons, 1865; Malthus, 1798). Hubbert (1956) believed that the nascent nuclear power sector of the 1950s would ultimately replace fossil fuels and that nuclear power would prove to be nearly limitless. His belief has, and will likely remain, unfulfilled (Dittmar, 2012). Most recently, Maggio and Cacciola (2012), Mediavilla et al. (2013), and Mohr et al. (2015) separately employed methods similar to those found in Hubbert (1982) to model the global peaking of non-renewable resources (oil, coal and natural gas) in the 21st century.

Some manner of linking energy and population has been discussed in the literature for many years. The ancient Chinese philosopher Han Fei-Tzu wrote, “The life of a nation depends upon having enough food, not upon the number of people.” (Hardin, 1969). The population debate has included so-called “Cornucopian” authors as well as “Malthusian” or “Neo-Malthusian” authors. Cornucopian papers are characterized by an encouragement of population growth, optimism in regard to future technology/innovation, and a general separation of human society from natural/animal ecology. Neo-Malthusian papers feature theorized limitations to population and resource use growth, pessimism toward the ability for technology to save the day, and the application of ecological principles to human populations.

Carbon dioxide was identified as a greenhouse gas in 1896 CE (Arrhenius, 1896). The contribution of fossil fuel carbon emissions towards global climate change was suggested in 1957 CE (Revelle and Suess, 1957). The Intergovernmental Panel on Climate Change’s *Fifth Assessment Report* (AR5) was released in 2014 (Pachauri et al., 2014). AR5 is divided into three sections: a physical science basis, an adaptation impact report, and a section on mitigating climate change. It is estimated that between 1870 and 2010, 1,890 gigatonnes (1.89×10^{15} kilograms) of carbon-dioxide equivalent ($GtCO_2$) were emitted (Pachauri et al., 2014). It is suggested that in order to avoid serious climate change effects, this number should not exceed 2900 $GtCO_2$ (Randalls, 2010).

Pimentel et al. (2010) suggest that if both sustainability and a European standard of living are desired for the global population, that population will have to decline to around two billion. Bierbaum and Matson (2013) describe future human populations as heavily dependent on sustainable energy. Wolfram et al. (2012) examined the trends and United States Energy Information Agency (EIA) projections in energy consumption within the developed and the developing world. They suggest that the major growth in energy demand in the 21st century will result from the developing world initially accessing energy-consuming devices such as automobiles and basic appliances. Each of these previous studies have made only qualitative links between energy and population.

Throughout each of these chapters, the first-person pronoun 'we' is used, rather than the singular, 'I'. This is because each of the chapters has been written in preparation for submission to a peer-reviewed journal under the authorship of myself and my adviser, Dr. Jones.

This dissertation is an ambitious attempt to quantify some of the largest problems that the world will face in the 21st century. Modelling eighty-five years of energy production and consumption, integrating these results with population projections and carbon emissions should not be viewed as an attempt to gaze into the future with certainty. The numerical model results within the following chapters are not intended as predictions. Over time, technologies are developed, societal values change, and wars are fought. Each of these will affect the accuracy of the model output. This work should be viewed as an extrapolation of the courses that we as a global community are on.

“Are these the shadows of the things that Will be, or are they shadows of things that May be, only? Men’s courses will foreshadow certain ends, to which, if preserved in, they must lead, but if the courses be departed from, the ends will change…Why show me this, if I am past all hope?” – Ebenezer Scrooge, *A Christmas Carol* (Dickens, 1843).

CHAPTER II

THE 21ST CENTURY POPULATION-ENERGY-CLIMATE NEXUS*

Introduction

Finding a beneficial solution to the interrelated problems of population growth, energy poverty, energy scarcity, and global warming is one of the great challenges of the 21st century. Global energy production is at the nexus of these problems. Nobel laureate Richard Smalley ranked energy as the greatest problem facing society and hypothesized that being able to supply sufficient quantities of energy is key to solving each of the other problems (Smalley, 2005). Global population has increased from 1.6 billion in 1900 to 7.3 billion today, while total global energy production has increased from 23 to 548 exajoules (EJ). As population is projected to increase to 10.9 billion (9.6-12.3 billion) by 2100 (Gerland et al., 2014), total energy demand will continue to rise as well. The World Bank's Sustainable Energy for All Initiative (SE4ALL) is a plan to provide the 15-20% of the world's population that, as of 2010, did not have access to electricity or modern cooking fuels (Banerjee et al., 2013). As of 2013, the SE4ALL results have been positive; however, increases in energy access have not kept pace with the growth in world population (Banerjee et al., 2013).

For the past 20 years policy-makers and scientists have argued that limiting global warming to 2˚C is necessary to prevent serious negative climate change consequences

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(Randalls, 2010). The non-renewable energy sources (NRES) comprise 91% (87% fossil fuels) of total energy used today and emitted an estimated 35.5 gigatonnes of carbon dioxide equivalent ($GtCO_2$) in 2014 (BP, 2015). The fossil fuels and nuclear power are projected to peak in production by mid-century (e.g., Maggio and Cacciola, 2012; Mohr et al., 2015). Subsequent declining non-renewable production will require a rapid expansion in the renewable energy sources (RES) if either population and/or economic growth is to continue. This is especially important in striving for universal electricity access in the developing countries, vis-à-vis SE4ALL. Continued unconstrained use of the known fossil fuel reserves will lead to an unavoidable >2˚C warming (Pachauri et al., 2014).

On June 9, 2015 the G7 leaders agreed in principle on "decarbonizing" the global economy by 2100. A climate constrained scenario limiting warming to <2˚C, requires total CO_2 emissions to be less than 2900 $GtCO_2$ from 1870 to 2100 (Pachauri et al., 2014). This in turn requires 50% or more of existing fossil fuel reserves to remain unused (McGlade and Ekins, 2015). If carbon emissions were to remain at the 2014 level indefinitely, total cumulative emissions since 1870 would surpass 2900 $GtCO_2$ in the year 2038. What has been lacking to date when addressing these interrelated problems is a quantitative assessment of the growth in, and mix of, energy required through the 21st century. As carbon-intensive fuel sources constitute less and less of the global energy mix (either via economic and geologic peaking or as a result of climate and environmental concerns), renewable energy production will have to expand to meet the demand-production gap.

We aim to quantify the year-to-year changes in the global energy mix that are likely to result from A) business as usual fossil fuel consumption that is only economically and/or geologically limited and B) the constraint of fossil fuel energy usage necessary to achieve the <2˚C climate goal. The IPCC (2014) recently presented four Representative Concentration Pathways (RCP) for cumulative CO_2 emissions to 2100: RCP 2.6 (nominally 2900 $GtCO_2$ and <2˚C warming), RCP 4.5 (~4500 $GtCO_2$ and 2.5^{o}C), RCP 6.0 (~5300 $GtCO_2$ and 3^{o}C) and RCP 8.5 (~7800 $GtCO_2$ and 4.5^{o}C).

We address the issue of NRES usage to 2100 under an unconstrained fossil fuel scenario (UC) and climate constrained energy production scenario (CC). The unconstrained scenario assumes that the discovery, production and subsequent decline of NRES will follow a logistic curve in which peak production occurs when one-half of the reserve has been extracted (Hubbert, 1956). This scenario is not limited in any way by climate concerns and will provide an estimate of future CO_2 emissions should government leaders fail to reach a global agreement on limiting fossil fuel emissions. While the likelihood of major NRES discoveries is decreasing, this scenario assumes only what is considered to be economically viable at present, and that the energy return on investment (EROI) of current and/or undiscovered energy sources must be favourable enough for economically viable exploitation (Hall et al., 2009). Despite recent advances in oil sands recovery, tight oil, and shale gas, questions pertaining to long-term viability and ultimate recoverable resources remain (Murray and Hansen, 2013). We acknowledge that future technological advances may allow for the growth of the NRES used within our models. As such, this scenario represents a minimum estimate of future recoverable NRES. In addition, our statistics rely on industry-specific and/or national reporting of present and recent past reserves and consumption that can deviate from the actual numbers, as recently revealed about China underreporting their coal consumption (Buckley, 2015).

The CC energy use scenario is based on limiting cumulative CO_2 emissions to 2900 $GtCO_2$ from 1870 to 2100 and in turn global warming to <2˚C. This goal was critically examined by McGlade and Ekins (2015). Our study is similar in that it also examines the amount of unburnable fossil fuels, but deviates in that on top of the means by which energy cannot be derived in the 21st century we quantify the additional RES production necessary to make up for the fossil fuels left unutilized, and the growth in world population.

Although RES potential is theoretically near-unlimited (de Vries et al., 2007; Marvel et al., 2013), we determine only the amount needed to meet total global energy demand in the two scenarios. Non-hydro, non-solid fuel RES was 2.4% of 2014 total energy production, nominally comprised of 50% wind,13% solar (primarily photovoltaic, or PV solar) and 37% other renewable energy sources. For the purposes of this study, the term 'solar' implies photovoltaic solar power. For our model scenarios we assume that the mix of non-hydro RES will be 60% wind, 25% solar and 15% biofuels (See Methods for rationale for these percentages). Our scenarios are used to calculate the rate of RES growth needed to offset the decline in the NRES and supply the additional energy needed to continue world population growth and per capita energy expansion in each of the UN's population scenarios (Gerland et al., 2014).

Data and Methods

Our model scenarios are based on three main components. The first part of the model is the most recent UN population projections (Gerland et al., 2014). These projections include a median estimate (used in the model scenarios as presented in the main body of this paper) and high and low confidence intervals. We did not model population ourselves; rather, we used these projections as the basis of our model. The projections are provided in five year intervals from 2010-2100. We interpolated the year by year populations from these five year values using a logistic curve fit. The dataset provided extends back to 1950. World population values from 1900-50 were from McEvedy and Jones (1978).

The second component of the model scenarios is energy. This includes production, consumption, and reserves data and logistic modelling. Several authors and agencies have estimated reserves. We constructed historical energy production using the statistics found in (BP, 2015). These production values are widely used by researchers and extend back to 1965-81 depending on the energy source. We used the oil production values from the Association for the Study of Peak Oil (ASPO) (2006) for the years 1859-1965. Coal production before 1981 was extended back using Rutledge (2011). We used the data provided within the extended worksheet published by Laherrère (2004) to fill out natural gas production from 1900-1970. Nuclear reserves were obtained from the World Nuclear Association (WNA, 2013) and historical production was available via British Petroleum (BP) (BP, 2015). Each of these combined datasets was cross-matched to ensure that the units and values overlapped with minimal error. Without reliable statistics available, hydropower was assumed to have grown from 1900-1965 at a similar rate as it was growing from 1965-80. Considering the global-scale of energy production, nuclear and RES production were considered to be negligible before 1965 (0.24 and 0.05 EJ in 1965 respectively).

Combining the reported reserve estimates (BP, 2015) and the cumulative historical production of each NRES results in an estimate of each resource's ultimate recoverable resource (URR). The URR is an estimate of the total energy that can be extracted from each NRES before extraction of the resource is limited either geologically, economically, or technologically. It is not an estimate of the total energy content initially in place. Our URR estimate is in close agreement with the estimates derived by others (table 1). Future production of the NRES was modelled using the normal logistic function as described in Hubbert (1956, 1982). Each NRES production was extrapolated from the 2000-2014 trend to the point of having produced ½ of the URR. This point is considered the peak year and production. The method and its variants are widely used for making projections of NRES energy production. The equation is the same as Equation 1 (Chapter I).

The result of this method is a singular peaking of each NRES production and a subsequent decline approaching exhaustion into the future. We estimated the production value and timing of each NRES peak after extrapolating the trends in production of each source from 2000-14. Hydropower was projected using an exponential growth trend from the 2014 production value of 36.9 EJ to 52.5 EJ in 2100. The 2100 figure represents the IPCC estimate of global hydropower potential (Seyboth et al., 2011). We assume that this potential will be built out by 2100.

Our next step in the modelling was to examine the rate of energy consumption. Because our model is based on projected population growth, energy consumption must be measured on a per capita basis. Using historic energy production and population numbers (Figure 1), we calculate (1900 to 2014) and project (2015 to 2100) global per capita energy consumption (Figure 2). We calculated historical per capita energy consumption by dividing energy production by population. We assumed that the total energy production in each year was consumed in the same year. Strategic reserves and other energy storages were assumed to be of negligible value, and the solid RES (i.e., wood and peat) were not included.

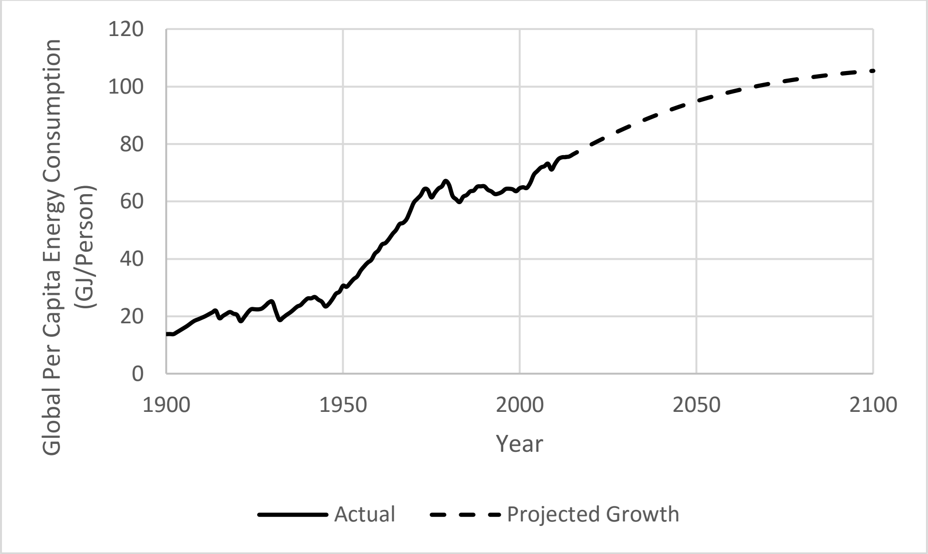


Figure 2: Per capita energy consumption extrapolation of projected growth to 2100. Data from (ASPO, 2006; BP, 2015; Gerland et al., 2014; Laherrère, 2004; McEvedy and Jones, 1978; Rutledge, 2011).

To estimate the future trajectory of world average per capita energy consumption, we used the relationship of population growth (Gerland et al., 2014) and energy consumption

(BP, 2015) over the period 2000-2014. We scaled the average annual growth of total global energy consumption (2.33%) relative to the average annual growth in global population (1.27%). We then applied the trend ratio (1.83) to the medium UN population scenario out to 2100 in order to determine our model's energy demand throughout the remainder of the century (figure 2). Total energy demand was derived by multiplying global population by the per capita energy consumption projection for each year. The RES production for each year was determined by subtracting the NRES and hydropower production values from the total energy demand. This remainder was assigned to RES production.

In 2014, 50% of non-hydro RES was derived from wind and 13% from solar. The remaining production was derived from every other source (biomass, geothermal etc.) (BP, 2015). We simplified non-hydro renewable energy production to three sources: wind, solar, and algae biofuels. Liquid fuels currently constitute 18% of total global energy use (Caspeta et al., 2013). To reflect the role of liquid fuels, algae biofuels were assigned 15% of total RES energy demand. The remaining 85% was divided between wind and solar energy. In 2014, wind energy production was approximately four times higher than solar production. The annual rate of growth since 2000 has been approximately 23% year for wind and 39% for solar. Considering both of these statistics, we assumed that solar would narrow the gap over time. Wind was assigned 60% and solar 25%.

We next scaled the three RES demand figures using 5MW wind turbines for wind energy, square kilometres of solar panels for solar energy, and square kilometres of algae biofuel production facilities for algae biofuels. A 5MW wind turbine operating at a capacity factor of 0.3 (EIA, 2016a) produces approximately 47.3 terajoules (TJ) in one year.

5MW x 8,766 hours x 0.3 capacity factor = 13.149 GWh/year

13.149 GWh/year x 3,600 seconds/hour = 47.336 TJ/year

Photovoltaic solar panels operating at 50% coverage and 10% conversion efficiency produce about 414 TJ/km^2 per year (Moriarty and Honnery, 2012). The most optimistic photobioreactor laboratory experiments for algae yield up to 58,700 litres of biofuel per hectare (186.2 TJ/km^2) (Chisti, 2007), theoretically making algae biofuels the most energy dense biofuel. However, scaling photobioreactors to large commercial-scale biofuel generation is impractical compared to open pond algae cultivation systems (Benemann, 2013). The most optimistic yield expected of the open pond process is closer to 25,000 litres of biofuel per hectare (Benemann, 2013), or approximately 79.3 TJ/km^2, the figure we use in our model.

To complete our assessment of future RES demand, we estimated how quickly the RES infrastructure will have to grow. Wind turbines and PV solar panels have a lifespan of approximately 20 years (Kubiszewski et al., 2010; Zweibel, 2010). We assumed that this lifespan applied to an algae growing facility as well. As such, our annualized installation figures for each of these three energy sources included a 5% replacement of the previous year's installed infrastructure. For each year of the model, we took the number of wind turbines that were required, subtracted the previous year's total, and then added 5% of the previous year's total. This figure represents our estimate of the number of 5MW turbines equivalent that must be installed for each of the years within the model. The same approach applies to PV solar panel and algae facility areas.

The climate constrained scenario was built in the same way as described above. The addition of this climate constrained scenario first required an examination of carbon dioxide emissions within the model. This is the third main component of the model. Carbon dioxide emissions based on the standard global average conversion factors are estimated at 3.07 tonnes per tonne of oil equivalent (TOE) for oil, 3.96 tonnes/TOE for coal and 2.35 tonnes/TOE for natural gas (BP, 2015). These numbers equal about 73, 94, and 26 megatonnes of CO_2 per EJ. The IPCC reports that as of 2010, a cumulative 1890 $GtCO_2$ had been emitted via anthropogenic means (Pachauri et al., 2014). The unconstrained scenario resulted in about 4,700 $GtCO_2$ emitted by 2100. The IPCC suggests that this number cannot exceed 2900 $GtCO_2$ in order to have a better than 50% chance of limiting global climate change to less than 2˚C.

Constructing the climate constrained scenario in accordance with the sub-2900 $GtCO_2$ goal, the URR of oil, coal, and natural gas had to be lowered, and RES was forced to make up the difference in energy production between the UC and the CC scenarios. This type of fossil fuel limitation was described in McGlade and Ekins (2015). Their model was used as the starting point for limiting fossil fuels in the climate constrained scenario. We used logistic modelling, global URR, and global reserve estimates (BP, 2015), whereas McGlade and Ekins did not use URR estimates and summed present reserve estimates from individual countries. Our estimates of energy reserves are within 2% of those used by McGlade & Ekins (see table 1).

Table 1: Sample set of fossil fuel ultimate recoverable resources (URR) and 2014 reserves. This chapter's URR estimate calculated from (ASPO, 2006; BP, 2015; Laherrère, 2004; Rutledge, 2011). Mohr et al. (2015) best guess fossil fuel URR. McGlade and Ekins (2015) conventional resources only. All units converted to exajoules (EJ) using BP (2015) conversion factors. *Reserves adjusted to 2014 value using BP (2015) production values.

	Ultimate Recoverable Reserves				***Reserves***			
Source	**Oil**	**Coal**	**Natural Gas**	**Total**	**Oil**	**Coal**	**Natural Gas**	**Total**
Maggio & Cacciola, 2012	14,898	27,300	13,125	55,323	-	-	-	-
Mohr et al., 2015	25,460	22,406	27,810	75,676	-	-	-	-
Capellan-Perez et al., 2014	16,710	27,800	13,600	58,110	-	-		
This Paper	17,400	25,895	11,085	54,380	-	-		
McGlade & Ekins, 2015	-	-	-	-	6,723	23,600	6,748	37,071
*World Energy Council, 2013**	-	-	-	-	7,023	24,473	7,543	39,039
*Bundesanstalt für Geowissenschaften und Rohstoffe, 2014**	-	-	-	-	8,933	20,201	7,398	36,532
British Petroleum, 2015	-	-	-	-	9,741	18,126	7,072	34,939
*US Energy Information Administration, 2014**	-	-	-	-	9,487	17,576	7,322	34,384
*International Energy Agency, 2013**	-	-	-	-	9,564	24,195	8,185	41,944

Results and Discussion

To satisfy the emission limit, we find that 37% of oil, 54% of natural gas and 86% of coal reserves available for use in the UC scenario need to remain unused in the CC scenario. Individual energy production curves for both scenarios by source are presented in Figure 3. In the UC energy use scenario NRES and hydropower production peak at 678 EJ by 2032 and decline to 152 EJ by 2100 (figure 3a). We project global per capita energy consumption to increase from 76 gigajoules (GJ) today to 106 GJ in 2100, and world energy demand to increase from 548 EJ to 1146 EJ (table 2). Independent of per capita energy change, total energy demand in 2100 varies by nearly 300 EJ based on the Gerland et al. (2014) population projections alone.

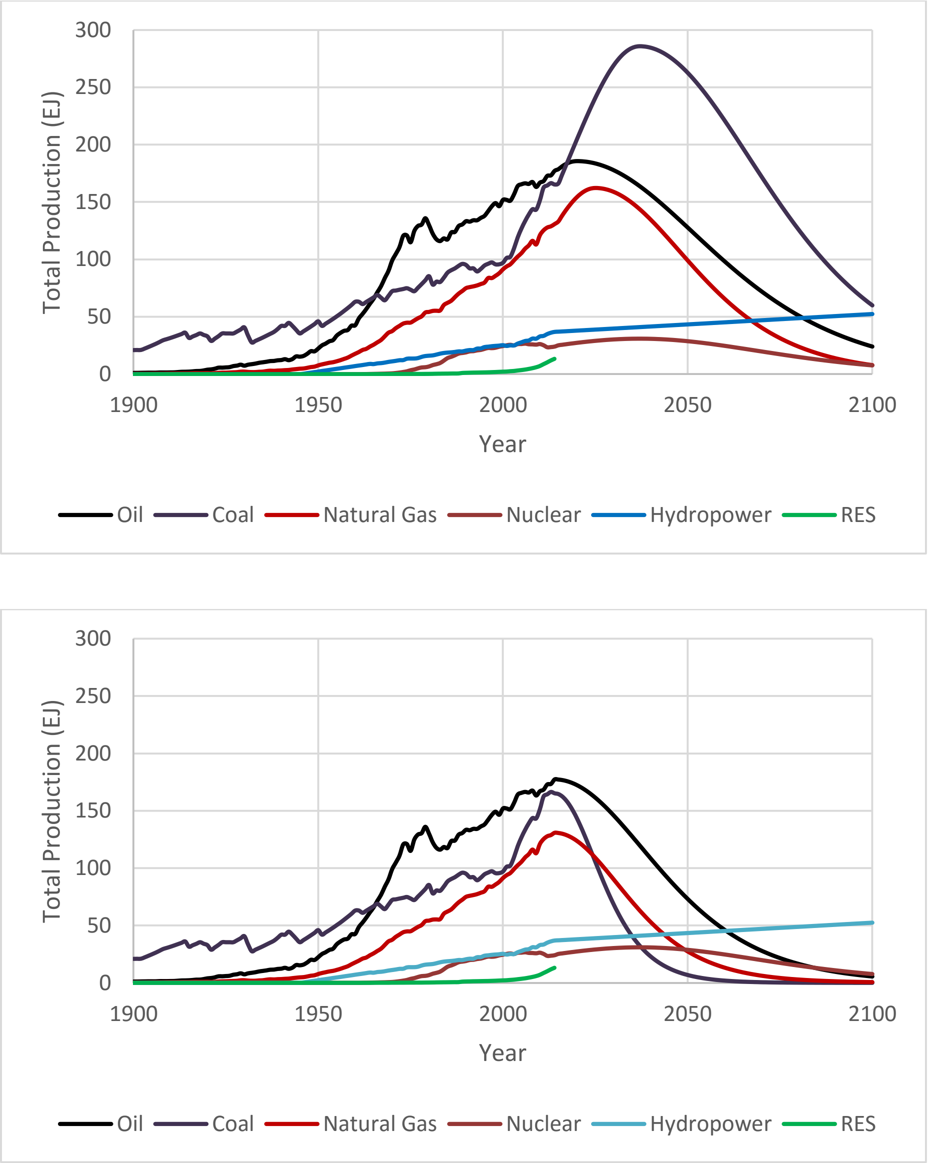


Figure 3: Energy production by source, 1900-2100. Unconstrained scenario based on 2000-2014 production trends and logistic model (a). Results in line with independently derived projections from (Höök et al., 2010; Mediavilla et al., 2013; Mohr and Evans, 2009; Mohr et al., 2015). Climate constrained logistic scenario in which all three fossil fuel sources peak immediately to keep cumulative anthropogenic CO_2 emissions to <2,900 Gt by 2100. All data compiled from (ASPO, 2006; BP, 2015; Laherrère, 2004; Rutledge, 2011; Seyboth et al., 2011; WNA, 2013).

Table 2. World population, energy production, and renewable energy source (RES) requirements; 2014, 2028, 2054, 2100. Based on energy production in our unconstrained (UC) and climate constrained (CC) scenarios. Gerland et al. (2014) median, high, and low population projections. Dates provided based on 50/50 RES/NRES production ratio in CC scenario (2028) and the UC scenario (2054). World population measured in billions. Energy production figures (± 1) measured in exajoules.

	2014	**2028**			**2054**			**2100**		
		UC	**CC**	***CC-UC***	**UC**	**CC**	***CC-UC***	**UC**	**CC**	***CC-UC***
Population (10^9)	7.2	8.3	8.3	*0*	9.7	9.7	*0*	10.9	10.9	*0*
Oil (EJ)	177	181	152	*−28*	116	61	*−55*	24	6	*−18*
Coal (EJ)	165	259	82	*−177*	248	4	*−243*	60	0	*−60*
Natural Gas (EJ)	131	161	98	*−63*	85	21	*−64*	8	1	*−7*
Nuclear (EJ)	24	30	30	*0*	27	27	*0*	8	8	*0*
Hydropower (EJ)	37	39	39	*0*	44	44	*0*	53	53	*0*
RES (EJ)	13	30	299	*268*	417	780	*362*	994	1,079	*86*
Total (EJ)	548	700	700	*0*	937	937	*0*	1,146	1,146	*0*
Wind (EJ)	7	18	179	*161*	250	468	*218*	596	647	*51*
Solar (EJ)	2	8	75	*67*	104	195	*91*	248	270	*22*
Algae[a] (EJ)	3	5	45	*40*	63	117	*54*	149	162	*13*
Gerland et al. 2014 High Population Projection										
Population	7.2	8.4	8.4	*0*	10.2	10.2	*0*	12.3	12.3	*0*
RES	13	40	308	*268*	459	821	*362*	1,150	1,236	*86*
Total	548	710	710	*0*	979	979	*0*	1,302	1,302	*0*
Wind	7	24	185	*161*	275	493	*218*	690	742	*52*
Solar	2	10	77	*67*	115	205	*90*	288	309	*21*
Algae[a]	3	6	46	*40*	69	123	*54*	173	185	*12*
Gerland et al. 2014 Low Population Projection										
Population	7.2	8.2	8.2	*0*	9.3	9.3	*0*	9.6	9.6	*0*
RES	13	20	289	*268*	378	740	*362*	861	947	*86*
Total	548	690	690	*0*	898	898	*0*	1,013	1,013	*0*
Wind	7	12	173	*161*	227	444	*217*	517	568	*51*
Solar	2	5	72	*67*	95	185	*90*	215	237	*22*
Algae[a]	3	3	43	*40*	57	111	*54*	129	142	*13*

[a] The 2014 algae production value includes all biofuels 3production as per BP [3]

Cutting carbon emissions in order to satisfy the conditions of the climate constrained scenario we find that non-hydro, non-nuclear NRES production needs to immediately begin to decline from 473 EJ to 6 EJ by 2100 (figure 3b). In 2014, global non-hydro, non-solid fuel RES was comprised of 141,800 5MW equivalent wind turbines, 4,300 km^2 of solar panels (an area slightly smaller than Trinidad and Tobago) and algae biofuels production remains in the testing phase (Benemann, 2013; Chisti, 2007); thus current commercial production may be considered zero. In 2014 all sources of biofuel production were equivalent to 37,500 km^2 of algae biofuels production (approximately the area of Bhutan).

The cumulative carbon emission trajectories from 1900 to 2100 for our two model scenarios are shown in Figure 4. The climate constrained model scenario restricts cumulative CO_2 emissions to 2900 Gt, whereas the unconstrained energy use model scenario maximizes NRES use within the constraints of our logistic modelling. Here we find a cumulative emission of 4700 $GtCO_2$, a value between RCP 4.5 and RCP 6.0. Although RCP 8.5 is theoretically possible if all probable and possible fossil fuel reserves are burned, it is an unrealistic scenario given estimates of fossil fuel URRs of geologically and economically extractable reserves.

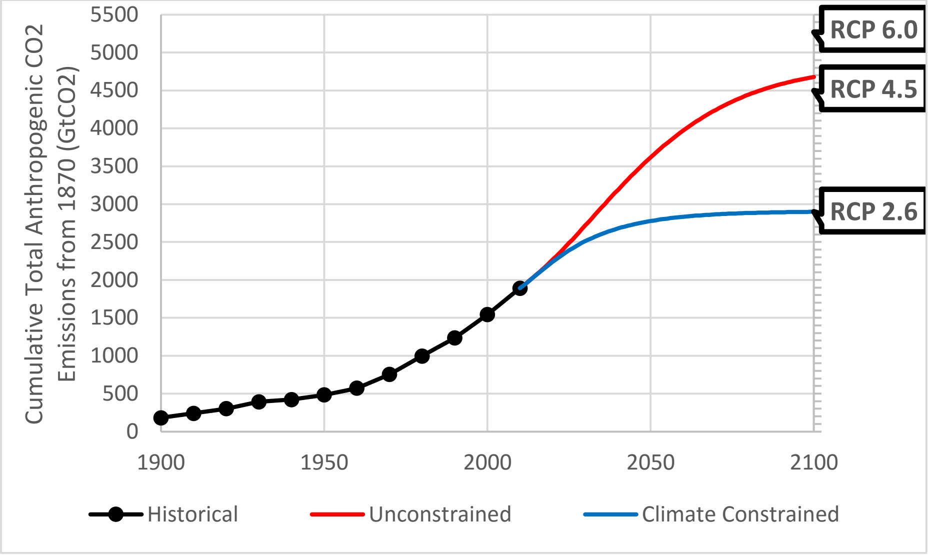


Figure 4: Cumulative anthropogenic carbon dioxide emissions, 1870-2100. From our climate constrained and unconstrained energy use scenarios. The IPCC AR5 (Pachauri et al., 2014) suggests that in order to have a better-than-even chance of avoiding a global average warming of 2°C, CO_2 emissions should remain below 2900 Gt (RCP 2.6).

Our model result for summed NRES and hydropower is shown in Figure 5. The 2100 energy demand that cannot be met via NRES and hydropower must be made up in RES production (table 2). For the unconstrained energy use scenario 87% of total energy in 2100 is derived from RES. This is a 75-fold increase from the 2014 level and would require the equivalent of 12.6 million 5MW wind turbines, 600,000 km^2 of solar panels (similar to the area of Ukraine) and 1.9 million km^2 of algae production facilities (approximately the area of Sudan). In the climate constrained scenario 94% of total energy in 2100 is RES. This is an 81-fold increase from the 2014 level and would comprise the equivalent of 13.7 million 5MW wind turbines, 652,000 km^2 of solar panels and 2.04 million km^2 of algae production facilities.

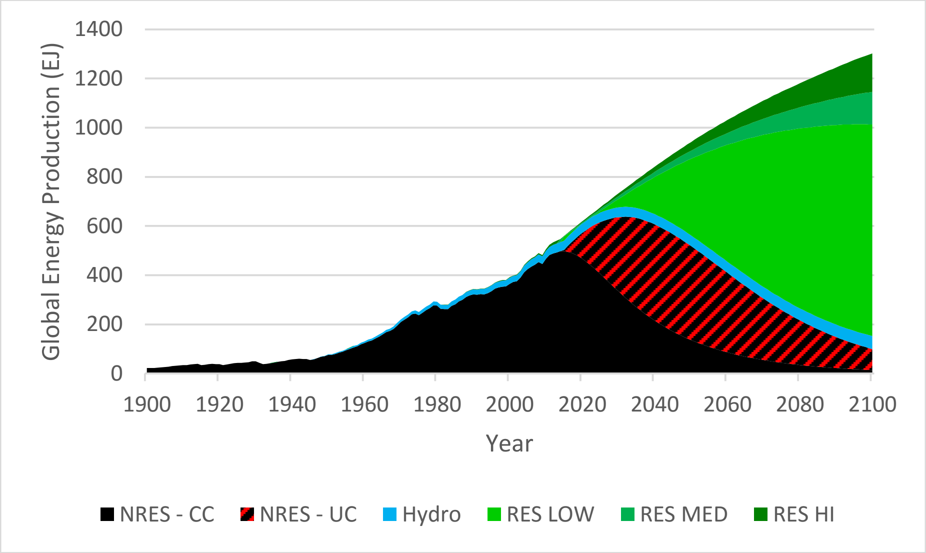


Figure 5: Energy production mixture, 1900-2100. Includes results of UC and CC model scenarios. Results for three population projections (HI, MED, LOW = High, Median, and Low projections) included (Gerland et al., 2014). NRES = oil, coal, natural gas, nuclear. Red hatched area represents NRES production in unconstrained scenario and RES production in the climate constrained scenario.

Table 3: Renewable energy source (RES) infrastructure requirements; 2014, 2028, 2054, 2100. Based on energy production in our unconstrained (UC) scenario and climate constrained (CC) scenario. Gerland et al. (2014) medium population projection. Wind energy production is measured in terms of 5MW wind turbines equivalent (47.3 terajoules/year). Solar energy production (414 terajoules/km^2/year) and algae biofuel production (79.3 terajoules/km^2/year) is measured in terms of area.

	2014	**2028**			**2054**			**2100**		
	Actual	UC	CC	CC-UC	UC	CC	CC-UC	UC	CC	CC-UC
Wind (5MW)	141,800	385,900	3,784,400	3,398,500	5,288,600	9,883,100	4,594,500	12,592,900	13,678,800	1,085,800
Solar (km^2)	4,300	18,400	180,300	161,900	252,000	470,800	218,900	599,900	651,700	51,700
Algae (km^2)[a]	37,500	57,600	564,800	507,200	789,400	1,475,100	685,700	1,879,600	2,041,600	162,100

[a] The 2014 algae production value includes all biofuels production as per BP (2015).

Assuming a 20 year lifespan (Kubiszewski et al., 2010), over 700,000 5 MW equivalent wind turbines will need to be installed under either scenario in the year 2099 alone (Figure 6). That is equivalent to adding the entire 2014 production of wind turbines (~13,150 five MW equivalents) every seven days in 2099. In the shorter term, 485,000 and 94,000 5 MW wind turbines will need to be installed in the climate constrained and the unconstrained energy use scenarios respectively in 2028 alone. That is a 37-fold and 7-fold expansion in the annual installation rate in only thirteen years.

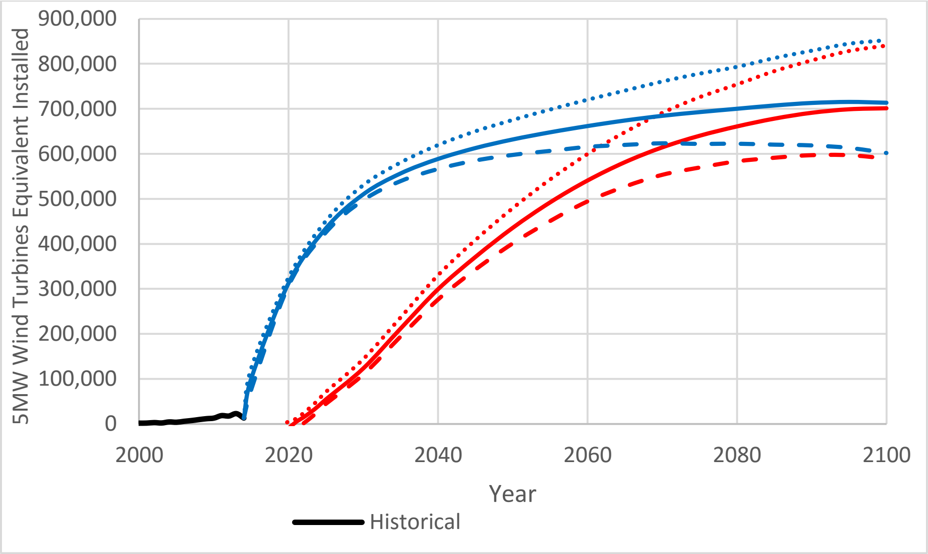


Figure 6: Annual 5 MW wind turbines equivalent installations per year, 2000-2100. Colour indicates energy scenario (UC – Red, CC - Blue) and line type indicates high, median and low population projection (Gerland et al., 2014). Solar panel and algae production facility area follow the same curve but on different scales. To convert to km^2 PV solar panel area, multiply 5MW wind turbines equivalent by 0.114. To convert to km^2 algae production area, multiply 5MW wind turbines equivalent by 0.597. Note: in the unconstrained scenario RES is theoretically unnecessary before 2020-25, whereas the immediate peaking of oil, coal, and natural gas in the climate constrained scenario results in a large up-front installation.

Despite increasingly energy efficient vehicles, appliances, and consumer electronics throughout the developed world, rebound effects (Sorrell, 2009) and global economic development (Wolfram et al., 2012) have led to overall growth in global per capita energy consumption. China (90 GJ/person) and India (21 GJ/person) account for 37% of the world's population, yet currently use very little energy per capita compared to the European Union (7% of world population, 133 GJ/person) or the United States (4% of world population, 299 GJ/person) (table 4). The 2014 global average is 76 GJ/person; yet, rates of individual countries span three orders of magnitude. Since 2000, overall EU and US per capita energy consumption has declined 12%, while China and India increased 174% and 77%, respectively. Over that same time, global per capita energy consumption increased 18%. Even if the consumption in the EU and US continues to decline, rapid economic growth (and projects such as SE4ALL) within the developing world is likely to offset any decline in per capita energy consumption within the developed countries.

Conclusions and Policy Implications

The ability of the world to continue to support population and consumption growth is dependent upon a timely transition to an increasingly RES world. Our model results indicate that, with or without climate considerations, RES will comprise 87-94% of total energy demand by the end of the century. Despite the similar RES requirement in 2100 under both scenarios, the trajectories from 2015 to 2100 are quite different (Figure 7). The growth in RES plus hydropower in the unconstrained energy use scenario has a longer shallower ramp up during much of the 21st century and does not reach 50% of total energy until 2054. In contrast, the climate constrained scenario requires an immediate and rapid expansion of RES, reaching 50% of total energy by 2028. In essence, the transition from

NRES to RES is a "pay me now, or pay me later" scenario. The benefits associated with allowing the world a slower transition come at the cost of global warming (i.e., >4700 $GtCO_2$), whereas the benefits of avoiding serious climate change repercussions would require a large up-front cost and likely be a detriment to the goal of providing universal access to electricity.

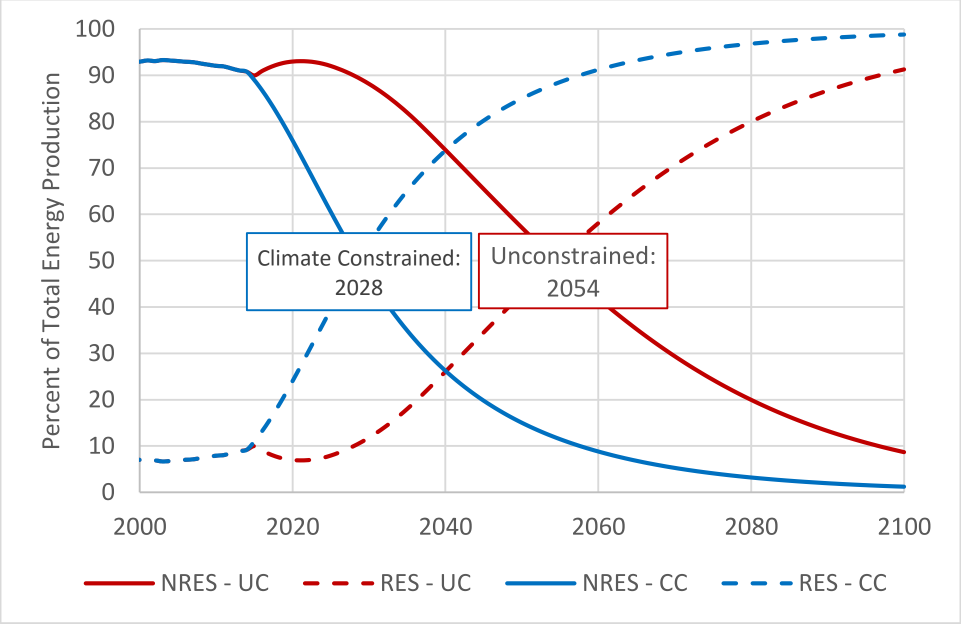


Figure 7: Comparison of NRES & RES energy mix, 2000-2100. Unconstrained (UC) scenario and Climate Constrained (CC) scenario with approximate dates at which 50/50 energy mix is projected. UC scenario projects a 50/50 mix by 2054 and CC scenario projects 2028. For this figure RES includes hydropower.

On paper, any form of scaling is simply a matter of numbers. In reality, it could prove a monumental task to develop RES to support world population projections. Energy return on investment (EROI) is a particularly important factor to consider in the transition to RES. Though the EROI of RES technologies has been increasing, there are theoretical limits (Atlason and Unnthorsson, 2014). The scaling of the RES infrastructure to our model output requirements would require the use of increasingly marginal lands and lower grade material inputs, leading to an overall lower EROI (e.g., Fizaine and Court, 2015; Moriarty and Honnery, 2012). Additionally, the transition to RES will require material resources (e.g., steel, copper and rare earth metals) whose per unit energy cost is significantly higher than for NRES (Vidal et al. (2013). Lower EROI fuels quickly reduce the share of net energy available for societal use (Murphy and Hall, 2010) and as less energy is available to societies, it is speculated that there will have to be a reprioritization of societal energetic needs (Lambert et al., 2014).

Coal, oil, and natural gas each took 35+ years to increase from 5% to 25% of total global energy production (Smil, 2014). A comparable transition to a renewable energy infrastructure will take decades, not years (Davis et al., 2010; Hirsch et al., 2005; Smil, 2014), time that is not available for a <2°C scenario. The energy invested in creating the RES infrastructure takes a period of time before these sources become net energy producers (i.e., energy payback time). For example, it is estimated that there is a 1-4 year energy payback time for PV solar panels (Bhandari et al., 2015) and between 1-3 months for smaller (0.3-0.5 MW) wind turbines (Uddin and Kumar, 2014). We have not explicitly included the energy or material required to construct the RES infrastructure, though this is an important avenue for future research. However, doing so here would exacerbate the already high RES installation rates in our model.

Table 4: Per capita energy consumption rates from 23 selected countries/regions. PCC = per capita consumption in gigajoules per person in 2014. Global average for 2014 and for projected in 2100 included. PCC calculated from data in (Gerland et al, 2014; BP, 2015). *Africa average excludes Egypt, Algeria, and South Africa.

Country	PCC
Canada	393
Norway	385
Saudi Arabia	343
United States of America	299
Australia	218
Russian Federation	201
Germany	158
France	154
Japan	151
European Union	133
United Kingdom	124
Venezuela	115
2100 Projected World	**106**
South Africa	100
China	90
2014 World Average	**76**
Mexico	65
Brazil	62
Algeria	55
Egypt	43
Indonesia	29
India	21
Pakistan	17
Bangladesh	8
Africa*	7

Our analyses of NRES decline, population, and per capita energy consumption increase suggest that RCP 8.5 is unlikely to occur in the unconstrained energy use scenario, and RCP 2.6 appears equally unachievable in the climate constrained scenario, a conclusion in agreement with the qualitative assessment of others (Sanford et al., 2014; Victor and Kennel, 2014). Trying to achieve <2°C warming (i.e., RCP 2.6 scenario) will require renewable energy to expand to >50% of total global energy by 2028, a 37-fold increase in the annual rate of supplying renewable energy in only 13 years. Our results further suggest that economic and geologic fossil fuel limitations will force the “ambitious” end-of-century decarbonisation goals set by the G7 leaders. This is true in even the unconstrained scenario in which little-to-no pro-active commitment to decarbonize is required.

The results of this study lead us to recommend that 1) the population-energy-climate nexus is not an either/or route for policymakers, rather 2) global efforts should focus on implementing adaptation responses to climate change under the IPCC RCP 4.5 and 6.0 scenarios, and 3) significant and rapid RES expansion should be undertaken well before mid-century.

CHAPTER III

A POPULATION-INDUCED RENEWABLE ENERGY TIMELINE IN NINE WORLD REGIONS

Introduction

Approximately 1.2 billion people currently have no access to modern energy supplies (Banerjee et al., 2013). To address that issue, in 2012 the World Bank and the International Energy Agency developed the Sustainable Energy for All (SE4ALL) initiative and set three goals for the year 2030: to provide universal access to electricity and safe cooking fuels, a doubled rate of improvement in energy efficiency, and the doubling of renewable energy production (Banerjee et al., 2013). It is implied within the initiative that renewable energy sources (RES) and hydropower should comprise 36% of total global energy production by the year 2030, up from 9% today. This goal includes pre-modern renewables such as solid biomass, whereas RES numbers in the BP Statistical Review of World Energy 2015 (BP, 2015) numbers do not. For the duration of this paper, "RES" will refer to the modern *non-hydro* renewable energy sources (e.g., wind, solar, biofuels) that comprised 2% of total global energy production in 2014.

In a world where 91% of the 548 exajoules (10^{18} Joules, EJ) of energy production is derived from non-renewable fuels, energy access and economic development come with the cost of carbon emissions. In addition to energy access goals, the G-7 countries announced a goal in June of 2015 to reduce global carbon emissions to one-half of 2010 levels by 2050 and to be 100% renewable by 2100. The Intergovernmental Panel on Climate Change's *Fifth Assessment Report* (Pachauri et al., 2014) estimates that in order to prevent >2°C warming, total carbon emissions from 1870 through 2100 should not exceed 2900 gigatonnes of carbon dioxide equivalent ($GtCO_2$). At the 2014 global emission of 35.5 $GtCO_2$ (BP, 2015), the world will likely surpass the 2˚C goal by 2038.

World population was 7.3 billion as of 2014 and the *United Nations World Populations Prospects 2015 Revision* (UN, 2015b) projects 11.2 billion by 2100 (range: 7.3-16.6). These latest projections do not take climate nor energy availability into account. Chapter II quantitatively included this connection within a global model that echoed qualitative suggestions that the world is unlikely to meet the 2˚C goal (Sanford et al., 2014; Victor and Kennel, 2014). Non-renewable energy sources (NRES) are projected to peak around mid-century (Jones and Warner, 2016; Maggio and Cacciola, 2012; Mohr et al., 2015). Given the projected NRES peak, the UN (2015) population projections will require that the non-hydro renewable energy sources (RES) production in 2100 will have to increase 75-81-fold from the 2014 level of 13 exajoules (chapter II).

In order to better understand the effects of energy production and population growth on the energy goals of SE4ALL and touch upon the 2˚C climate goal, we expand the global model from chapter II to include nine geographic regions (Figure 8) based largely on the BP's *Statistical Review of World Energy* (BP, 2015). The regions are abbreviated in this paper as follows: North America (NOAM), South & Central America (SCAM), Europe (EUR), the former Soviet Republics (FSR), the Middle East & North Africa (MENA), Sub-Saharan Africa (SSAF), China (CHINA), South Asia (SAS), and Asia Pacific (ASPAC). This approach allows us to examine how the world will be shaped by non-renewable and renewable energy production in the 21st century. In this paper we also examine two scenarios of future per capita energy consumption. A similar analysis was performed for the SSAF region by Lucas et al. (2015).

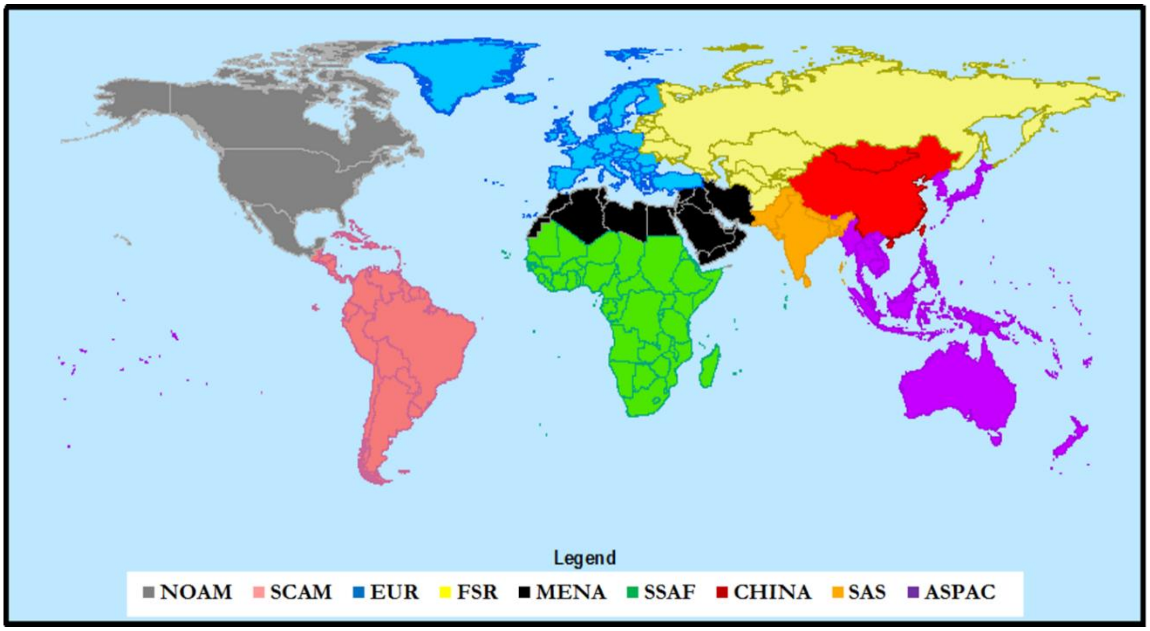
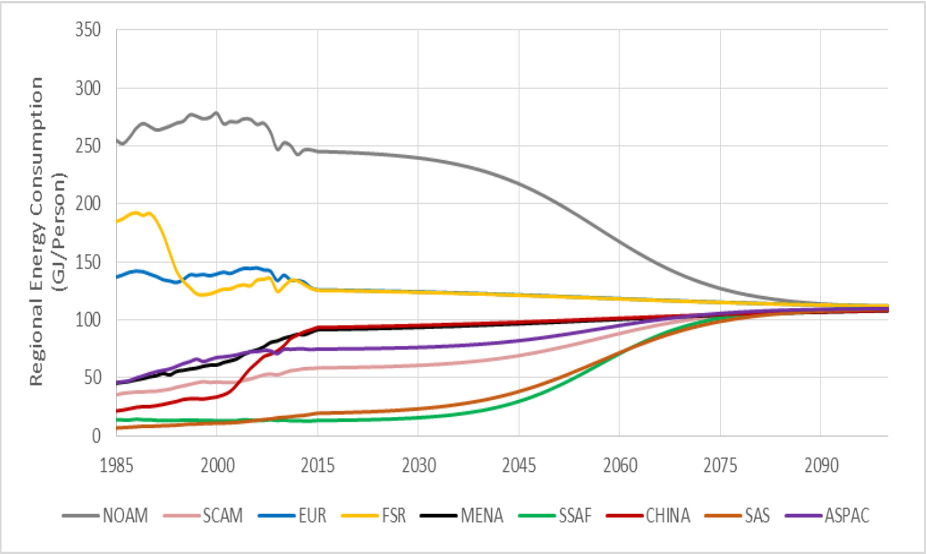


Figure 8: World regions as defined in this study. NOAM – North America, SCAM – South & Central America, EUR - Europe, FSR – Former Soviet Republics, MENA – Middle East and North Africa, SSAF – Sub-Saharan Africa, CHINA – China, SAS – South Asia, ASPAC – Asia Pacific. These regions are based off of regions as defined by BP (2015) and the World Bank. Regions are defined solely for the purposes of this model and do not reflect political, economic or any other judgments.

The first model scenario emulates an aggressive approach to the SE4ALL goals (Figure 9a). In general, we have the regions converge toward a per capita energy consumption value of 110 gigajoules (10^9 joules) per person (GJ/person) for two reasons: First, Jones & Warner (2016) projected the global average increasing from 75 GJ/person in 2014 to 106 GJ/person in 2100. In that model, efficiency gains are not considered important on a global level. The second reason for our 110 GJ/person goal is that the link between energy consumption and quality of life indices has been quantitatively correlated and found significant improvements begin at ~100 GJ/person, and no further improvement of quality life above ~150 GJ/person (Lambert et al., 2014). Thus, we use 110 GJ/person as an (albeit aggressive) goal for best achieving the SE4ALL and United Nations Millennium Development Goals. These goals include achieving universal energy access, eradicating poverty/hunger and universal education. Our study is aimed at (1) determining how per capita energy consumption trends will affect different regions of the world, and (2) to examine issues that each region may confront in a post-peak energy world.

a



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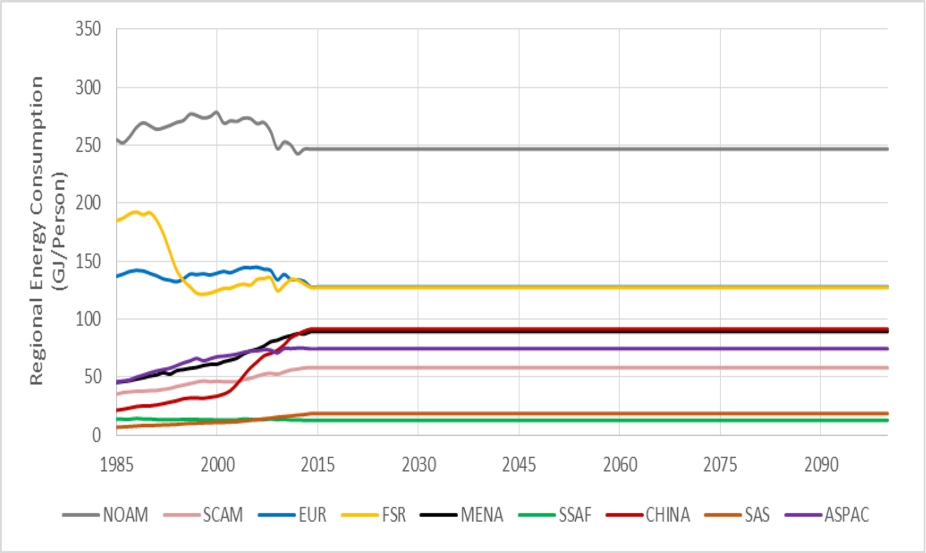


Figure 9: Regional per capita energy consumption trends, Scenario 1 (a) and Scenario 2 (b). Scenario 1 works each region to the target value of 110 GJ/person, similar to the 106 GJ/person projection via Jones and Warner (2016) and 100-150 GJ/person range in Lambert et al. (2014). Scenario 2 keeps each region's per capita energy consumption at the 2014 level throughout the 21st century. These scenarios provide a range of energy demands and mixtures to represent the uncertainty of the population-energy nexus.

Since 1965, per capita energy consumption has more than quintupled in more than ten countries (BP, 2015; UN, 2015b). Most notable among these is the growth in South Korea from 10 to 230 GJ/person in ~50 years. The lowest consuming regions in 2014 were SSAF & SAS (13 and 18 GJ/person, respectively). These are the two out of the nine regions that are consuming less than one-fifth of the target consumption level. The only region consuming significantly more than the target consumption today is North America (247 GJ/person). In this scenario, our model has North American per capita energy consumption (as well as EUR and FSR, each at 127-128 GJ/person) declining to the target level (110 GJ/person) by 2100, via lifestyle change or efficiency gains. Spreng (2005), (Griggs et al., 2013), and Moriarty and Honnery (2012) argue that in addition to making a transition to the RES, per capita energy consumption must decrease. Yet, rebound effects (Sorrell, 2009) and global economic development (Wolfram et al., 2012) have led to overall growth in global per capita energy consumption, despite increasingly energy efficient vehicles, appliances, and consumer electronics throughout the developed world. Unlike the global model of Jones & Warner (2016), we assume that energy efficiency will be a major contributor to the energy consumption in NOAM, EUR, and FSR throughout the 21st century. This scenario forms the upper bound of energy consumption and RES demand throughout the 21st century.

The second scenario forms a lower bound by assuming steady state per capita energy consumption (Figure 9b). In this scenario, every region consumes energy at their 2014 per capita rate throughout the century. Energy demand will be higher in NOAM, EUR, and FSR for the second scenario; however, the global average per capita energy consumption in this scenario declines from 75 to 58 GJ/person throughout the century as the lower consuming regions become a larger share of the total global population.

Data and Methods

The global population-energy model of Jones & Warner (2016) used the UN best estimate as well as the upper and lower confidence intervals of world population from 2010-2100 (Gerland et al., 2014). The same approach cannot be used in this regional model because the confidence intervals for the world and the summed confidence intervals for each individual country do not equal each other (Gerland et al., 2014). For continuity with Jones & Warner (2016), our regional model only considers the UN (2015b) medium fertility estimate of 11.2 billion by 2100.

The methods used in this study are similar to those used in Jones & Warner (2016). For each region of the model we start with the region's population (UN, 2015b) and energy production/consumption by resource (ASPO, 2006; BP, 2015; Höök et al., 2010; Laherrère, 2004; Rutledge, 2011; WNA, 2013) from 1965-2014. Major energy producing region data was extended as far back as 1800 from these sources. We then use single-Hubbert modelling (Hubbert, 1982) to forecast each region's oil, coal, natural gas and nuclear production throughout the remainder of the 21st century. Hydropower in each region was scaled in proportion to its 2014 contribution to total global hydropower generation from 36.9 EJ in 2014 to the 52.5 EJ estimate, as per Seyboth et al. (2011) by

2100. The RES (i.e., wind, solar, and biofuels) was projected by filling in the gap between NRES energy production and the total regional energy demand from 2014-2100. The ratio of wind (60%), solar (25%), and biofuels (15%) were estimated using the rationale of Jones & Warner (2016).

The regional trends in each of the model variables are expanded to provide a better understanding of the implications of population and economic development within each region given the energy resource available. The main assumption in this model is that each region is a composite of the nations within the region. As such, issues of intraregional borders, corruption, and class separation (GINI) are assumed to be negligent and every person within the region is equal. The key complication comes from the fact that the world is a global market and these nine regions are not necessarily self-sufficient. Energy, like most commodities, is traded across borders. Each of the nine regions either over-produces or under-produces energy relative to the region's specific demand. As a result, our model incorporates an import-export module. If a region produces in excess of its demand, the excess is put into a source box labelled, "the global market." If a region produces in deficit of its demand, the deficit is put into a sink box labelled, "the global demand." Each deficit region can draw from the global market in proportion to its contribution to the global demand. (e.g., if a region's energy deficit constitutes 30% of the global demand, that region is allotted up to 30% of the global market). A region cannot withdraw energy from the global market in excess of its deficit. Uranium reserves in regions with little to no nuclear production (e.g., SSAF) were divided up among the nuclear-producing regions (e.g., NOAM, EUR) in the same manner.

The per capita energy consumption in each of the regions in scenario 1 approaches 110 GJ/person in the year 2100 (Figure 9A). Extrapolating the 21st century historical trends in the MENA, CHINA, and ASPAC indicated that the per capita energy consumption in these regions would intercept the 110 GJ/person goal before the end of the 21st century. Alternatively, the extrapolated trends in SSAF and SAS indicate that these regions will not reach 100 GJ/person by 2100. For these cases, the per capita energy consumption was "forced" to the 110 GJ/person goal by 2100. In 2014, North American per capita energy consumption (247 GJ/person) was roughly double that of the next highest region (Europe at 128 GJ/person). The per capita energy consumption in scenario 2 did not require any adjustment/forecasting, as scenario 2 holds the 2014 value constant in each region out to 2100 (Figure 9B). This scenario represents the lowest theoretical RES demand in the year 2100.

Each additional assumption increases the potential for errors within the model results. For example, we acknowledge that reserve estimates are a moving benchmark. Every year, new technology and better data consolidation affect the valuation of reserves. Additionally, the model cannot be made to foresee new or more efficient energy production technologies (e.g., fusion). All energy production methods are therefore assumed to remain at the technical engineering and capacity factors presented in the most recently cited articles (therefore, fusion, further enhanced production techniques, increased EROI, etc. are not included in any scenario). Without the assumptions inherent to our model, however, the model could not be satisfactorily bounded. Either there is insufficient data to eliminate the assumption, a different assumption would increase the likelihood of unscientific bias, or a different assumption would necessitate an inordinate number of additional (and likely less reasonable) assumptions.

Results and Discussion

The numerical results of the model, including historical data from 1965 and 2014, are presented in Table 5. Some energy statistics for EUR and FSR are backdated to only 1985, as the data in BP (2015) does not separate the FSR from "Other Europe" before 1985. Overall, world population increases by 50% from 2014-2100. In scenario 1, increasing per capita energy consumption (75 GJ/person in 2014 to 110 in 2100) and the growing population result in a 2.3–fold increase in total global energy demand by 2100. Additionally, the share of RES in the energy mix increases from 2% to 82%. Scenario 2 indicates that at constant consumption rates within each region, global per capita energy consumption would drop on average to about 58 GJ/person. This is because, again, the majority of the projected population growth is projected to occur in the lower consuming regions (UN, 2015b). Figure 10 illustrates the changes in total energy demand within each region over the course of scenario 1 (Figure 10a) and scenario 2 (Figure 10b) of the model. One of the most important results of the model is that business-as-usual energy production is adequate until about 2025, when RES production will need to begin a significant expansion. Because each regional part of the model does not have the same initial conditions, the results of the model vary across regions.

The Former Soviet Republics is the region that is most “safe” in both scenarios of the model. The population of the FSR region grew from 237 million in 1965 to 319 million in 2014. The UN projects the population to reach 334 million in 2030 and decline to 316 million by 2100. FSR comprises 2.8% of the projected 2100 global population. At 110 GJ/person, the region’s population will demand 35 exajoules in 2100. The scenario 1 consumption in 2030 is estimated at 124 GJ/person, resulting in a total energy demand of 41 exajoules. This is a 2% increase in total energy demand in 16 years. If energy consumption were to remain at the 2014 value of 127 GJ/person, energy demand would increase to 43 and drop to 40 exajoules in 2030 and 2100, respectively.

Table 5: Results of the regional model. Historical statistics, Scenario 1 (A) and Scenario 2 (B). Global energy balance does not include pre-modern RES (e.g., solid biomass). This explains the negative balance in 1965 (as per (Banerjee et al., 2013), 10% of global energy consumption in 2010 was traditional biomass). BP (2015) reports an excess of energy production to consumption in 2014. Though no official reason is stated, this may be due to strategic reserves or aggregate rounding of each country's data. A positive balance indicates energy exported and negative values indicate imported energy. Due to rounding, all figures are accurate to within ± 1, summed world figures may be up to ± 3.

	1965						**2014**					
Region	**POP**	**PCC**	**ED**	**NRES**	**RES**	**BAL**	**POP**	**PCC**	**ED**	**NRES**	**RES**	**BAL**
NOAM	264.7	227	60	52	0	−8	480.4	247	119	111	3	*−4*
SCAM	207.9	22	5	11	0	*6*	502.3	58	29	32	1	*4*
EUR	477.5	87	41	28	0	*−13*	612.6	128	78	39	5	*−35*
FSR	238.9	122	29	24	0	*−5*	318.7	127	41	73	0	*32*
MENA	122.8	20	2	22	0	*20*	455.1	89	41	90	0	*50*
SSAF	300.3	8	2	1	0	*−1*	936.9	13	12	21	0	*9*
CHINA	716.7	8	6	6	0	*0*	1,380.2	91	126	103	2	*−21*
SAS	628.5	4	3	2	0	*−1*	1,688.6	18	31	18	1	*−13*
ASPAC	414.7	25	10	5	0	*−5*	901.6	74	67	49	1	*−17*
WORLD	***3,372***	***46.9***	***158***	***151***	***0***	***−7***	***7,276.4***	***75***	***543***	***535***	***13***	***5***
	2030-A						***2030-B***					
Region	**POP**	**PCC**	**ED**	**NRES**	**RES**	**BAL**	**POP**	**PCC**	**ED**	**NRES**	**RES**	**BAL**
NOAM	544.3	240	131	88	11	*−32*	544.3	247	134	88	7	*−39*
SCAM	573.0	61	35	39	0	*−4*	573.0	58	33	39	0	*6*
EUR	628.8	124	78	24	14	*−40*	628.8	128	80	24	8	*−48*
FSR	334.5	124	41	69	0	*28*	334.5	127	43	69	0	*26*

Table 5: continued

	2100-A						***2100-B***					
MENA	586.0	93	55	126	0	*71*	586.0	89	52	126	0	*74*
SSAF	1,396.9	15	22	23	0	*1*	1,396.9	13	18	23	0	*5*
CHINA	1,427.7	95	136	125	3	*−8*	1,427.7	91	130	125	1	*−4*
SAS	2,014.1	23	47	22	6	*−19*	2,014.1	18	37	22	2	*−13*
ASPAC	1,009.3	76	77	68	3	*−6*	1,009.3	74	75	68	1	*−6*
WORLD	***8,514.5***	***73***	***622***	***583***	***37***	***−2***	***8,514.5***	***71***	***602***	***583***	***19***	***0***
	2100-A						***2100-B***					
Region	**POP**	**PCC**	**ED**	**NRES**	**RES**	**BAL**	**POP**	**PCC**	**ED**	**NRES**	**RES**	**BAL**
NOAM	648.5	111	72	45	27	*0*	648.5	247	160	45	113	*−2*
SCAM	572.9	110	63	25	38	*0*	572.9	58	33	25	9	*1*
EUR	580.0	112	65	17	48	*0*	580.0	128	74	17	57	*0*
FSR	316.5	112	35	47	0	*7*	316.5	127	40	47	0	*7*
MENA	903.9	108	97	35	62	*0*	903.9	89	81	35	45	*−1*
SSAF	3,934.8	110	431	11	416	*−4*	3,934.8	13	50	11	38	*−1*
CHINA	1,017.8	108	110	15	94	*−1*	1,017.8	91	93	15	77	*−1*
SAS	2,238.6	109	244	13	229	*−2*	2,238.6	18	41	13	28	*0*
ASPAC	1,023.0	110	112	11	100	*−1*	1,023.0	74	76	11	64	*−1*
WORLD	***11,236.0***	***110***	***1229***	***217***	***1014***	***−2***	***11,236.0***	***58***	***648***	***217***	***431***	***0***

POP – Regional population in million

PCC – Per capita energy consumption in GJ/person

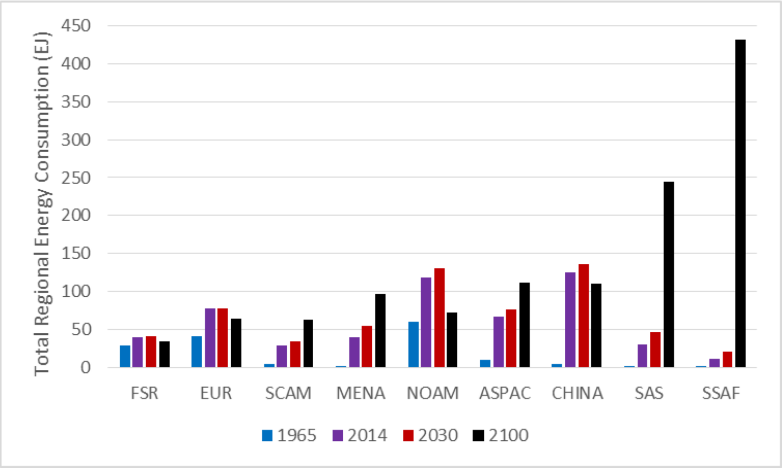
ED – Total regional energy demand in EJ

NRES – Total regional energy production (oil, coal, natural gas, nuclear ***and hydropower***) in EJ

RES – Total regional energy demand from wind, solar, biofuels in EJ

BAL – Regional energy balance (NRES+RES-ED) in net energy exports (+) or net imports (−)

a



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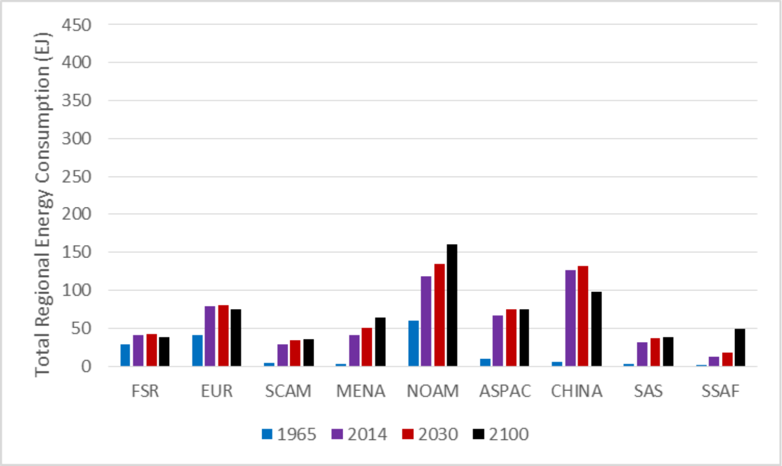


Figure 10: Total energy consumption by region, Scenario 1 (a), Scenario 2 (b). Energy consumption in FSR, EUR, and CHINA peak in both scenarios. Note the substantial difference in NOAM, SAS, and SSAF energy consumption between the two scenarios (based on per capita energy consumption scenario conditions). Regions arranged from lowest to highest demand in scenario 1.

The FSR region's remaining NRES reserves are 11% oil, 58% coal, 27% natural gas and 5% uranium. Together, these reserves total 7584 EJ. This is equivalent to 187 years of production at the 2014 total energy consumption rate of 41 EJ. Though this is the first of three regions listed that has a higher 2100 per capita energy consumption in scenario 2 than scenario 1, NRES and hydropower are projected to produce 116-134% of 2100 energy in both scenarios. Therefore RES production will not theoretically be necessary at any point throughout the 21st century (Figure 11). The FSR region is the sole energy exporting region by 2100, producing an excess of 12 EJ/year over consumption in scenario 1 and 6 EJ/year in scenario 2. This is due to the fact that both the population (in both scenarios) and the consumption rate are projected to decline (in scenario 1) or to remain stable (in scenario 2) throughout the 21st century.

Under the conditions of the model as stated, the Former Soviet Republics region will not be affected by peak energy; rather, the region can continue to export NRES energy to the global market throughout the 21st century. The main concern is the question of per capita energy consumption. Before the dissolution of the Soviet Union, per capita energy consumption in the region peaked at 192 GJ/person (in 1988). The breakup of the Soviet Union has been attributed via Granger causality to declining oil and coal production (Reynolds and Kolodziej, 2008). From 1988-2014, per capita energy consumption in the region decreased from 192 GJ/person to 127 GJ/person. According to BP (2015), decreased oil consumption accounted for 57% of the drop in energy consumption in the Russian Federation from 1992-96. From 1990-96, military expenditures decreased 92% (SIPRI, 2015); however, the Human Development Index for Russia was relatively unchanged from 1990 (0.729) to 2000 (0.717) (UNDP, 2015). This suggests that the reason for the drop in per capita energy consumption in the FSR region was more likely due to military cuts, and not a significant change in the average citizen's life. If economic/social/military changes return consumption in the region to the 1988 level by 2100, the region would no longer be an energy exporter and would require 14 EJ from RES.

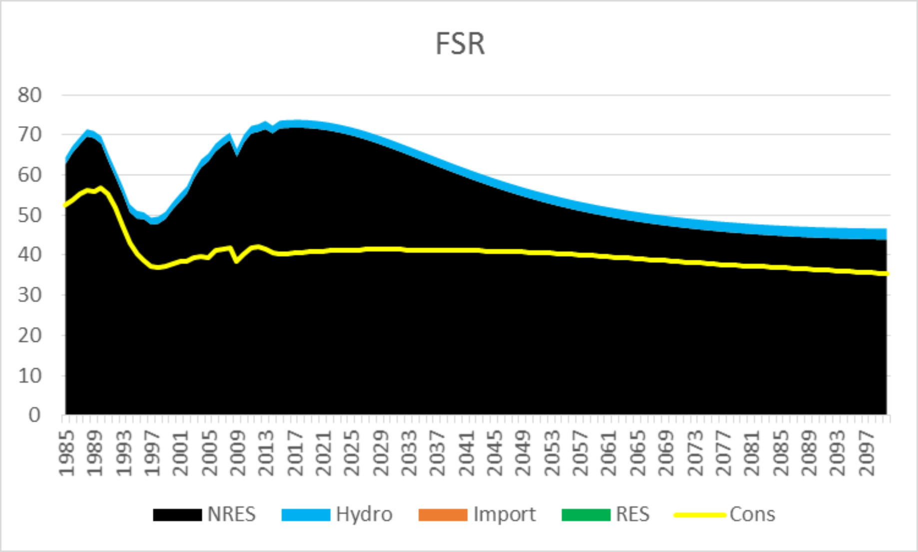


Figure 11: Energy mix, Former Soviet Union. Energy production in EJ. Regional consumption included to highlight energy exporting capacity over time.

The population of the Europe region grew from 480 million in 1965 to 613 million by 2014. The UN projects the population to reach 629 million in 2030 and decline to 580 million by 2100. EUR comprises 5.2% of the projected 2100 global population. At 110 GJ/person, the region's population will demand 64 exajoules in 2100. The consumption at the 2030 SE4ALL goal is estimated at 128 GJ/person, resulting in a total energy demand of 78 exajoules. This is a 0.3% decrease in total energy demand in 16 years. If energy consumption were to remain at the 2014 value of 128 GJ/person, energy demand would increase to 80 and decrease to 74 exajoules in 2030 and 2100, respectively.

The EUR region's remaining NRES reserves are 4% oil, 76% coal, 8% natural gas and 12% uranium. The uranium reserve includes reserves that are not utilized by the end of the century in Sub-Saharan Africa. Together, these reserves total 1677 EJ. This is equivalent to 21 years of production at the 2014 total energy consumption rate of 78 EJ; however, our logistic modelling suggests that NRES and hydropower will contribute 26% of 2100 energy demand in scenario 1 (Figure 12). RES will have to produce 47 EJ by 2100. This is a 9-fold increase from the 2014 RES production of 5 EJ. This is the second region that has higher RES energy demand in scenario 2 than in scenario 1. The NRES and hydropower contribution drops to 23% of 2100 energy demand in scenario 2, requiring 58 EJ of RES production by 2100.

The EUR region exhibits the largest discrepancy between energy reserves and energy consumption. As Figure 9 shows, the per capita energy consumption in the European region has been the most consistent of the nine regions, remaining between 128-144 GJ/person since 1985. The European region imported the most energy (35 EJ) of the nine regions in 2014. The region imports 38% of the energy available on the "global market" in the first year of the import-export module (2015). That said, the region also produces 15% of its energy consumption from renewable sources (including 8% from hydropower and 7% from RES). As NRES begin to decline, the region will need to put forth a major effort to expand from the current 7% of energy consumption that RES provides. Nuclear energy contributed over one-fifth of total energy consumption in France (42%), Sweden (29%), Slovakia (23%), Switzerland (22%), and Finland (21%); however, the region has no significant uranium reserves (WNA, 2013). The reserves reflected in the model are a result of the excess uranium reserves in Sub-Saharan Africa and South & Central America.

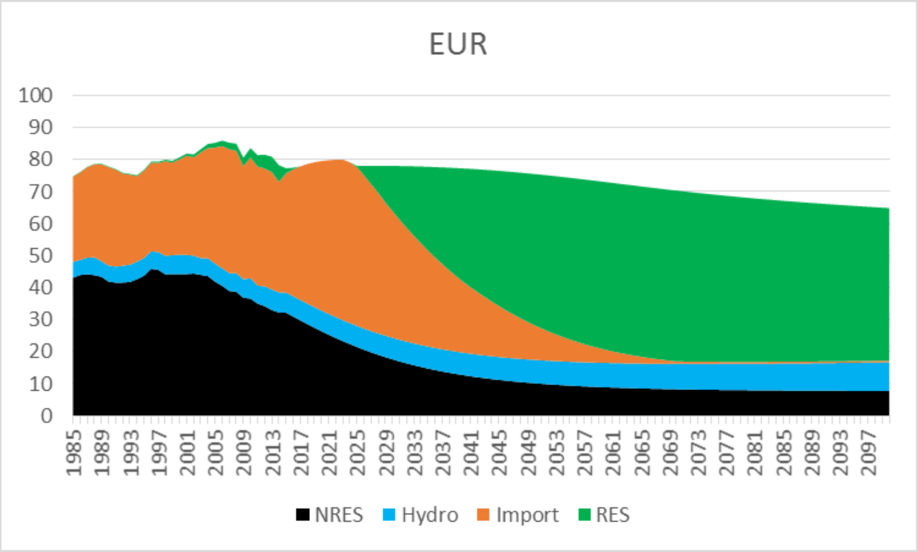


Figure 12: Energy mix, Europe. Energy production in EJ.

The population of the South & Central America region more than doubled from 209 million in 1965 to 502 million in 2014. The UN projects the population to reach 573 million in 2030, peak at 627 million in 2061, and return to 573 million by 2100. SCAM comprises 5.1% of the projected 2100 global population. At 110 GJ/person, the region's population will demand 63 exajoules in 2100. The consumption at the 2030 SE4ALL goal is estimated at 61 GJ/person, resulting in a total energy demand of 35 exajoules. This is a

19% increase in total energy demand in 16 years. If energy consumption were to remain at the 2014 value of 58 GJ/person, energy demand would increase to 33 exajoules in both 2030 and 2100.

The SCAM region's remaining NRES reserves are 77% oil, 11% coal, 11% natural gas and 1% uranium. Together, these reserves total 2775 EJ. This is equivalent to 95 years of production at the 2014 total energy consumption rate of 29 EJ. NRES and hydropower are forecast to contribute 39% of 2100 energy demand in scenario 1 (Figure 13). RES will have to produce 39 EJ by 2100. This is a 43-fold increase from the 2014 RES production of 0.9 EJ. The NRES and hydropower contribution increases to 74% of 2100 energy demand in scenario 2, requiring 9 EJ of annual RES production by 2100.

The trends of the SCAM region best fit the energy and population development goals as laid out by Scenario 1. A linear trend of 21st century per capita energy consumption results in the region consuming about 115 GJ/person by 2100, suggesting that a goal of 110 GJ/person is not unreasonable for this region. The population is projected to peak around mid-century (UN, 2015b) and the Scenario 1 total energy consumption projects near perfectly along the historical trend. The region also benefits from already receiving 26% of total energy consumption (7.5 EJ) via hydropower and RES (the next largest percentage is Europe at 15%, producing 11.5 EJ). Peaking population and continued growth in RES may allow for a smooth transition towards a region that it fully RES-powered by the end of the 21st century.

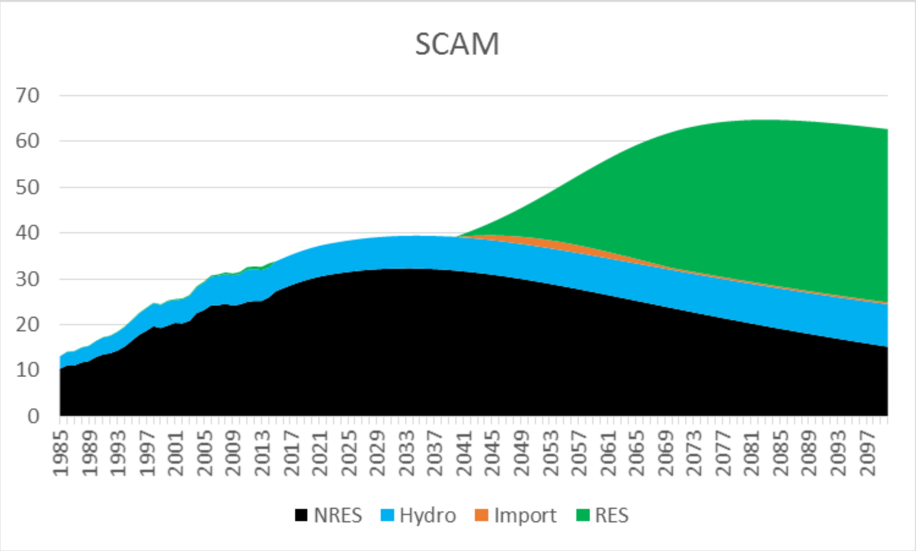


Figure 13: Energy mix, South & Central America. Energy production in EJ.

The population of the Middle East & North Africa region more than tripled from 130 million in 1965 to 455 million in 2014. The UN projects the population to reach 586 million in 2030 and grow to 904 million by 2100. MENA comprises 8.0% of the projected 2100 global population. At 110 GJ/person, the region's population will demand 99 exajoules in 2100. The consumption at the 2030 SE4ALL goal is estimated at 93 GJ/person, resulting in a total energy demand of 55 exajoules. This is a 35% increase in total energy demand in 16 years. If energy consumption were to remain at the 2014 value of 89 GJ/person, energy demand would increase to 52 and 81 exajoules in 2030 and 2100, respectively.

The MENA region has the largest remaining NRES reserves (8316 EJ). Of these, 60% are oil and 40% are natural gas. There are no significant reserves of coal or uranium. The reserves are equivalent to 205 years of production at the 2014 total energy consumption rate of 41 EJ; however, from 1965-2014, per capita energy consumption in the region increased from 19 GJ/person to 89 GJ/person. NRES and hydropower are forecast to contribute 35% of 2100 energy demand in scenario 1 (Figure 14). RES will have to produce 64 EJ by 2100. This is an 1852-fold increase from the 2014 RES production of 0.035 EJ. The NRES and hydropower contribution increases to 44% of 2100 energy demand in scenario 2, requiring 46 EJ of RES production by 2100.

Though the NRES reserves in the region are large, the production trends in the region suggest the region is likely to provide the majority of the global market energy only throughout the first half of the century (Figure 14). In 2014, the region produced over twice as much energy as it consumed (BP, 2015), and had the lowest current RES production among the nine regions examined. Fortunately, the NRES capabilities of the region precludes the need for any RES until 2070 (Scenario 1) or 2075 (Scenario 2). The issue is that the currently abundant NRES reserves are exported in the model. This assumption within the model is supported by (Narayan and Smyth, 2009)that increasing energy exports will be beneficial to the region's economy. This results in a growth of RES demand from essentially zero in 2070 to 63 EJ by 2100 (Scenario 1). Of course, the model does not account for diminishing supplies and foresight in export policy in the first half of the 21st century. Given that seven other regions will have peaked in NRES production before the Middle East and North Africa, the conditions of the import/export model will likely change to adapt to the global market shifts.

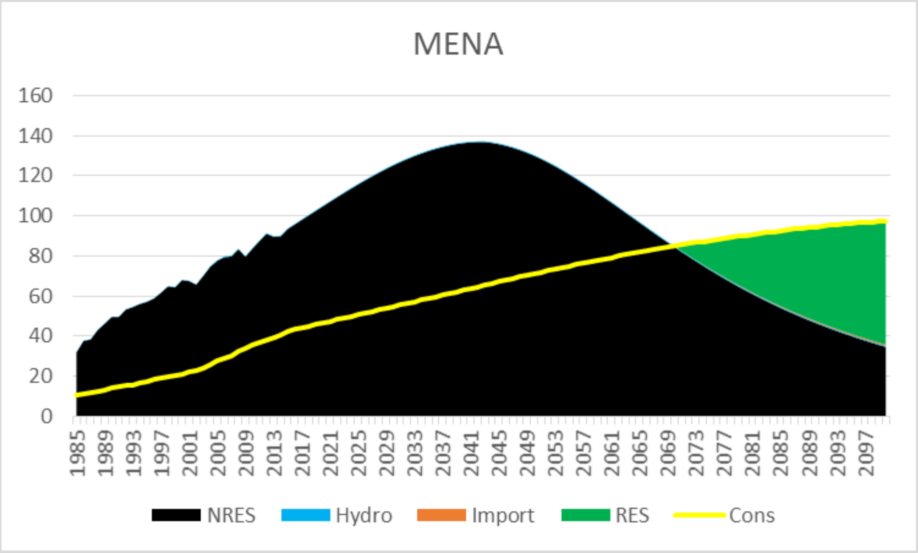


Figure 14: Energy mix, Middle East & North Africa. Energy production in EJ. Regional consumption included to highlight energy exporting capacity over time.

The population of the North America region grew from 264 million in 1965 to 480 million in 2014. The UN projects the population to reach 544 million in 2030 and 648 million by 2100. NOAM comprises 5.7% of the projected 2100 global population. At 110 GJ/person, the region's population will demand 72 exajoules in 2100. The consumption at the 2030 SE4ALL goal is estimated at 240 GJ/person, resulting in a total energy demand of 131 exajoules. This is a 10% increase in total energy demand in 16 years. If energy consumption were to remain at the 2014 value of 247 GJ/person, energy demand would increase to 134 and 160 exajoules in 2030 and 2100, respectively.

The NOAM region's remaining NRES reserves are 21% oil, 63% coal, 6% natural gas and 10% uranium. The uranium reserve includes reserves that are not utilized by the end of the century in Sub-Saharan Africa. Together, these reserves total 7145 EJ. This is equivalent to 60 years of production at the 2014 total energy consumption rate of 119.0 EJ. NRES and hydropower are forecast to contribute approximately two-thirds of 2100 energy demand in scenario 1 (Figure 15). RES will have to produce 27 EJ by 2100. This is a 9-fold increase from the 2014 RES production of 3 EJ. This is the third region that has higher RES energy demand in scenario 2 than in scenario 1. As a result, the NRES and hydropower contribution can meet only 28% of 2100 energy demand in scenario 2, requiring 115 EJ of RES production by 2100.

Typically, high energy consumption is associated with lower fertility rates (Lambert et al., 2014); however, NOAM is unique in that it has a growing population despite the highest per capita energy consumption. This is due to immigration into the United States and Canada and a high fertility rate in Mexico (UN, 2015b). Fortunately, the region is relatively rich in energy reserves, including 28% of the global total coal reserve (BP, 2015). As the difference in the results from the two scenarios indicate, the key to energy and population security in the region is decreased per capita energy consumption. By reducing to the 110 GJ/person target, solar panels would need only cover an area the size of Connecticut (~16,000 km^2), and algae production facilities slightly larger than the area of New Jersey (~22,000 km^2). Otherwise, Scenario 2 suggests these areas would need to be the size of West Virginia (~69,000 km^2) and Maine (~92,000 km^2), respectively.

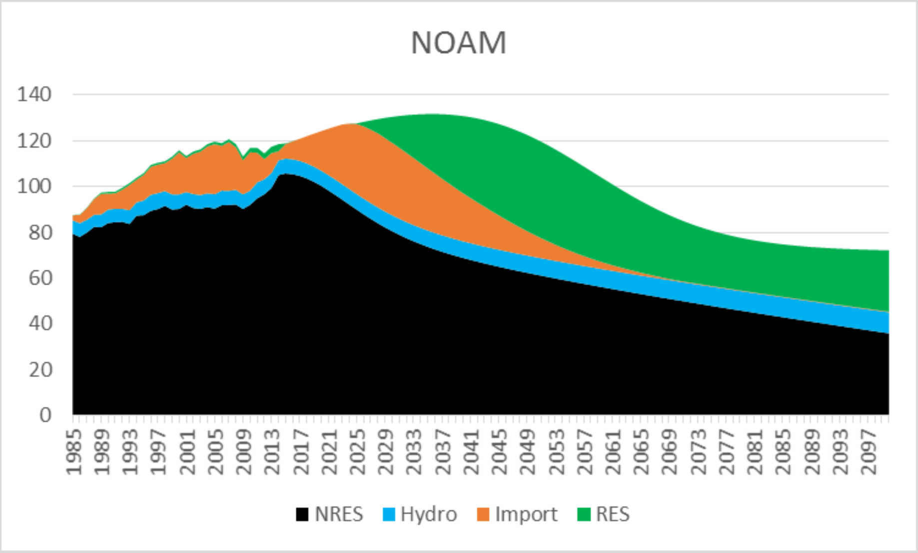


Figure 15: Energy mix, North America. Energy production in EJ.

The population of the Asia Pacific region more than doubled from 418 million in 1965 to 902 million in 2014. The UN projects the population to reach 1.01 billion in 2030 and 1.02 billion by 2100. ASPAC comprises 9.1% of the projected 2100 global population. At 110 GJ/person, the region's population would demand 112 exajoules in 2100. The consumption at the 2030 SE4ALL goal is estimated at 76 GJ/person, resulting in a total energy demand of 77 exajoules. This is a 15% increase in total energy demand in 16 years. If energy consumption were to remain at the 2014 value of 74 GJ/person, energy demand would increase to 75 and 76 exajoules in 2030 and 2100, respectively.

The ASPAC region's remaining NRES reserves are 3% oil, 66% coal, 11% natural gas and 20% uranium. Together, these reserves total 3190 EJ. This is equivalent to 48 years of production at the 2014 total energy consumption rate of 67 EJ. NRES and hydropower are forecast to contribute only 10% of 2100 energy demand in scenario 1 (Figure 16). RES would have to produce 100 EJ by 2100. This is an 88-fold increase from the 2014 RES production of 1.13 EJ. The NRES and hydropower contributes 14% of 2100 energy demand in scenario 2, requiring 65 EJ of RES production by 2100.

The Asia Pacific region may be the most heterogeneous of the nine regions. From 1965-2014, per capita energy consumption in the region tripled from 24 GJ/person to 74 GJ/person. This increase in consumption was not equal across all of the nations within the region. Included are the developed nations of Japan, South Korea, Australia, and New Zealand, as well as the least developed countries of Bhutan, Cambodia, East Timor, Laos, and Myanmar (North Korea is not classified). Four of the top 15 most populated countries in the world are within the region. Another four are in the CHINA and SAS regions. With a relatively stable population throughout the second half of the 21st century, the main issue facing the region will be the development of parity throughout the economies within the region.

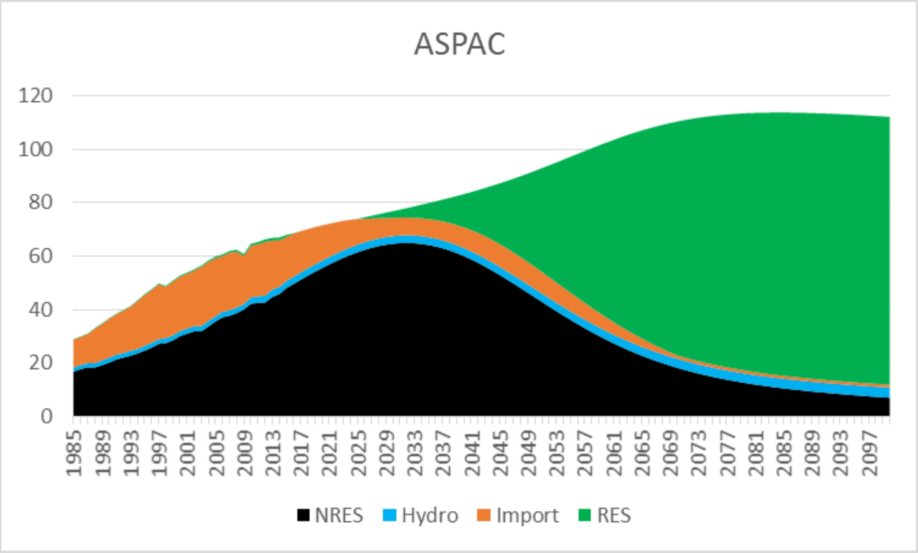


Figure 16: Energy mix, Asia Pacific. Energy production in EJ.

The population of the China region nearly doubled from 711 million in 1965 to 1.38 billion in 2014. The UN projects the population to reach peak at 1.43 billion in 2028 and decline to 1.02 billion by 2100. CHINA comprises 9.1% of the projected 2100 global population. At 110 GJ/person, the region's population will require 112 exajoules in 2100. The consumption at the 2030 SE4ALL goal is estimated at 95 GJ/person, resulting in a total energy demand of 136 exajoules. This is an 8% increase in total energy demand in 16 years. If energy consumption were to remain at the 2014 value of 91 GJ/person, energy demand would be 130 and decrease to 93 exajoules in 2030 and 2100, respectively.

The CHINA region's remaining NRES reserves are 3% oil, 89% coal, 4% natural gas and 4% uranium. Together, these reserves total 3573 EJ. This is equivalent to 28 years of production at the 2014 total energy consumption rate of 126 EJ. NRES and hydropower are forecast to contribute 13% of 2100 energy demand in scenario 1 (Figure 17). RES will have to contribute 97 EJ by 2100. This is a 44-fold increase from the 2014 RES production of 2 EJ. The NRES and hydropower contribution is 16% of 2100 energy demand in scenario 2, requiring 78 EJ of RES production by 2100.

As a result of meeting the per capita energy goal and a peaking population, scenario 1 of the model results in a period of 47 years (2021-2068) in which total energy demand in the region is 130-132 EJ. CHINA is projected to produce only 1 EJ from NRES production by 2100 (Figure 17). Coal production in the region increased 6-fold from 1981-2014. The proven reserves-to-production ratio (R/P) of oil in China is 12 years, 30 years for coal, and 26 years for natural gas (BP, 2015). The region also increased RES production by 15% from 2013-14. This region (and Europe) will likely be the leaders in the development of a global RES infrastructure (Yang et al., 2010). Our model projects that coal will remain the primary fuel in the region throughout the SE4ALL 2030 timeframe.

The greatest issue in the region is the sub-regional differences in economic and social development (Chen et al., 2010) and energy efficiency (Hu and Wang, 2006). Though CHINA is the fastest developing of the nine regions, that development has relied on unsustainable and high-polluting practices (Zhang, 2010). While economic and social development does not preclude environmental conservation, the CHINA region will need to combine strict regulations with both a transition to RES infrastructure and more efficient energy use (Yuan et al., 2015). It is interesting to note that China's recently announced goal of peaking CO_2 emissions by 2030 (Landler, 2014) is close to the model's projection that RES will overtake coal production in the year 2044. The model projects that carbon emissions in CHINA will peak in 2025 in both scenarios, ahead of the proposed schedule.

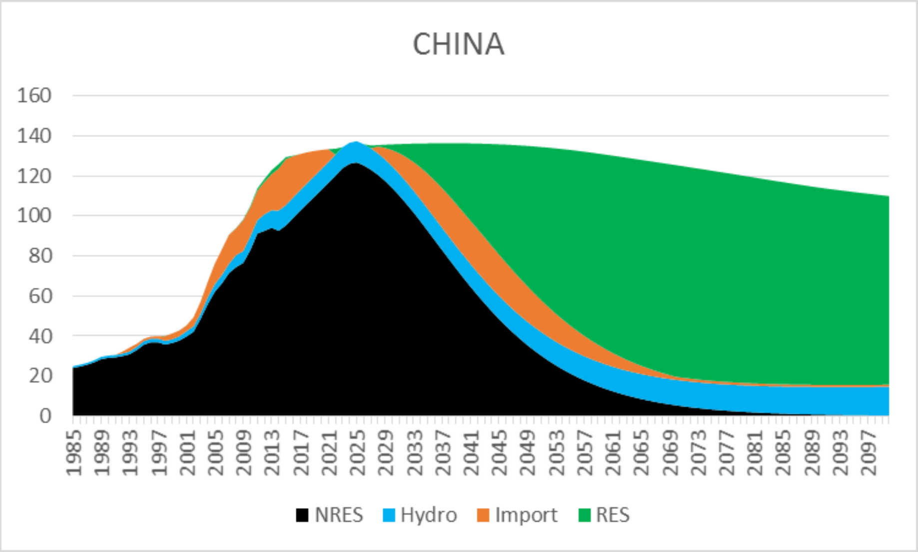


Figure 17: Energy mix, China. Includes Mongolia, Hong Kong SAR, and Macao SAR.

Energy production in EJ.

The population of the South Asia region nearly tripled from 627 million in 1965 to 1.69 billion in 2014. The UN projects the population to reach 2.01 billion in 2030 and to 2.24 billion by 2100. SAS comprises 20% of the projected 2100 global population. At 110 GJ/person, the region's population would demand 246 exajoules in 2100. The consumption at the 2030 SE4ALL goal is estimated at 23 GJ/person, resulting in a total energy demand of 47 exajoules. This is a 50% increase in total energy demand in 16 years.

If energy consumption were to remain at the 2014 value of 18 GJ/person, energy demand would increase to 37 and 41 exajoules in 2030 and 2100, respectively.

The SAS region's remaining NRES reserves are 2% oil, 93% coal, 5% natural gas and 0% uranium. Together, these reserves total 1794 EJ. This is equivalent to 58 years of production at the 2014 total energy consumption rate of 31 EJ. NRES and hydropower are forecast to contribute only 5% of 2100 energy demand in scenario 1 (Figure 18). RES will have to produce 234 EJ by 2100. This is a 400-fold increase from the 2014 RES production of 0.6 EJ. The NRES and hydropower contribution is 30% of 2100 energy demand in scenario 2, requiring 29 EJ of RES production by 2100.

India is projected to surpass China as the most populous nation on Earth in 2022. The three most populous countries within this region (India, Pakistan, and Bangladesh) struggle with balancing energy/economic/social development with the environment (Ahmed et al., 2014; Awan and Khan, 2014; Chaudhary et al., 2015). In India, quality electrification of non-agricultural homes was found to increase household income by nearly 30% from 1994-2005 (Chakravorty et al., 2014); however, the government has recently announced that it will double its coal consumption by 2019 (Harris, 2014). The growing economy has required the development of expanded coastal ports, railways, and power plants to handle the increased importation of energy fuels; this infrastructure is vulnerable to both sea level rise and the anticipated increase in extreme weather events associated with future climate change (Garg et al., 2015).

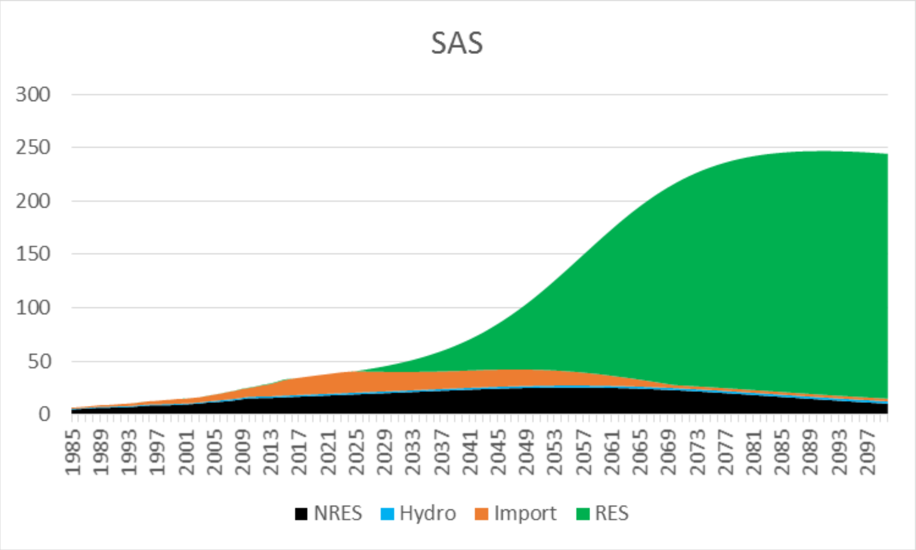


Figure 18: Energy mix, South Asia. Energy production in EJ.

The population of the Sub-Saharan Africa region nearly quadrupled from 249 million in 1965 to 937 million in 2014. The UN projects the population to reach 1.40 billion in 2030 and continue to grow to 3.93 billion by 2100. SSAF comprises 35% of the projected 2100 global population. At 110 GJ/person, the region's population would demand 433 exajoules in 2100. The consumption at the 2030 SE4ALL goal is estimated at 16 GJ/person, resulting in a total energy demand of 22 exajoules. This is an 82% increase in total energy demand in 16 years. If energy consumption were to remain at the 2014 value of 13 GJ/person, energy demand would increase to 18 and 50 exajoules in 2030 and 2100, respectively.

The SSAF region's remaining NRES reserves are 24% oil, 59% coal, 16% natural gas and 1% uranium. Together, these reserves total 1514 EJ. The region does have more uranium reserves, but lacks the appropriate infrastructure to utilize it (in our model the additional uranium is transferred to reserves in EUR & NOAM). This is equivalent to 128 years of production at the 2014 total energy consumption rate of 12 EJ; however, NRES and hydropower are forecast to contribute only 3% of 2100 energy demand in scenario 1 (Figure 19). RES will have to produce 422 EJ by 2100. This is an over 4000-fold increase from the 2014 RES production of 0.1 EJ. The NRES and hydropower contribution is 22% of 2100 energy demand in scenario 2, requiring 39 EJ of RES production by 2100.

Sub-Saharan Africa is one of the least stable regions in the model. Despite having the lowest per capita energy consumption, the region was a net energy exporter in 2014. Per capita energy consumption increased from 8 to 14 GJ/person from 1965 to 1988; however, the consumption rate has actually decreased from the 1988 peak to 13 GJ/person in 2014. The region faces a Red Queen situation: In order to keep the already undeveloped population at the same consumption level (Scenario 2), population growth will drive energy demand to 50 EJ. The region will continue to be dominated by external processes and policies (see Cooke et al., 2015), but the main in-region issue is population growth. Energy availability projections throughout the 21st century are incongruous with significantly raising the development status of four billion people.

A per capita energy consumption value of 110 GJ/person would require over three quarters of the 2014 total global energy production to support. That said, the Scenario 1 energy consumption growth goal could be achieved in 2030 with only a 4-fold increase in RES production. The analysis of SSAF by Lucas et al. (2015) focuses more on the role of the region in future carbon emissions than our paper. Lucas et al. (2015) independently derived that both population will be a driving factor in 21st century SSAF concerns and that economic development in the region would greatly outpace global rates. It is important that these independent models are run, and more important that the results reveal a similar future.

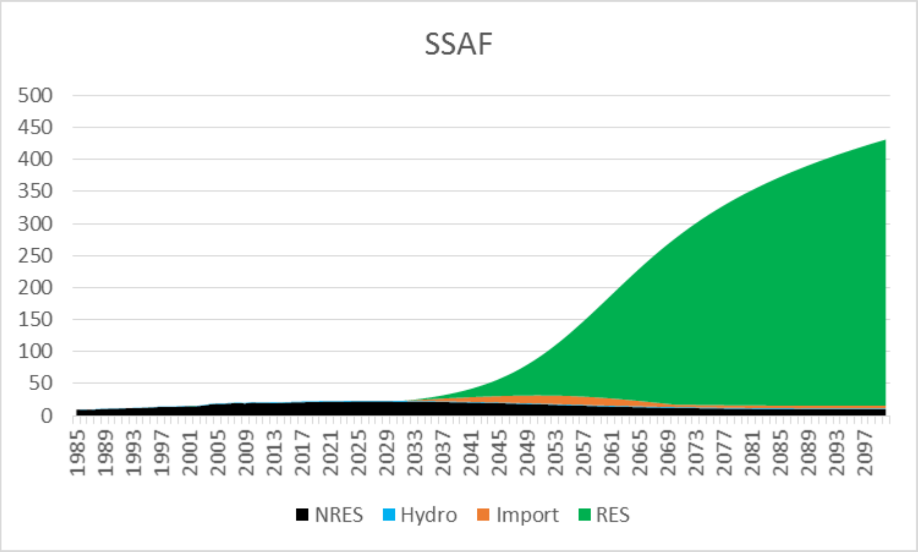


Figure 19: Energy mix, Sub-Saharan Africa. Energy production in EJ.

The world's population more than doubled from 3.3 billion in 1965 to 7.3 billion in 2014. The UN projects the population to reach 8.5 billion in 2030 and 11.2 billion by 2100. At 110 GJ/person, the world's population will demand 1236 exajoules in 2100 (Figure 20). As population growth in low-consuming countries outpaces per capita energy consumption growth and the high-consuming, more stable population regions (i.e., FSR, EUR, NOAM) consume less energy per person, the consumption at the 2030 SE4ALL goal is estimated to decline in the short-term to 73 GJ/person, resulting in a total energy demand of 620 exajoules. This is a 14% increase in total energy demand in 16 years. If energy consumption were to remain at the 2014 value of 75 GJ/person, energy demand would increase to 603 and to 648 exajoules in 2030 and 2100, respectively.

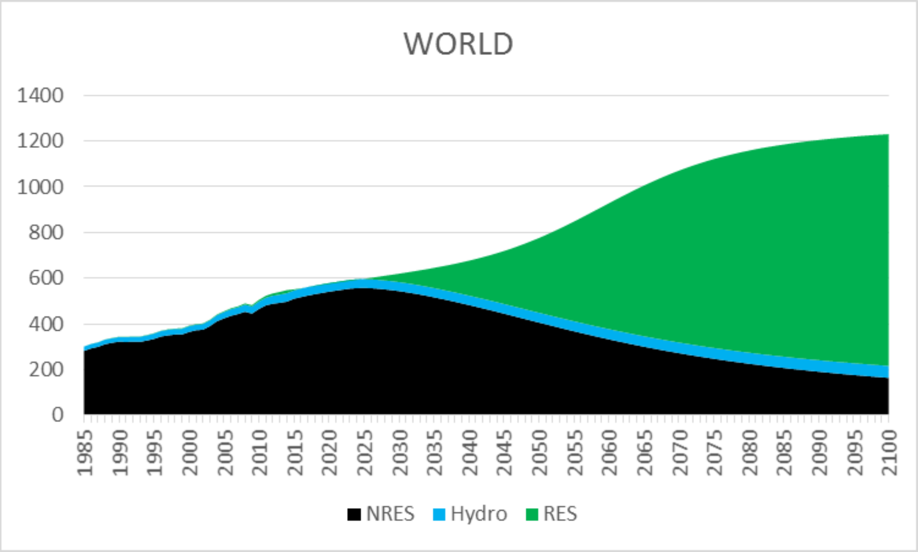


Figure 20: Energy mix, world total. Energy production in EJ.

To reiterate the conditions of the model, the UN (2015) projects that the world population will grow to 11.2 billion by 2100 and ~55% of this population will live in the SSAF and SAS regions. According to BP (2015) the world's remaining NRES reserves total approximately 38,000 EJ. This is equivalent to 70 years at current consumption rates. The average world per capita energy consumption in 2014 was 75 GJ/person (BP, 2015; UN, 2015b). The UN/World Bank Sustainable Energy for All initiative was created in order to set goals to achieve universal access to energy and safe cooking fuels, double the rate of improvement of energy efficiency, and double the percent share of RES and hydropower in the global energy mix.

MENA and FSR are the largest energy exporters throughout the model. As the largest holder of oil and natural gas reserves, these regions are the source of the most dominant carbon emitting fuels in the model. The fossil fuels extracted from the region are projected to emit 700 $GtCO_2$ by 2100. That is 80% of the emissions allowable under the 2˚C climate goal and 32% of the 4100 $GtCO_2$ emitted in the model. The two regions export a total of 4527 EJ from 2015-2100 while importing only 14 EJ. Any successful climate plan must include the cooperation of these two regions.

The regional model results indicate that while the global peak in NRES production will occur at one finite time, each region will reach their own peak at different times throughout the century. As the dominoes start to fall, the adaptation and mitigation of peak energy and population growth will spread from region to region. It follows that as the first regions to confront the energy bottleneck will respond and develop the necessary RES infrastructure to adapt. EUR (5 EJ), NOAM (3 EJ), and CHINA (2 EJ) were the largest RES producers in 2014, producing 79% of all RES. These regions are the early “testing ground” for post-peak energy production. Unfortunately, the global share of energy production attributed to RES is growing slower than any of the fossil fuels did at their conception and long-term plans rarely work out (Smil, 2014).

Of particular note, SSAF and SAS are both projected to experience significant population growth and significant growth in energy demand by 2100. The 2014 per capita energy consumptions of SSAF (12 GJ/person) and South Asia (18 GJ/person) were considerably below the ideal target of 110 GJ/person. Within the scope of the SE4ALL initiative, these regions will require relatively little RES infrastructure investment by 2030 (assuming that NRES reserves are used within the regions); however, beyond mid-century, the model results suggest that population growth and/or per capita energy consumption growth will become the defining issue in these regions (Figure 10a). By 2100, the energy demands (Scenario 1) of these two regions would be nearly seven times more than that of EUR and FSR combined.

Conclusions and Policy Implications

In addition to our model, it is independently projected (Jones and Warner, 2016; Maggio and Cacciola, 2012; Mohr et al., 2015) that fossil fuel production will peak by mid-century and decline significantly by the end of the century. In comparison to the global model from chapter II, our regional model uses a higher global per capita energy consumption in 2100 (110 input vs. 106 calculated GJ/person) and thus projects RES demand about 2-3% higher in 2100. Due to individual regional trends, NRES and hydropower peaks earlier (2025 vs. 2032) and at a lower value (596 vs. 678 EJ) than in the global model. This is due to the fact that in the global model most NRES are exploited to their full URR, whereas in this model there are remaining reserves totalling almost 6,400 EJ for the 22nd century (compared to only 2,100 EJ in the global model). Coal makes up the majority of this reserve and could act as a “swing fuel” in this model to allow more time to develop an RES infrastructure. Full exploitation would lower the RES demand throughout the century, but it would exacerbate atmospheric CO_2 concerns.

We acknowledge that climate change is a critical global issue. The carbon emissions projected in this model exceed the 2˚C global warming goal (Figure 21); however, climate change aside, NRES will be necessary in the future global energy mix. To leave the NRES sources in the ground seems neither likely nor in anyone's best interest. Regardless, providing universal access to energy may be feasible through the first half of the century, but the ambitious goal of *Sustainable* Energy for All is not likely to be fulfilled through the second half of the century without limiting population growth. The developing regions may be overly dependent on rapidly peaking energy resources (Collier and Venables, 2012). The energy mix at the end of this century will have to be significantly more RES dependent than has been the case in the past. Figure 13 illustrates 2014 regional energy mix by source (figure 22) and the shift from an NRES infrastructure to a renewable system as outlined in this regional model scenario 1 (figure 23a) and scenario 2 (figure 23b).

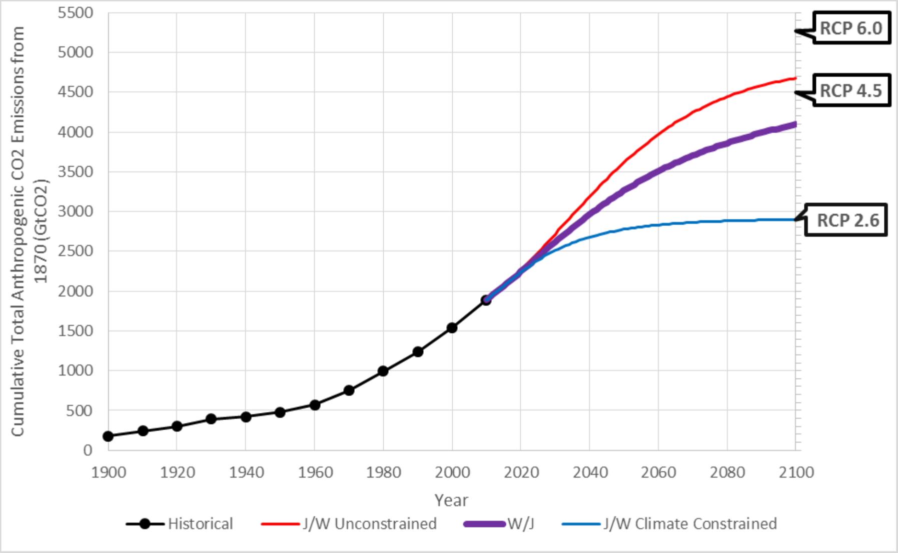


Figure 21: Cumulative fossil fuels CO_2 emissions, 2010-2100. Global total (W/J) compared to results from Jones and Warner (2016) (J/W) and IPCC (Pachauri et al., 2014) RCP scenarios compared to <2˚C (IPCC RCP 2.6) climate goal.

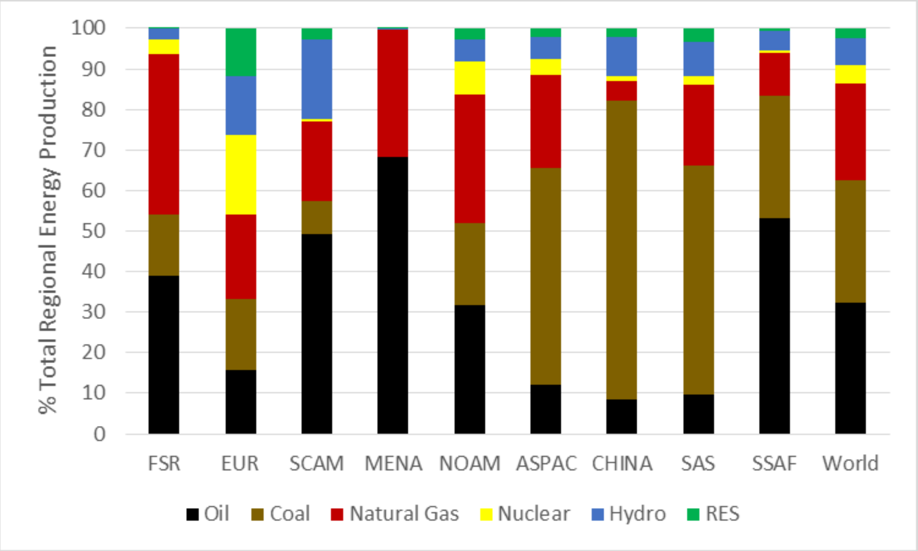
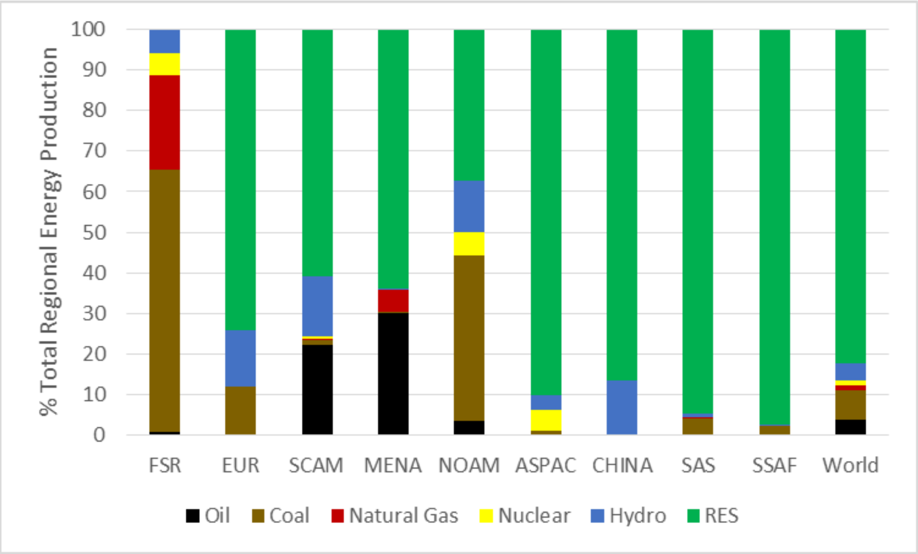


Figure 22: Regional energy mix, 2014. Percent contribution of each energy source to total regional energy production.

a



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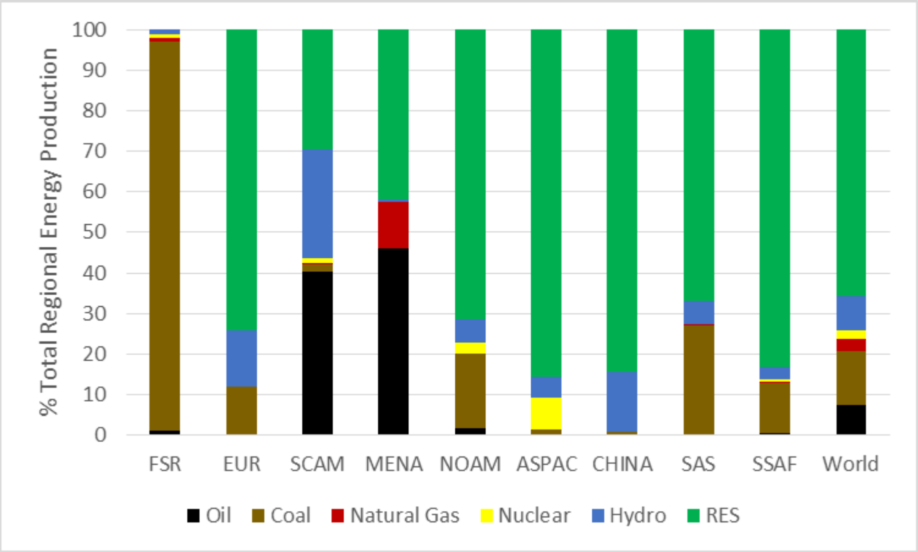


Figure 23: Regional energy mix, 2100, Scenario 1 (a) and Scenario 2 (b). Percent contribution of each energy source to total regional energy production. Note the growth of RES between 2014 and 2100.

Ahmed et al. (2014) conclude that investing in RES now rather than pay the ever-increasing costs of NRES imports will be much more beneficial in the long run. This will be crucial in the South Asia region considering the implications of the net energy cliff (see Lambert et al., 2014). As the high energy density fuels (current NRES) are depleted, small shifts in the energy return on investment (EROI) are not as impactful as small EROI changes among the lower-density fuels (such as RES). This suggests to us that while fossil fuels are a stable and cheap source of energy, establishing a reliable and efficient RES infrastructure before it is needed is important to ensure a smooth transition away from NRES. If India and other countries in the less stable regions continue to increase their dependence on fossil fuels, they will be less capable of making the transition, as they will already be utilizing marginal EROI reserves. These countries regions are likely to be more susceptible to "falling off the energy cliff" as they are less likely to have made the transition to RES while global EROI declines.

It has been noted that decreased energy availability and consumption in the 21st century will inhibit past trends in economic growth (Murphy and Hall, 2011). The combination of increases in both population and per capita energy consumption can only be reconciled with a concurrent rapid expansion of RES infrastructure around the world. The energy and subsequent population surplus afforded by fossil fuels could potentially become an energy and population burden rather quickly. It is estimated that a complete transition to a RES infrastructure would take between 30-50 years (Chu and Majumdar, 2012; Davis et al., 2010; Hirsch et al., 2005; Smil, 2014). These combined factors lead us to conclude that regions of high population, growing per capita energy consumption, and exhausting NRES reserves will have a much more difficult time developing in the second half of the 21st century than is currently considered. Climate goals and initiatives such as SE4ALL only compound the potential climate population issues by also increasing per capita energy consumption. Population will be the key to determining the extent to which each of these regions will find success or hardship in a post-peak NRES world.

CHAPTER IV

PER CAPITA ENERGY CONSUMPTION AND RESERVE ESTIMATES: POSSIBLE FUTURE OUTLOOKS

Introduction

Computer models allow scientists to organize, assess and optimize complicated data sets (Hall, 1990). The greatest limitation to computer modelling is that no matter how well a model is constructed, the quality of the model's inputs and the model output is inherently linked (Lidwell et al., 2010). Models of population growth, energy demand, and climate change are integral components of policy decisions. Previous work (Jones and Warner, 2016) was centred upon a global model of population, energy production, energy consumption, and climate. Here we test the range over which the assumptions within that global model may vary (i.e., the sensitivity of the model) to (A) different development goals (in terms of per capita energy consumption, or PCC), (B) different estimates of fossil fuel reserves. Sensitivity analyses can allow a modeller to assess how important variations in the original input data or subsequent assumptions are to the output of the model.

Total global energy demanded is a function of the global population and the per capita energy consumption rate. We will examine two PCC tracks. The first track in our study (projected consumption growth to 106 GJ/person by 2100) was tested in chapter II. Chapter II used the average annual energy consumption (BP, 2015) and population growth (Gerland et al., 2014) trends from 2000-2014 to determine the rate at which PCC might increase with the UN population projections from Gerland et al. (Gerland et al., 2014). Jones and Warner (2016) found that by 2100 the population as projected by Gerland et al. (2014) would require 994 EJ of non-hydropower renewable energy sources (RES), equivalent to the combined energy production of 12.6 million 5MW wind turbines, 600,000 square kilometres of photovoltaic solar panels and 1.9 million square kilometres of open-pond algae biofuels production. Lambert et al. (2014) determined that societal quality of life indices greatly improve in countries that consume 100-150 GJ/person. This track fits within that PCC range and forms the upper bound per capita energy consumption in our study.

The second track assumes that there will be no growth in per capita energy consumption and that the global PCC will only change as a function of population growth. Though some individual societies, nations, and regions of the world exhibit declining PCC, the world average per capita has more than quintupled since 1900 and more than doubled since 1950 (Jones and Warner, 2016). Wolfram et al. (Wolfram et al., 2012) argues that the largest growth in energy consumption will come from the least developed nations. As much as 20% of world population live with no access to modern energy (Banerjee et al., 2013). The vast majority of the 2100 population projected by Gerland et al. (Gerland et al., 2014) is expected within the nations currently designated as least developed (55% in Sub-Saharan Africa & South Asia). Warner and Jones (in review) calculated that, based on the PCC in nine world regions, global PCC would decline from 75 GJ/person in 2014 to 58 GJ/person by 2100 as the population in the lower consuming regions of the world is projected to grow to a larger percent of total global population.

This track is similar to the 2000 Watt (63 GJ/person) society evaluated by Kesselring and Winter (1995) and subsequently used in several studies (Schelling, 2013; Schulz et al., 2008; Smalley, 2005; Spreng, 2005; Stulz et al., 2011). This track forms the lower bound per capita energy consumption in our study.

In addition to the two per capita energy consumption tracks, this study will examine three models of NRES production based on published energy reserves. Many international agencies publish NRES reserve estimates. We have previously used the *BP Statistical Review of World Energy 2015* (BP, 2015) because the dataset is widely available, widely cited, and contains nearly 50 years of detailed data in one source. In addition to the BP (BP, 2015) proven NRES reserves, the International Energy Agency (IEA) published Resources to Reserves in 2013 (IEA, 2013). The report includes both proven and remaining recoverable resource estimates for oil and gas (both conventional and unconventional). The proven reserve estimates are in close agreement with BP (BP, 2015). This paper will use the remaining recoverable resource estimates to create the second model (henceforth "the IEA model"). McGlade and Ekins (McGlade and Ekins, 2015) provide an estimate of the remaining fossil fuel reserves that must remain in the ground in order to prevent the average global temperature from exceeding 2˚C above the pre-industrial level. Though unlikely, we use these low-end fossil fuel reserve estimates to create the third model (henceforth "the 2C model") to estimate the RES infrastructure timeline necessary to prevent potentially catastrophic global climate change.

Data and Methods

This paper focuses on the sensitivity of Jones and Warner (2016) to both estimates of per capita energy consumption and the uncertainty of oil and natural gas reserve estimates. We have developed six energy consumption and reserve scenarios. The Jones & Warner (Jones and Warner, 2016) model (henceforth “the global model”) used proved reserve estimates from the BP Statistical Review of World Energy (BP, 2015) and applied a single-cycle Hubbert logistic model (Hubbert, 1982) to project 21st century production of non-renewable energy sources (NRES). Combined with 21st century population projections from Gerland et al. (Gerland et al., 2014), the global model projected the renewable energy source (RES) demand and makeup (i.e., wind turbines, solar panels, and biofuel algae ponds) required to keep up with the projected 21st century global energy demand.

The Jones & Warner (Jones and Warner, 2016) global model is a three-body model. It is built on estimates and projections of population, energy production, and energy consumption. The population piece is assumed using Gerland et al. (Gerland et al., 2014). The energy production is projected from estimates provided by BP (BP, 2015) in the global model, the IEA additional reserves (IEA, 2013) in the IEA model, and from the 2˚C climate change reserve estimates from McGlade & Ekins (McGlade and Ekins, 2015). The third body of the model is PCC. As an economy grows, energy consumption grows as well (Kraft and Kraft, 1978). The causality of this correlation is the subject of no small scholarly debate (see (Akkemik and Goksal, 2012; Jumbe, 2004; Lee, 2005; Narayan and

Popp, 2012; Soytas and Sari, 2003)). For a more detailed regional/national consideration of PCC and economic development see (Lambert et al., 2014; Warner and Jones, in review). Regardless of causality, the correlation suggests that PCC will continue to grow.

We have developed six energy consumption and reserve scenarios. There are two PCC tracks and three sets of NRES reserve estimates (Table 6). Population is the one aspect of the model that will not be varied throughout this study. The UN population projections are the most commonly cited projection within scientific studies as well as media reports (Lutz and Samir, 2010). Before the 2014 update, projections were made considering past trends in fertility and mortality. The high and low fertility scenarios arbitrarily raised the fertility rate ± 0.5 children per woman (Gerland et al., 2014). This method was replaced with Bayesian probability statistics in the 2014 update. The new method includes probabilistic projections of total fertility rate and life expectancy at birth. The results of the approach were fitted to the median estimates of the 2012 Revision of World Population Prospects. These new projections preclude the likelihood of world population peaking during this century. The 2015 Revision of World Population Prospects includes both methods of projections (UN, 2015b). We continue to use the Gerland et al. (Gerland et al., 2014) projections in this study because those are the projections used in Jones & Warner (Jones and Warner, 2016).

Table 6: Conditions of each of the six NRES reserves and per capita energy consumption scenarios. Zetajoule (ZJ) figures represent the NRES reserves (2014) in each energy model. PCC values represent the target PCC in 2100 for each track.

	Global Model	**IEA Model**	**2C Model**
106 GJ/person by 2100	36.9 ZJ, 106 GJ/person	74.0 ZJ, 106 GJ/person	14.2 ZJ, 106 GJ/person
58 GJ/person by 2100	36.9 ZJ, 58 GJ/person	74.0 ZJ, 58 GJ/person	14.2 ZJ, 58 GJ/person

The energy consumption portion of the analysis will test the Jones & Warner (Jones and Warner, 2016) PCC projection and a zero growth . The first track projection reaches 106 GJ/person in the year 2100. This scenario is supported by the findings of Lambert et al. (Lambert et al., 2014) in that quality of life indices were found to begin to saturate at levels above 100 GJ/person and ultimately saturate at ~150 GJ/person. The second track models zero growth per capita consumption. Warner and Jones (in review) modelled nine world regions in a manner similar to Jones and Warner (2016) and determined that zero per capita energy consumption change in the nine regions would result in a global PCC decline to 58 GJ/person by 2100 due to population growth in low consuming countries. This track is a low end scenario and the track is similar to the 2 kW/person sustainable energy consumption of 63 GJ/person suggested in Kesselring and Winter (1995).

The peak energy portion of the Jones & Warner model (Jones and Warner, 2016) was constructed using raw production/consumption data by resource from 1900-2014 (ASPO, 2006; BP, 2015; Laherrère, 2004; Rutledge, 2011; WNA, 2013). All units were converted into exajoules. This model uses the single-Hubbert modelling approach (Hubbert, 1956,

1982) to forecast global oil, coal, natural gas and nuclear production throughout the remainder of the 21st century.

Additional assumptions within Jones & Warner (Jones and Warner, 2016) include: that the energy that each of these sources provides is interchangeable with any of the others at 100% efficiency and that the energy will be allocated as needed, regardless of political borders; that the estimated total global hydroelectric potential of 52.5 EJ (Seyboth et al., 2011) could be built out by the year 2100; and that the energy required to build the RES infrastructure is included in the rise in energy consumption.

We then multiplied each year's per capita demands by the year's global population to derive each year's global energy demand and compared the demand with each year's projected hydropower and NRES production. The result is a year-by-year global surplus or deficit of energy availability. Our model then requires that any inability for the NRES and hydropower resources to support the projected population must be made up by the RES sources.

We created two more energy production models. The methodology was the same in each model. The difference is in oil and natural gas reserve values. Our first model (IEA) uses reserve and additional resource data from the IEA Resources to Reserves 2013 (IEA, 2013). Coal, nuclear energy and hydropower projections were unchanged between these two models. Our third model (2C) limits fossil fuel consumption to the levels suggested in McGlade and Ekins (McGlade and Ekins, 2015) to be necessary in order to avoid increasing the average global temperature more than 2˚C beyond pre-industrial levels. We used the numbers required in a world without extensive carbon capture systems because, though negative emissions in the second half of the 21st century are necessary to keeping the climate change target, the questions as to the physical capabilities of long-term carbon capture, the biophysical responses, the costs, and the social barriers of carbon capture systems make relying on these systems in future projections risky (Fuss et al., 2014). Using the same frameworks as the first two models, the oil, coal, and natural gas reserves were replaced with the usable fossil fuel reserves projected for the non-carbon capture scenario within McGlade & Ekins [24].

We ran both PCC tracks with NRES and hydropower production values from the global, the IEA, and the 2C model for a total of six scenarios. When necessary, we then ran each scenario independently to adjust the NRES production values for different energy demands. This prevents the RES demand from dropping below zero exajoules. The scaling of the RES demands in each scenario follows the same methodology as in Jones and Warner (2016).

Results and Discussion

The six scenarios in the model are resultant of the per capita energy consumption models (Figure 24) and the energy reserve/production projection (Figure 25). The total NRES reserves double from 37,000 EJ in the global model to 74,000 EJ in the IEA model. The more imminent peaks in oil and natural gas production could be delayed if these reserves were to be realized. The total NRES reserves in the 2C model total 12,700 EJ.

Oil, natural gas, and coal peak in 2020, 2024, and 2047 respectively in the global model (106 GJ/person). Including the additional reserves, the IEA model delays those peaks until 2072, 2055, and 2047. All fossil fuel energy production peaks in 2014 in the 2C model. In the IEA model, under the median population projection and accompanying 106 GJ/person PCC by 2100, significant expansion of RES production (greater than 20 EJ) is not needed until 2041. This need presents itself in the year 2027 in the global model and immediately in the 2C model.

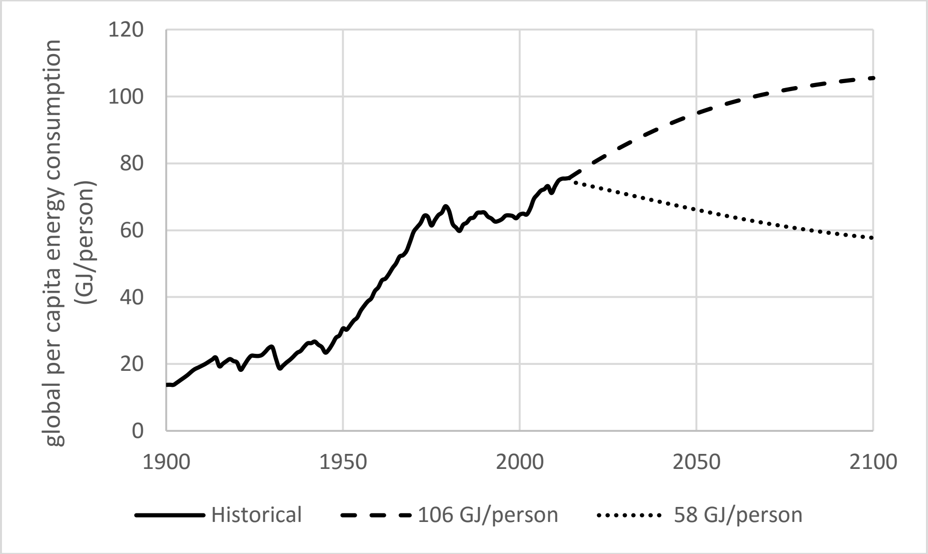


Figure 24: Two per capita energy consumption tracks, 1900-2100.

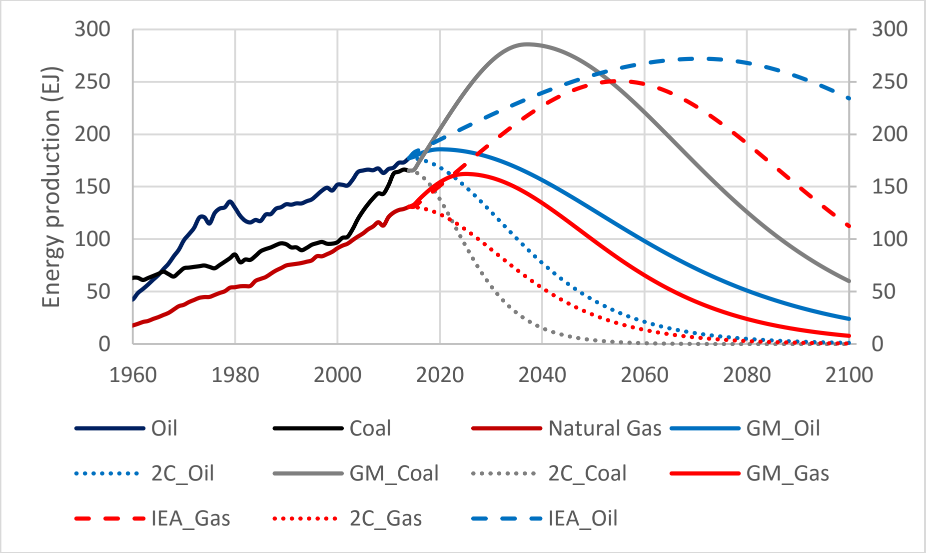


Figure 25: Fossil fuel production for each model's reserve values, 1960-2100. Oil, Coal, Natural Gas = Historical production of oil, coal, and natural gas. GM_Oil, GM_Coal, GM_Gas = Global model projection of fossil fuel production. IEA_Oil, IEA_Gas = IEA model of oil and gas production (coal follows GM_Coal track in the IEA model). 2C_Oil, 2C_Coal, 2C_Gas = 2C model production of fossil fuels.

Table 7 lists the differences between the models in terms of actual RES infrastructure. The IEA model RES demand is 32% lower than the global model demand. The 2C model RES demand is 9% higher than the global model. Despite the small difference in the year 2100, the 2C model requires approximately 2/3 of the 2100 RES infrastructure to be in place by the year 2050, whereas only 1/3 of the 2100 RES infrastructure is required by 2050 in the global model. The scaling to wind, solar and algae biofuels production follows the same methodology as in Jones & Warner (Jones and Warner, 2016). The global, IEA, and 2C models require 89, 59, and 96 times the current number of installed 5MW equivalent wind turbines (~142,000) in 2100, respectively. The same figures are 140, 93, and 152 times in 2100 for solar panel area (~4,300 km^2).

Table 7: RES requirements of each NRES reserve model in the year 2100. Based on the projected growth per capita energy consumption scenario (106 GJ/person by 2100) and 2100 population of 10.9 billion. The IEA model requires 32% less RES production than the global model. The 2C model requires 9% more RES production than the global model. Area is relative to the land area of the most similarly sized country and does not denote any other implications.

RES Source	**Global Model**	**Global Model Area**	**IEA Model**	**IEA Model Area**	**2C Model**	**2C Model Area**
5MW Wind Turbine Eq.[1]	12,600,000	N/A	8,500,000	N/A	13,700,000	N/A
Solar Panel Area (km^2)[2]	598,000	Ukraine	406,800	Paraguay	654,300	Afghanistan
Algae Biofuel Area (km^2)[3]	1,900,000	Sudan	1,274,600	Niger	2,004,900	Mexico

[1] Based on 47.3 terajoules (TJ)/turbine. Conversion based on data in (EIA, 2016a)

[2] Based on value of 414 TJ/km^2 (Moriarty and Honnery, 2012)

[3] Based on 79.3 GJ/km^2. Conversion based on data in (Benemann, 2013)

Table 8 is comprised of the year 2100 results of each of the six scenarios run independently. The independent analysis accounts for a shifting of NRES energy production from the base models as depicted in figure 25 to a demand-based projection. These analyses result in slightly different peak NRES plus hydropower dates (Table 9). The 2C model does not require any adjustment from the base model in order to account for the change in per capita energy demand.

Table 8: Results of each of the six NRES reserves and per capita energy consumption scenarios. Results for the year 2100. Assumes median global population growth from Gerland et al. (Gerland et al., 2014). NRES+H = Non-renewable energy sources plus hydropower.

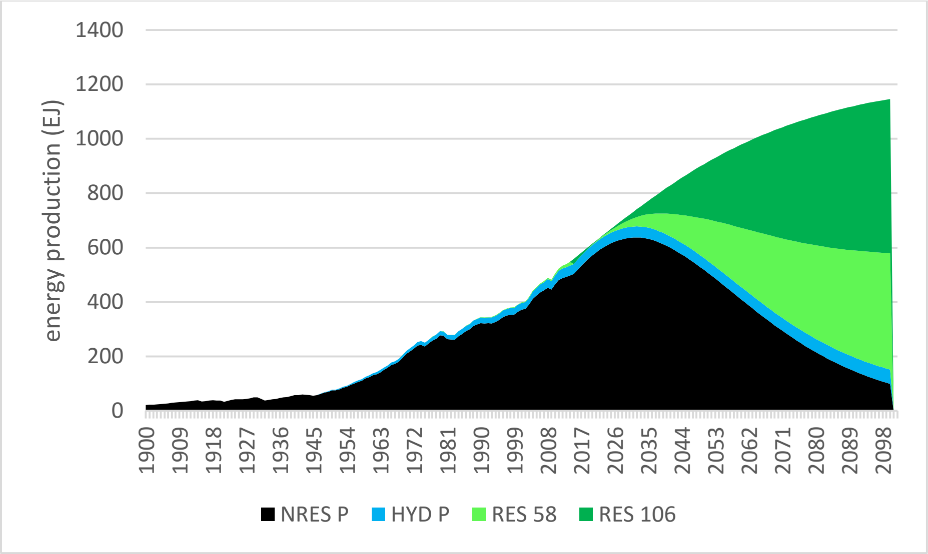
PCC Track	Global Model	IEA Model	2C Model
106 GJ/person by 2100	152 EJ NRES+H 1146 EJ Demand 994 EJ RES	472 EJ NRES+H 1146 EJ Demand 674 EJ RES	62 EJ NRES+H 1146 EJ Demand 1084 EJ RES
58 GJ/person by 2100	198 EJ NRES+H 626 EJ Demand 428 EJ RES	531 EJ NRES+H 626 EJ Demand 95 EJ RES	62 EJ NRES+H 626 EJ Demand 564 EJ RES

Table 9. Peak non-renewable energy sources plus hydropower production dates and values within the global and IEA reserve models, dependent upon each PCC track.

PCC Track	Global Model	IEA Model
106 GJ/person by 2100	2032, 678 EJ	2052, 847 EJ
58 GJ/person by 2100	2026, 573 EJ	2066, 637 EJ

Figure 2 depicts the modelled global energy mix from 1900-2100. Though the NRES shapes are slightly different for each PCC track in order to prevent energy oversupply, the 106 GJ/person growth track results are presented. Each of the three reserve models requires the same amount of energy within each track, as demand is not dependent on reserves or production. The growth of RES in the energy mix changes significantly based on both reserve model and PCC track. The 2014 global production of RES is ahead of schedule in the 58 GJ/person track in both the global (figure 26a) and the IEA models (figure 26b). RES growth begins immediately in the 2C energy production model in both PCC tracks (figure 26c) as well as the 106 GJ/person track of both the global and the IEA model.

a



b

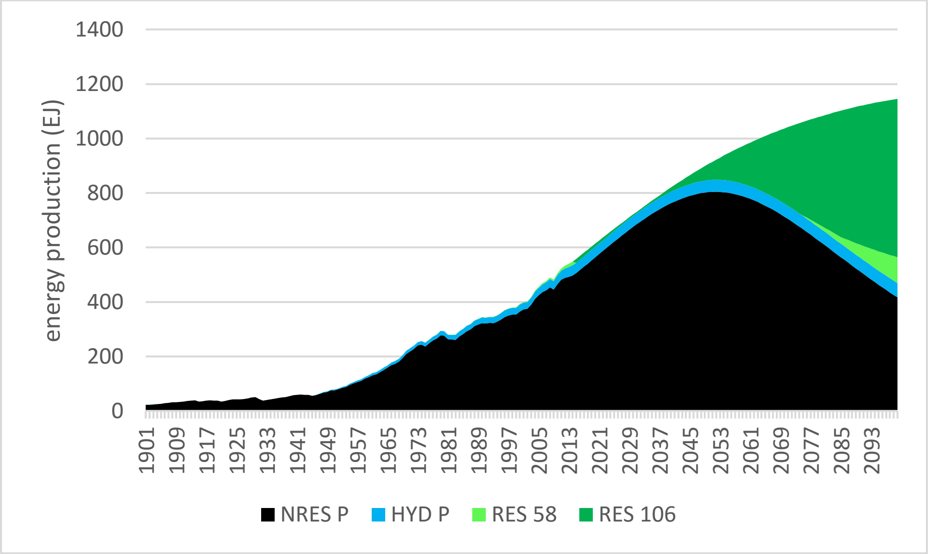


Figure 26: Global energy mix profile, 1900-2100. Global model energy production (a), IEA model energy production (b), 2C model energy production (c). NRES curve is from 106 GJ/person by 2100 PCC track.

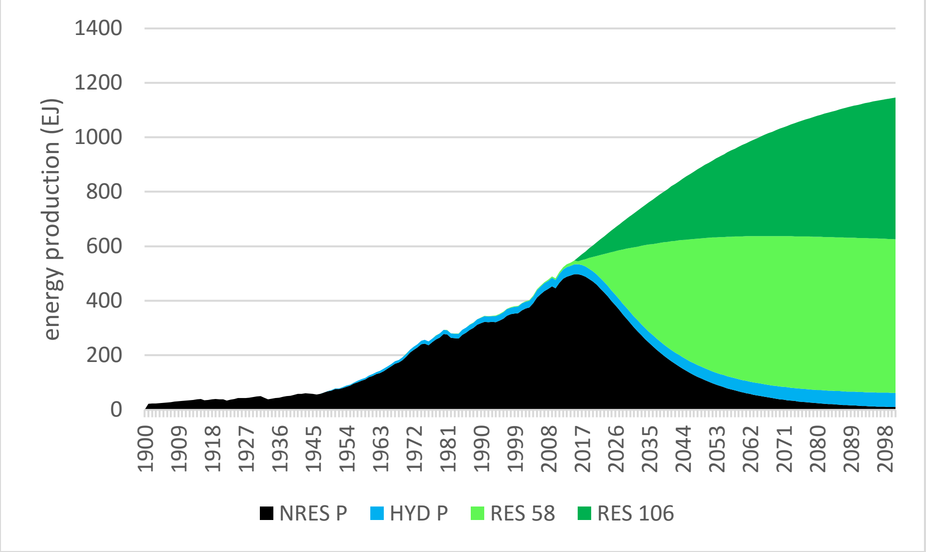


Figure 26: continued

Throughout all three energy production scenarios, per capita energy consumption has more of an impact on total RES demand in 2100 than reserve estimates. The global model and the 2C model both project the peak of oil and natural gas production before the year 2030, yet world population is projected to increase 18% in that time. Accounting for additional possible oil and natural gas reserves allows for a more optimistic estimation of 21st century energy production. The issues of population growth and energy scarcity are only delayed in the most optimistic scenarios, not solved. It is important to note that though resources (IEA model) have been assumed to be exploitable, questions surrounding energy return on investment (Gagnon et al., 2009) may have a significant impact on the total recoverability of additional reserves. More likely, optimistic resource (rather than reserve) estimates are significantly overestimated (Reaver and Khare, 2014). In any case, aggressive expansion of RES is not projected to be necessary before 2030; that said, aggressive RES expansion is necessary by the end of the century in each scenario.

Per capita energy consumption is the flow rate of energy from the supply model to the population projections. Even in the absence of a PCC increase, population growth is a serious strain on any global energy infrastructure, much less one in transition to RES. In a world of eleven billion people, a change of ± 1 GJ/person results in ± 11 EJ of energy demand. The global total production of non-hydropower RES was 13.3 EJ in 2014. Extending the difference between a global PCC of 106 GJ/person and 58 GJ/person to 2100 is 520 EJ of total global energy production. The total global energy production in 2014 was 547.6 EJ.

In the developed world, PCC is well above the global average. While environmental concerns limit the extent to which developed economies consume energy, economic development and increasing the wellbeing of the citizenry determines the energy consumption of underdeveloped economies (Spreng, 2005). Initiatives such as the World Bank's Sustainable Energy for All (SE4ALL) seek to provide universal access to modern electricity and cooking fuels by the year 2030 (World Bank, 2013). As such, we do not anticipate the global PCC declining at all, much less declining to 58 GJ/person by 2100.

As an economy grows, energy consumption grows as well (Kraft and Kraft, 1978). The causality of this correlation is the subject of no small scholarly debate (see (Akkemik and Goksal, 2012; Jumbe, 2004; Lee, 2005; Narayan and Popp, 2012; Soytas and Sari, 2003)). For a more detailed regional/national consideration of PCC and economic development see (Lambert et al., 2014; Warner and Jones, in review). Regardless of causality, the correlation suggests that PCC will continue to grow. Moriarty & Honnery (Moriarty and Honnery, 2012) projected that if everyone in the world consumed at the 2008 OECD average PCC, global energy production would need to be three times higher than the 2013 total. Differing trends in per capita energy consumption may have enabling or limiting effects on RES development. Varying the amount of energy available to the average global citizen has a drastic effect on not only the quality of one's life, but on the RES stress of the world energy supply.

Usable fossil fuels are referred to as resources. Recoverable resources are called reserves. There are three types of reserves. Proven reserves are those that are confirmed to exist and have a 90% chance of being exploited (abbreviated as 1P). Probable reserves are those that have at least a 50% likelihood of production (abbreviated as 2P). Possible reserves are the remainder of the resource estimate that may or may not exist (abbreviated as 3P). These reserves are assigned a 10% chance of being exploited. The reserves used in the global model are based on proven reserves (BP, 2015). The reserves used in the IEA model are based on proven reserves as well as remaining resources (IEA, 2013).

Commonly, energy reserves are described in terms of, "we have x number of years of y energy left." These statements reflect the reserves to production ratio (R/P). This is the total estimated remaining reserve divided by the previous year's production. The problem with these ratios is that they do not factor in the increased or decreased use of the resource over time. At year-end 2014, the R/P for global coal was 110 years (BP, 2015). Coal was not addressed in the IEA model because the additional reserves estimated within the IEA Resources to Reserves 2013 were so high that the model would not require RES in any scenario. Several factors limit the extraction of coal, and therefore global peak coal will more than likely occur before the year 2100 (Höök et al., 2010). As an example, coal reserves are more than likely overestimated, and recovery of those estimates may be as low as 20% of the expected value in the United States (Reaver and Khare, 2014).

In addition, unconventional sources of oil and gas contribute a considerable fraction of total production (Murray and Hansen, 2013). US oil production had peaked at 11.3 million barrels per day in 1970 (BP, 2015). The recent boom in US oil production has surpassed the 1970 peak as the US averaged 11.6 million barrels per day in 2014 (BP, 2015). This resurgence is attributed to tight production. Most of the tight production in the United States is from small sweet spots and exhibit sharp and predictable depletion rates (Patzek et al., 2013). Aided by the recent drop in oil prices worldwide, the boom has called into question the notion of peak oil. In fact, global conventional crude oil production has been relatively constant for nearly a decade (Murray and King, 2012). It seems likely that continued depletion of conventional resources will keep the market favourable for tight oil and gas (Brandt et al., 2013) and the oil inelastic price phase as suggested by Murray & King (Murray and King, 2012) may have been a temporary anomaly. Tight oil and gas reserves are not likely to be as expansive as initially estimated (Inman, 2014). Despite the potential health and environmental risks (Finkel and Law, 2011), tight gas production will be necessary towards smoothing the drop in conventional gas production that is projected by mid-century (Melikoglu, 2014).

This analysis would not be rigorous without qualifying the use of the single-cycle Hubbert model. There are several other curve fitting models used to project future non-renewable resource extraction. Oil production is the most common subject of these models. Reynolds and Baek (Reynolds and Baek, 2012) examined several symmetrical and asymmetrical variants of Hubbert, Cauchy, Gaussian, Gompertz, Ramsay and lognormal methods and found the best method varied based on the level of production investigated, though the Hubbert model performed adequately at the largest aggregation levels. Brandt (Brandt, 2007) rigorously tested several aspects of the Hubbert model and found that Hubbert models were not likely to vary (by methodology) significantly in predicted peak date, though it was emphasized that no single methodology was universally applicable and a more broad application of Hubbert theory (developing a family of predictive curves) would best suit predictions of future production.

Similar studies have focused on coal, natural gas, uranium and total non-renewable energy sources. Hook et al. (Höök et al., 2010) found that simple logistic model results of regional and global coal production were comparable with more complex, variable-laden models. Mohr et al. (Mohr et al., 2015), Maggio & Cacciola (Maggio and Cacciola, 2012), and Mediavilla et al. (Mediavilla et al., 2013) each modelled oil, coal, and natural gas production throughout the 21st century and beyond, finding in each case that fossil fuel production is likely to peak by 2100. Based on the results of this (and additional) literature, we feel confident that the single-cycle Hubbert model will not be disadvantageous to use in our analysis.

Of the six scenarios developed in this study, five require over 30 EJ of RES production by the year 2050. The sixth scenarios is the 58 GJ/person by 2100 track and the full exploitation of the IEA remaining oil and natural gas resources. Policy makers must strike a balance between climate change, energy demands and development. The remaining NRES reserves remain the cheapest and easiest solution to the increasing energy demand. The infrastructure is in place and the technology is mature. As technology improves, the amount of these resources made available for exploitation will also increase. Figure 2 illustrates that there were few declines and no sustained decreases in per capita energy consumption in the 20th century. It is almost a certainty that global energy consumption will continue to increase. The reserve-limitations in the 2C model are unrealistic and the proven reserves used in the global model are all but certainly going to be consumed. The actual production of oil and gas in the 21st century will most likely lie between the estimates made in the global and the IEA models. Eliminating the 58 GJ/person track and the 2C reserve limitation places the NRES and hydropower peak energy date between 2032 and 2052.

There is the ethical dilemma of how to distribute these remaining allowable fossil fuel emissions. Who makes the decision as to who can and cannot burn these fuels: the developed nations, the highest emitting yet most capable of moving towards RES infrastructure, or the least developed, the lowest emitting but attempting to catch up to the developed nations? The social and political challenges to distributing the remaining allowable carbon emissions do not excuse the biophysical reality of the situation (Raupach et al., 2014). In preventing a global climate change of 2˚C or greater, the peaking of carbon-intensive energy production must be made imminent. We do not believe that the 2C model to be relevant for any purpose other than highlighting the climate change issue and providing a high-end estimate of RES demand throughout the century.

Conclusions and Policy Implications

This study illustrates the importance of per capita energy consumption statistics in 21st century policymaking. Again, consumption growth or decay of 1 GJ/person results in a corresponding 1 EJ change in energy consumption per billion people. If the 2014 global population consumed 2 GJ/person more, it would in effect negate the 2014 global total production of non-hydropower RES. One aspect of per capita energy consumption that we have not yet discussed is total population. World population projections are not modelled in this study. We have assumed the numbers as projected by Gerland et al. (Gerland et al., 2014).

Increased per capita energy availability (especially for women) is associated with many shifts in demographic trends (most notably in fertility rates) (Lambert et al., 2014). Economic development and energy access in these regions could drastically alter the population projections made by Gerland et al. (Gerland et al., 2014). It is entirely possible that a large investment in projects such as the World Bank’s Sustainable Energy for All Initiative may serve to “bend” the population projections towards lower numbers by the end of the century. However, without drastic and rapid changes in fertility rates, the population issue will only become a greater ecological stress (Bradshaw and Brook, 2014). The current population projections do not implicitly account for energy availability.

This study also expands the range of estimates for future RES production calculated in Jones and Warner (2016). NRES reserves are likely to be higher than those used in the global model, but less than those used in the IEA model. Even in theory, the 2C model does not appear practical. The allowed NRES reserves combined with the projected hydropower production could only cover projected energy demand (in the 106 GJ/person consumption scenario) until 2033. By 2034, RES would have to be prepared to produce over 300 EJ. The key insight here is that including the IEA additional reserves allows for a smoother transition towards a fully renewable energy infrastructure. At any rate, each of the three reserve models project fossil fuel production peaking in the 21st century. Historically, becoming the prime component of global energy consumption has taken over half a century of development (Smil, 2014). Renewables are still in competition with pre-peak oil, coal, and natural gas.

We have modelled both energy reserves and PCC independently and combined the results. We do not take into account non-energy source scarcity projections such as copper (Kerr, 2014), lithium (Vikstrom et al., 2013), or phosphorus (Cordell and White, 2011). If the ramifications of burning the fossil fuel reserves of the global model exceed climate change goals, then the transition to RES must begin immediately. Otherwise, the world may be heading towards exploitation of fossil fuels on par with the IEA model. There is need for more studies integrated into global, regional, and national plans for socio-economic development and climate/environmental resource conservation.

CHAPTER V

ENERGY FOR FOUR BILLION: HOW CAN SUB-SAHARAN AFRICA PROVIDE ENERGY FOR DEVELOPMENT THROUGHOUT THE 21ST CENTURY?

Introduction

Economic and social development is a global concern in the 21st century. In the world today there are developed nations boasting strong economies and high standards of living, developing nations transitioning towards stronger economies and lower fertility rates, and least developed economies are characterized by low gross per capita national incomes (<\$900 USD_{2006}), low human asset index (a relative measure of undernourishment, under-five mortality, literacy, and secondary education enrolment), and high economic vulnerability (a relative measure of population, economic, and agricultural statistics) (UN, 2008). Sub-Saharan African countries are, for the most part, at the low end of the development spectrum. This paper is an energy-based examination of the development issues facing Sub-Saharan Africa. We examine the extent to which energy availability can limit the development of economies and compare the current conditions in Sub-Saharan Africa with the recent historical development of other nations.

For the purpose of our study, Sub-Saharan Africa (hereafter, 'SSAF') refers to all nations not defined by the UN as 'Northern Africa'. This includes the countries and territories on the continent of Africa without a Mediterranean shoreline, South Sudan but not Sudan, as well as the island nations of Cabo Verde, Comoros, Mauritius, Réunion, São Tomé and Principe, and Seychelles. In total there are 51 nations included in SSAF (table 10). This designation excludes the North African countries and territories of Algeria, Egypt, Libya, Morocco, Tunisia, and Western Sahara.

Table 10: Countries in Sub-Saharan Africa. UN sub-region designations from UN (2015b).

Country	**UN Sub-region**	**Country**	**UN Sub-region**
Angola	Middle Africa	Malawi	Eastern Africa
Benin	Western Africa	Mali	Western Africa
Botswana	Southern Africa	Mauritania	Western Africa
Burkina Faso	Western Africa	Mauritius	Eastern Africa
Burundi	Eastern Africa	Mayotte	Eastern Africa
Cabo Verde	Western Africa	Mozambique	Eastern Africa
Cameroon	Middle Africa	Namibia	Southern Africa
Central African Republic	Middle Africa	Niger	Western Africa
Chad	Middle Africa	Nigeria	Western Africa
Comoros	Eastern Africa	Réunion	Eastern Africa
Congo	Middle Africa	Rwanda	Eastern Africa
Côte d'Ivoire	Western Africa	Saint Helena	Western Africa
Democratic Republic of the Congo	Middle Africa	Sao Tome and Principe	Middle Africa
Djibouti	Eastern Africa	Senegal	Western Africa
Equatorial Guinea	Middle Africa	Seychelles	Eastern Africa
Eritrea	Eastern Africa	Sierra Leone	Western Africa
Ethiopia	Eastern Africa	Somalia	Eastern Africa
Gabon	Middle Africa	South Africa	Southern Africa
Gambia	Western Africa	South Sudan	Eastern Africa
Ghana	Western Africa	Sudan	Northern Africa
Guinea	Western Africa	Swaziland	Southern Africa
Guinea-Bissau	Western Africa	Togo	Western Africa
Kenya	Eastern Africa	Uganda	Eastern Africa
Lesotho	Southern Africa	United Republic of Tanzania	Eastern Africa
Liberia	Western Africa	Zambia	Eastern Africa
Madagascar	Eastern Africa	Zimbabwe	Eastern Africa

Africa (specifically SSA) was known as “the dark continent” after Henry Stanley remarked on Europe’s relatively poor understanding of the continent in 1878 (Pimm, 2007). The “Scramble for Africa” and subsequent colonization have resulted in low economic growth rates and regional heterogeneity in SSAF (Bertocchi and Canova, 2002). Separate from the fossil fuel-rich Northern Africa, SSAF may also be considered a modern day dark continent because the region has the world's lowest per capita energy consumption (Warner and Jones, in review). Additionally the region is projected to have the fastest growing population in the world in the 21st century (UN, 2015b). The combined population of the 51 countries comprising SSAF was 937 million in 2014 and is projected to have nearly four billion (3.93) people in 2100 (UN, 2015b).

Many development and sustainability initiatives focus on food production and per capita GDP. The carbon contribution of African countries generally do not prominently feature in climate change debates. More recently energy (particularly electricity) has become an area of focus. For example, the Sustainable Development for All initiative (Banerjee et al., 2013) was developed with the goals of eradicating global energy poverty, including universal access to electricity and modern cooking fuels. There is a strong correlation between electricity consumption and economic development (Ferguson et al., 2000). Analysis from years 1971-1992 indicate that developing countries tend to converge to similar patterns of energy use, further reinforcing the development link with energy consumption and complicating decarbonisation efforts (Mielnik and Goldemberg, 2000).

Fossil fuel and nuclear energy consumption in SSAF was 10.7 EJ in 2014 while renewable energy sources provided 1.1 EJ (BP, 2015). In 2012, it was estimated that 86% of the world's population had access to electricity and 59% had access to non-solid cooking fuels (WB, 2015). The same 2012 statistics were 35% and 18% in SSAF (WB, 2015). The year-end 2014 fossil fuel reserves in SSAF were estimated at 1500 EJ (24% oil, 60% coal, 16% natural gas) (BP, 2015). Total energy consumption was 11.8 EJ, or 12.6 GJ/person. Consuming energy at 12.6 GJ/person means that, assuming no exportation or population change, the region has 76 years of fossil fuel energy in proven reserves (BP, 2015).

SSAF has been a net exporter of energy since 1969. Uranium is abundant in the region (WNA, 2013); however, nuclear energy is unused in the region outside of South Africa. In 2014 the region was a net exporter of energy (9.2 EJ) and carbon emissions (0.7 $GtCO_2$) (BP, 2015). At 99 GJ/person, the highest consuming country in SSAF is South Africa (BP, 2015; UN, 2015b). The remainder of Africa (less Algeria, Egypt, and South Africa) consumes at a rate of 6.7 GJ/person (BP, 2015; UN, 2015b).

In our study, we set three per capita energy consumption scenarios for SSAF and use energy production modelling to determine the energy requirements for satisfying each energy consumption scenario in the face of the population projections for the region. We then examine historical analogues for each scenario, seeking precedent for the scale of the energy solutions within our consumption scenarios.

Data and Methods

The energy demand portion of this paper will involve three energy consumption scenarios. The first scenario holds per capita energy consumption in the region at the

2014 value (13 GJ/person) in order to quantify the effect of the projected population growth only. If we assume that 65% of the population in SSAF (606 million) is not on the energy grid (WB, 2015) and consuming 0 GJ/person, then the remaining 35% (331 million) are consuming the total SSAF energy consumption of 10.8 EJ (36 GJ/person). The SE4ALL initiative schedules its goals to be met by 2030, so our second energy consumption scenario will project the entire 2030 population (1.4 billion) to consume at 36 GJ/person. Similar to the first scenario, the per capita energy consumption will be held constant from 2030 throughout the remainder of the 21st century.

We developed our third scenario via three different approaches. First, (Jones and Warner, 2016) extended the global trend in average annual population and energy consumption growth from 2000-2014 and projected that the global per capita energy consumption would reach 106 GJ/person in 2100. This scenario is similar to the second per capita energy scenario used in Warner and Jones (in review). Second, The Human Development Index (HDI) is a measure of a country's life expectancy, education, and per capita income. Lambert et al. (2014) sought to quantify the effect of energy quality on the quality of the consumers' life. One of the aspects of their study included comparing energy usage to various quality of life indices including HDI. Lambert et al. (2014) found a logarithmic correlation between per capita energy consumption and HDI ($R^2 = 0.4859$) using their datasets. We use a different dataset and also found the same correlation ($R^2 = 0.5949$). Using our data, we determine that achieving an HDI of 0.8 corresponds with a per capita energy consumption of 95 GJ/person (figure 27). Third, the overall findings in (Lambert et al., 2014) suggest that significant improvements to most quality of life indices occurs at a consumption rate of 100 GJ/person (and do not significantly increase above 150 GJ/person). Our third energy consumption scenario will raise the consumption level to 100 GJ/person by 2100.

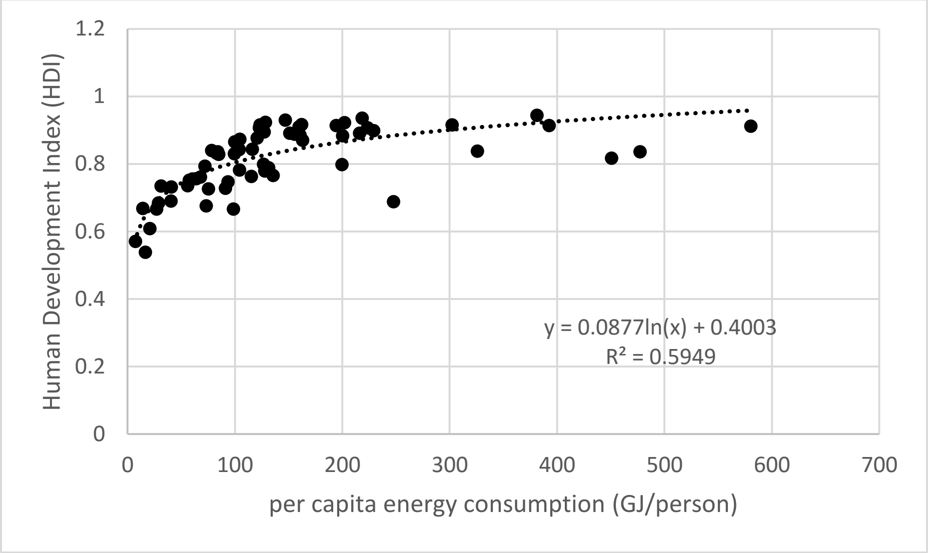


Figure 27: Human Development Index and per capita energy consumption, 2014. Data includes 63 countries. Sources - (BP, 2015; UN, 2015b; WB, 2015)

We modelled annual per capita energy consumption in the second and third scenarios using a logistic growth curve. The remaining modelling is based on the 2015 UN population projections (UN, 2015b), the 2015 BP proven fossil fuel reserve estimates (BP, 2015), and the World Nuclear Association reasonably assured uranium reserves (WNA, 2013). Historical production and consumption was based on data from BP (2015). Additional coal production data was obtained from Rutledge (2011). From 2015-2100 we model the production of fossil fuels and nuclear energy using the Hubbert single-cycle technique (Hubbert, 1982). SSAF produced 1 EJ of hydropower in 2014 (BP, 2015), though it was estimated that as of 2002 (0.65 EJ produced) Africa only utilized 4% of technically feasible hydropower potential. We can then estimate the hydroelectric potential of Africa at 16 EJ. This potential is modelled to be reached in 2100. The total energy demand is a function of each the per capita consumption in each scenario and the projected population. From total energy demand, we subtracted the fossil fuel and hydropower production, leaving renewable energy (or import) demand.

We decided to specify a renewable energy mixture into the future using the approach of Jones and Warner (2016), though the specific breakdown of renewable energy by source is not the aim of this study. We use this breakdown only as a means of relating the scale of the issues at hand. In this study we will use the rounded breakdown of SSA: 50% wind, 15% solar, and 35% other renewables (BP, 2015). The average wind turbine in the United States operates at a capacity factor of 0.3 (EIA, 2016a), producing about 47.3 TJ per year. One square kilometre of solar panels produce about 414 TJ per year (Moriarty and Honnery, 2012). Our representative other renewable energy source is algae biofuels. We use biofuels from algae because liquid fuels comprise ~18% of total global energy consumption (Caspeta et al., 2013) and algae biofuel (in a laboratory setting) out produces other sources (Chisti, 2008). One square kilometre of algae production yields approximately 79.3 TJ, per year (Benemann, 2013). Using these yields we were able to assign relative figures to the production needs of the region in each scenario.

Finally, we sought historical analogues to development efforts similar to our development proxy scenarios in SSAF. We looked at energy consumption (BP, 2015) and population data (UN, 2015b) from 1965-2014. Using these data, we sought nations that consumed at or around the 2014 SSAF level and their consumption in 2014. We grouped the countries generally into our three scenarios and evaluated each country's economic and energy history from 1965-2014. Using these evaluations, we determined whether or not there are historical analogues for the current situation in SSAF and made policy recommendations based on the successes and failures of each historical evaluation.

Results and Discussion

Figure 28 illustrates the per capita energy projections in each consumption scenario from 1965-2100. Without adjusting per capita energy consumption in SSAF (scenario 1), the region is on track to increase total energy consumption from 12 EJ in 2014 to 18 EJ by 2030 and 50 EJ by 2100. The second scenario (36 GJ/person by 2030) would require 50 EJ of energy in SSAF in 2030 and 142 EJ by 2100. The third scenario (100 GJ/person) results in a per capita energy consumption of 26 GJ/person in 2030, corresponding to an energy demand of 37 EJ. At 3.93 billion people, the third scenario would require 392 EJ of energy by 2100 (72% of total global energy production in 2014). Table 11 displays per capita energy consumption, energy demand, and 2014 reserves to 2100 consumption ratio for SSAF in 1965, 2014, 2030, 2050, and 2100.

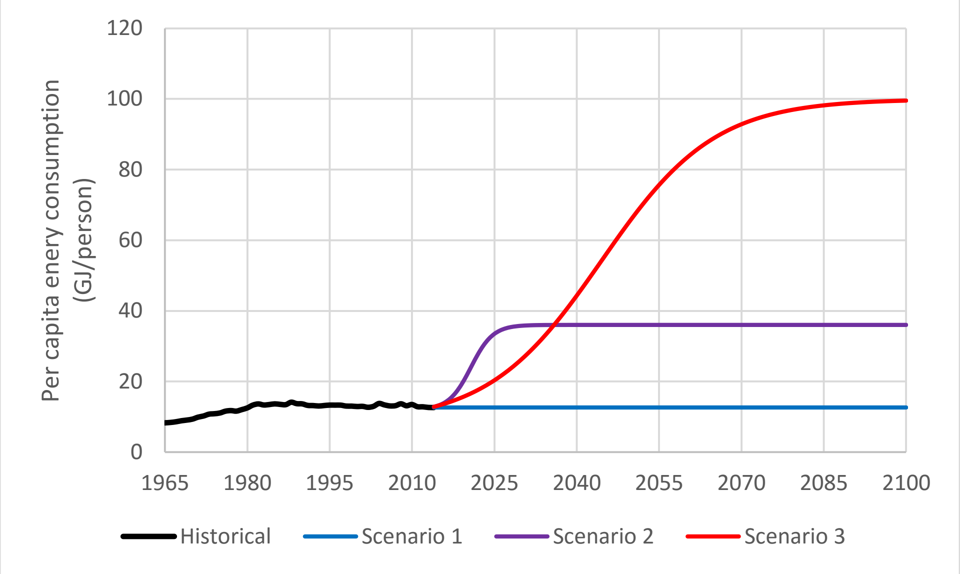


Figure 28: Modelled per capita energy consumption, 1965-2100. Scenario 1 removes increasing energy consumption from the model, resulting in a population only estimate of energy demand. Scenario 2 is based on providing equal energy access to the entire SSAF population by 2030 (SE4ALL). Scenario 3 is based on the global per capita energy consumption in Jones and Warner (2016), our estimated per capita energy consumption required to achieve an HDI of 0.8, and the quality of life indices improvement suggestions in Lambert et al. (2014).

Table 11: Per capita energy consumption & total energy demand, 1965-2100 *selected*. Per capita energy demand in each scenario and year is listed first, in gigajoules per person, followed by total Sub-Saharan Africa energy demand in exajoules. Note the smaller differences at the SE4ALL initiative end-date of 2030 compared to 2100.

	Per capita energy consumption & total energy demand					
Scenario	1965	2014	2030	2050	2075	2100
1	8, 2	13, 12	13, 18	13, 27	13, 39	13, 50
2	8, 2	13, 12	36, 50	36, 76	36, 112	36, 142
3	8, 2	13, 12	26, 37	66, 140	95, 297	100, 392

In 2014 SSAF produced 21 EJ of energy, of which 9.2 is exported. Over 90% of this was fossil based and essentially no power came from non-hydro renewable energy (figure 29). We find that by 2100, fossil fuels will only produce 7.5 EJ (assuming that the region remains an exporter for as long as possible in each scenario). Combined with the hydropower potential (16.3 EJ), the region may produce up to 24 EJ (less than half of the 2100 energy demand in scenario 1). The 21st century estimated energy production by source is illustrated in figure 30. The scale of energy required in order to increase per capita energy consumption by the end of the century highlights the need for a readjustment of either development and aid goals or the population projections in SSAF.

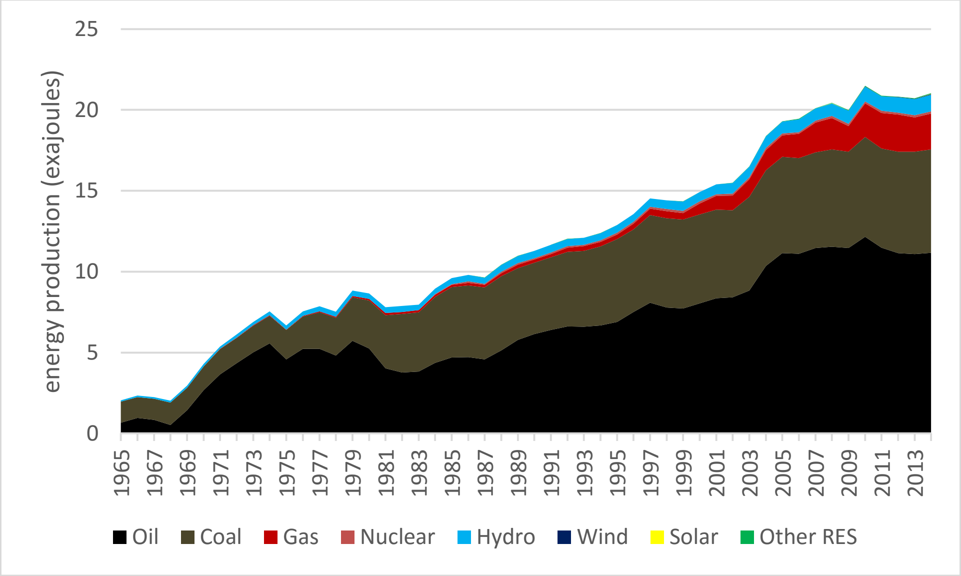


Figure 29: Energy production in Sub-Saharan Africa by source, 1965-2014. Energy production in the region has been historically dominated by fossil fuels. Production from fossil fuels peaked in 2010, though our model suggests that the true fossil fuel peak will occur around 2030-31. Sources - (BP, 2015; Rutledge, 2011).

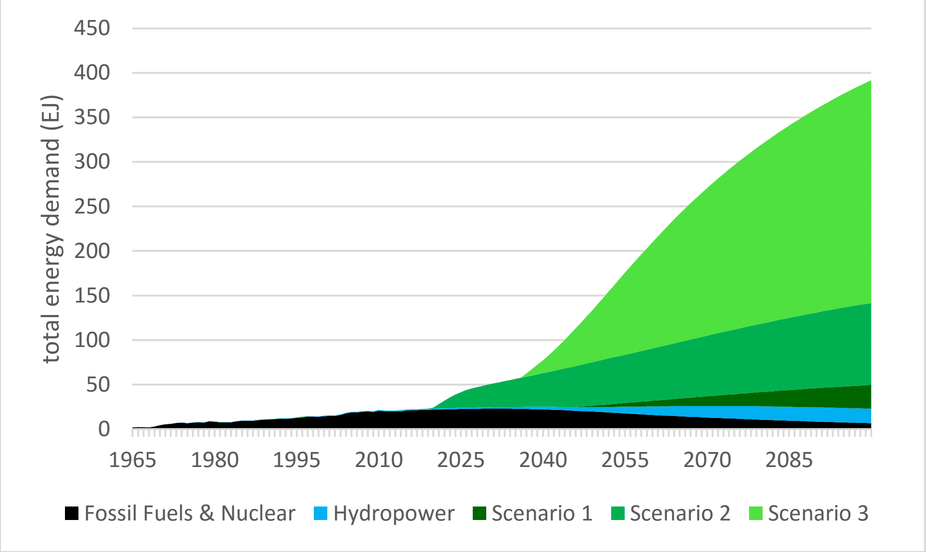


Figure 30: Modelled energy production/consumption by source, 1965-2100. Based on per capita energy consumption scenarios 1-3 (figure 2) and UN medium fertility population projections (UN, 2015b). Scenarios 1-3 represent non-hydropower renewable energy demand within the corresponding scenario.

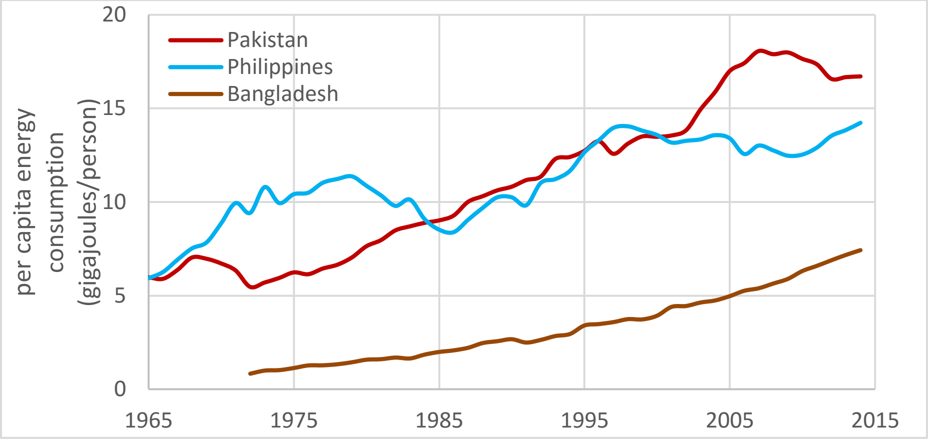
Scaling the renewable/import energy demand into infrastructure requirements vis-à-vis Jones and Warner (2016) results in a 2100 demand equivalent to 284,000 5MW wind turbines, 13,000 square kilometres of photovoltaic solar panels, and 102,000 square kilometres of open-pond algae biofuel production in scenario 1. Scenario 2 requires a large up-front investment from 2015-2030, reaching similar numbers to the 2100 demand in scenario 1 by 2030 and 1.25 million 5MW wind turbines, 57,000 square kilometres of photovoltaic solar panels, and 449,000 square kilometres of open-pond algae biofuel production by 2100. Scenario 3 renewable/import energy demand begins to outpace scenario 2 by 2036 and requires 3.90 million 5MW wind turbines, 178,000 square kilometres of photovoltaic solar panels, and 1.4 million square kilometres of open-pond algae biofuel production by 2100. Table 12 displays the scaled requirements in 2030, 2050, 2075, and 2100.

Table 12: Relative units of renewable energy demand necessary to power Sub-Saharan Africa energy demand, 2014-2100, *selected*. Wind power is listed first, expressed in million 5MW wind turbine equivalents. Solar power is listed second, expressed in thousand square kilometres of solar panel coverage. Algae biofuel production facilities are listed third, expressed in thousand square kilometres of production. Approximate conversions based on findings in (Benemann, 2013; EIA, 2016a; Moriarty and Honnery, 2012). Note that in Scenario 1, the region remains an energy exporter beyond 2030.

		Total Estimated Wind, Solar, Algae Demand			
Scenario		2030	2050	2075	2100
1	Wind Solar Algae	0 0 0	0.02 0.95 7.44	0.14 6.43 50.35	0.28 12.97 101.57
2	Wind Solar Algae	0.27 12.28 96.15	0.54 24.91 195.11	0.91 41.48 324.91	1.25 57.37 449.35
3	Wind Solar Algae	0.13 5.92 46.37	1.22 55.78 436.92	2.86 130.74 1023.97	3.90 178.23 1395.95

Four countries consumed energy around the 2014 Sub-Saharan level (~13 GJ/person) in 1965 and have since increased to consuming near 100 GJ/person (Figure 31a): South Korea (10 to 229), Malaysia (11 to 128), Iran (13 to 136), and China (8-91 GJ/person). Egypt (11-40), Brazil (11-60), Colombia (16-34), and Peru (17-31) each consumed near the 2014 Sub-Saharan level in 1965 and grew consumption to 31-91 GJ/person by 2014 (figure 31b). There were no countries in our analysis that consumed near the 2014 SSAF level in 1965 and remained near that level by 2014, though the Philippines, Pakistan, and Bangladesh (not independent from Pakistan until 1971) each consumed less than 6 GJ/person in 1965 and none consumed more than 17 GJ/person in 2014 (figure 31c).

a



b

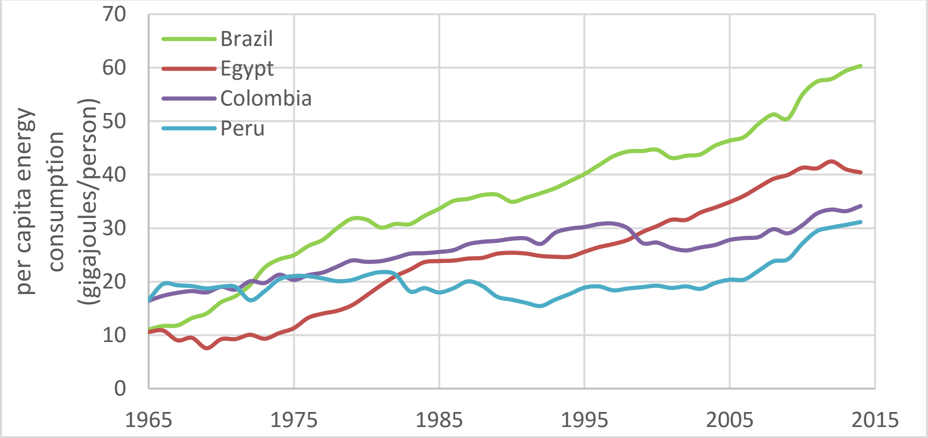


Figure 31: Per capita energy consumption, 1965-2014. Pakistan, Philippines, and Bangladesh (a). These three countries have increased consumption similar to scenario 1. Brazil, Egypt, Colombia, and Peru (b). These four countries have increased consumption similar to scenario 2. South Korea, Iran, Malaysia, and China (c). These four countries have increased consumption similar to scenario 3. Sources - (BP, 2015; UN, 2015b).

c

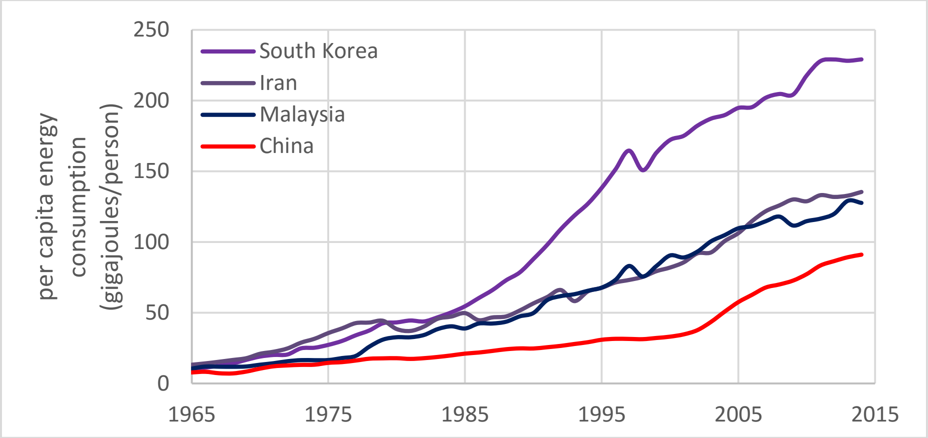


Figure 31: continued

Though currently a net energy exporter, the argument can be made that exporting energy at this point in time is a potentially short-sighted resource management strategy. First, even in scenario 1, SSAF becomes a net energy importer in 2047. This is theoretically the longest that SSAF could be a net exporter (barring extensive fossil fuel discoveries or a decline in per capita consumption). The options available to the region regarding export potential are 1) cease exporting energy and instead use the excess fossil fuel production capacity to build the renewable energy infrastructure that will be necessary for the back half of the century, or 2) make the region's fossil fuel energy available on the world market and use the revenue to develop a renewable energy infrastructure. Implementing either of these options would require a unified plan. SSAF is a regional aggregate of countries, not a united organization with defined strategies and policies. The African Union is an organization comprised of every African nation except

Morocco (Burkina Faso and the Central African Republic are currently suspended). There may be some limited hope for a united effort to combat this and similar global and regional issues in Africa.

We have identified eleven countries that may serve as historical analogues to the scenarios we have developed for SSAF in the 21^{st} century. Of those eleven, eight have increased per capita energy consumption significantly from 1965-2014. We will now briefly examine the nature of the increase in each of the eight countries. We did not examine the remaining three countries because we are not interested in using them as examples for the future trajectory of development and energy consumption in SSAF.

Post Korean War economic growth in South Korea is attributed to foreign investment and aid (Frank et al., 1975). South Korea made the most dramatic growth in per capita energy consumption from 1965-2014. Ko et al. (1998) noted that the economic development success in South Korea has been tightly correlated with per capita energy consumption. Yoo (2005) corroborates this, finding that the economic growth in South Korea was heavily dependent on growth in per capita electricity consumption. While total energy consumption increased 43-fold from 1965-2014, fossil fuel use only increased 38-fold (BP, 2015).

Before the Iranian Revolution in 1979, the economy was growing, as was income inequality (Shahbaz et al., 2015b). From 1965-1979 energy consumption quintupled and per capita energy consumption tripled (BP, 2015; UN, 2015b). Revolution and war, combined with a growing population reversed these trends throughout the 1980s, and since 1990 income inequality has decreased while GDP has increased (Shahbaz et al., 2015b). The exportation of oil and gas is a critical component of the Iranian economy (Kalehsar, 2015). Newly lifted sanctions on Iran will allow the greater access to the world market that Iran will need in order to continue growth and development (Amir-Mokri and Biglari, 2015).

At a GDP growth rate of 6% since 1991, Malaysia has transformed from an agrarian economy to a developing nation on the cusp of reaching high human development status (Tenth Malaysia Plan, 2010). Causality analysis supports the governments claims that the growth in the Malaysian economy has been a result of industrialization, and is thus energy dependent (Ang, 2008). Additionally, the urbanization of Malaysia since 1970 has Granger caused the increase in energy consumption (Shahbaz et al., 2015a). Accounting for 97% of energy consumption in 2014 (BP, 2015), the country is currently fossil fuel dependent. With no appreciable coal reserves and only 62 EJ of oil and gas (BP, 2015), the success in Malaysia has been heavily reliant on imported energy.

China and Brazil are members of the BRICS economies of the nearly developed nations. Also in this group is South Africa, Russia, and India. The growth in the Chinese economy since the 1970s has been shown to be Granger caused by energy use; however, the effect of international trade has been an important component of China’s 9% per year economic growth rate (Shahbaz et al., 2013). Economic growth in China has also come at the cost of environmental health (Zhang, 2010). China’s consumption of coal has doubled since 2003 (BP, 2015). There is evidence that growth in China’s economy and a reduction in carbon intensity may be possible (Zhang and Cheng, 2009). China has increased its HDI from low human development status in (0.501) 1990 to high status (0.727) in 2014 (UNDP, 2015).

In the mid-20th century, several Latin American countries grew their economies on the backs of large international loans, that in turn allowed their economies to exhibit desirable, loan-friendly growth (Devlin and Ffrench-Davis, 1995). In the 1980s, the debt of these countries exceeded the ability to pay and as part of the loan restructuring agreement, the countries had to raise exports and taxes and cut many government funded programs (Feldstein, 1998). Colombia and Peru were involved in this Latin American “lost decade” of the 1980s. Interestingly, Peru has a relatively high HDI (.734) despite low per capita energy consumption (31 GJ/person); this may be due to the large discrepancy in urban and rural electrification as 60% of rural Peru does not have access to electricity (Groh, 2014), compared to a national value of 91% (WB, 2015). Increasing debt remains a primary concern of the economies of several Latin American countries, including Colombia and Brazil (Mendoza and Oviedo, 2009).

Brazil was among the fastest growing economies in the world until the 1980s when the second oil shock and debt restructuring resulted in economic stagnation. The economic growth in Brazil is attributed to price instability, high tariffs and significant government intervention in economic activities; however after stagnation in the 1980s these policies have been replaced with more globally-oriented open market, albeit only moderately successful, approaches (Pinheiro et al., 2004). Despite any policy changes, per capita energy consumption in Brazil has grown steadily at about 1 GJ/person per year while increasing energy consumption 13-fold since 1965 (BP, 2015; UN, 2015b). Additionally, the HDI has increased from medium (0.608) to high human development status since (0.755) 1990 (UNDP, 2015).

Egypt has had mixed success in achieving economic and social development. In addition to engaging in two foreign wars, the Egyptian government enforced state control of banks and limited private credit availability in the early 1970s through the 1980s, suppressing growth (Abu-Bader and Abu-Qarn, 2008). The per capita energy consumption increased remarkably in the 1970s, due to declining real energy prices (Abdel-Khalek, 1988). It was suggested by Choucri and Lahiri (1984) that this meant that changes in the price of oil would require significant adjustments in the economy. The economy moved towards privatization throughout the 1990s and the economy began to grow at a faster rate (Abu-Bader and Abu-Qarn, 2008). After the Arab Spring events of 2011, the current struggle to establish a stable government will require input and support from the international community (Ghanem, 2014).

What might these historical examples tell us about SSA? First and foremost, there do not appear to be any good historical analogues. The magnitude of the problem in SSAF is on a scale incomparable to any of these examples. Raising the 2014 SSAF population to even 36 GJ/person would immediately make the region dependent on energy imports. The population of the region is most similar to that of China; however, China exploited vast quantities of domestic fossil fuel reserves. In addition, there are several other issues surrounding the feasibility of economic and social development in SSAF.

One question of particular note is how climate change will affect the energy export ability of the region. The economy of the region is 20-40% agricultural (Godfray et al., 2010). As a net energy exporter, the region may be selling its precious energy reserves without regard for future need. The problem is that in a world more sensitive to the effect of carbon-intense growth, what market (for exports or domestic use) will be available for fossil fuels in the future? SSAF as a whole faces a dilemma that several other energy producing regions (e.g., the Middle East, North Africa, Russia) face: If the climate agreements around the world are to be achieved, the next decade is the last chance for these countries to cash in on their fossil fuel reserves. Exploitation and exporting of fossil fuels has been an effective means of increasing per capita energy consumption and GDP in Iran. However, the projected expansion of renewable energy infrastructure in the 21st century suggests that non-renewable energy could be better used internally for the transition to renewable energy, either exported for revenue or used in creating the renewable infrastructure.

Both Iran and Malaysia developed using fossil fuel energy. The increase in fossil fuel consumption outpaced total energy consumption in both countries. Fossil fuel use increased 33–fold in Iran and 39–fold in Malaysia from 1965-2014, compared to a 32- and 37-fold increase, respectively, in total energy consumption (BP, 2015). It would not seem desirable to follow the course of actions that resulted in the Latin American Debt

Crisis of the 1980s, so relying on extensive foreign loans is not a viable option for SSA. In each of the example countries discussed above, carbon emissions are associated with (regardless of causality) economic growth. It has been suggested via Granger causality analysis that transitioning to renewable energy does not prevent economic growth (Lotfalipour et al., 2010). Energy consumption and per capita GDP trends indicate that an accelerated transition to renewable energy is in the best interest of Sub-Saharan African countries (Keho, 2016).

There are additional economic concerns in SSAF. Weakening of the global economy and variability in commodity prices have slowed economic growth in SSAF (IMF, 2015). One growing source of foreign investment in SSAF is China. China has taken great interest in the resources of the region, gaining trade consideration with its non-interference policy that does not require consideration of the environment and ignores corruption (Ciochetto, 2014). The investments made by China are mostly focused on supplying oil and other material for the growing infrastructure of an economy that was, until recently, growing at nearly 10% per year (Kaplinsky et al., 2007). Though it should be noted that Foreign Direct Investment is impacted by the price and availability of oil (Mileski, 2000), and with recent changes in availability and our projected peaks (chapters II and III), this investment source may shrink in the near future. China refers to the partnerships with Sub-Saharan African countries as beneficial trade amongst developing nations, sometimes referred to as South-South cooperation (Kaplinsky et al., 2010). Chinese trade is often more favourably looked upon in SSAF, as the benefits are more symbiotic than was the case during European colonization

(Ciochetto, 2014). What is not clear is what impact that trade relationship is having on the long-term sustainable development of China or SSAF (Kaplinsky et al., 2010).

We have assumed that HDI acts as a general indicator of developmental success in the analysis of these countries. This is not to suggest that HDI is either a perfect indicator or the only metric that should be used in sustainable development policy. Though HDI is a useful starting point for measuring development success, Bilbao-Ubillos (2013) suggests that the inclusion of additional parameters such as economic and social inequality would increase the reliability of the HDI. It is important to note that there is evidence that the trend of lowering fertility with increased HDI may reverse at HDI values greater than 0.86 (Harttgen and Vollmer, 2014). Given that the majority of the countries in Sub-Saharan are significantly below this level, we do not consider this an immediate development problem.

Conclusions and Policy Implications

Importing energy is not ideal for any economy. Europe and North America burned their energy reserves in order to fuel the Industrial Revolution, fight two World Wars, and (re)construct some of the most powerful economies in the world. Global production of fossil fuels is not expected to peak until mid-century (Jones and Warner, 2016; Maggio and Cacciola, 2012; Mohr et al., 2015). There is still plenty of energy available, plenty of energy, on the world market (119 EJ of oil were traded in 2014 (BP, 2015)); however, the real challenge today is to translate remaining energy reserves and the energy available on the world market to building a renewable energy infrastructure. Waiting for peak global energy production is not likely to lead to a smooth transition away from those peaking fuels. The carbon pledges and immediacy of climate change should stand as a better motivator for these nations to begin the transition now.

More specifically to the issues affecting SSAF, population growth, poverty, health, emigration, climate change, and food security are each real concerns. Is the low 2014 level of consumption of 13 GJ/person even possible with 4 billion people? We doubt that the projected population will be achieved in SSAF, especially at such a low per capita energy consumption rate. The fossil fuel energy reserves of the region are ample at current population and low consumption levels, though inadequate if either or both figures are to significantly increase. There is a question as to what nuclear energy may produce. Based on historical trends in the region, there will be very limited nuclear power in SSAF. These issues can make it difficult to envision SSAF in the near future.

Sub-Saharan African nations have some of the highest total fertility rates (TFRs) in the world (UN, 2015b). There are several reasons for this. The Sahara Desert shielded SSAF from the spread of fertility beliefs that were not as based on the importance of ancestors and family lineage (Caldwell and Caldwell, 1987). As a route for further research, we have examined the correlation of per capita energy consumption and TFR. Figure 32 illustrates this relationship across 67 countries. Declining fertility rate can be attributed to higher female literacy and increased health care expenditure per capita (Lambert et al., 2014). Education in turn results in delayed fertility (Black et al., 2008), increased use of contraception (Rosenzweig and Schultz, 1989), and overall declines in total fertility rate (Cygan-Rehm and Maeder, 2013). Ideal family size and desired fertility were shown to both decrease as a result of increased education in Malawi, Uganda, and Ethiopia (Behrman, 2015). Sub 1.5 TFRs in Europe (an extreme value for SSAF) correlate with five separate variables, including social and economic incentives to postpone fertility, that suggests that single-generation changes in TFR can have a large effect of age cohort numbers (Kohler et al., 2002).

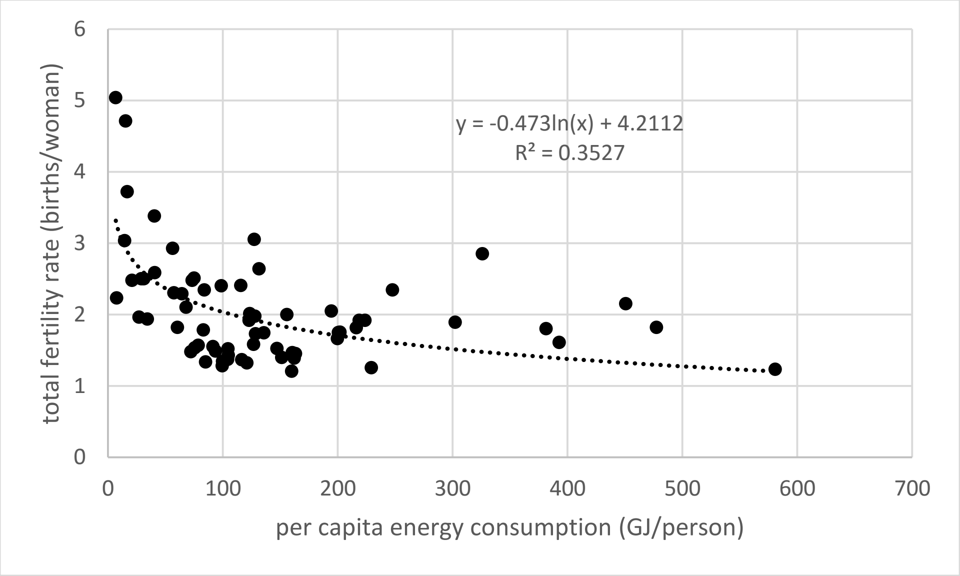


Figure 32: Total fertility rate and per capita energy consumption. Data includes 67 countries. Sources - (BP, 2015; UN, 2015b; WB, 2015)

The IPCC's *Fifth Assessment* Report on global climate change (Pachauri et al., 2014) outlines the climate change issue in SSAF: increased drought risk in already at-risk areas; reduced crop productivity; and adverse effects on food security. The renewable energy sources used in our analysis are all climate-dependent. The effect of climate change on the hydropower potential of SSAF must be incorporated into plans for the next century (Lumbroso et al., 2015). The available potential for wind and solar power in southern Africa is not likely to change significantly out to at least 2050 (Fant et al., 2016). This further reinforces both the need for expansion of these infrastructures and our choice in example renewable energy sources.

The IPCC expects climate change to significantly increase the movement of human populations throughout the 21^{st} century due to such risks as increasing natural disaster events, land-use changes, and ecosystem shifts (Pachauri et al., 2014). Without proper planning, migration can stress local health services and spread infectious diseases (McMichael, 2015). Climate change (specifically warming) in Africa is also linked to increased conflict (Burke et al., 2009). It has been suggested that climate change plays a significant role in the current conflicts around the world, including Syria (Kelley et al., 2015). The immigration "crisis" currently experienced in Europe and elsewhere therefore has a certain climate aspect about it. It is, therefore, not unreasonable to infer that an unexpected consequence of anthropogenic climate change in Africa will be conflict and emigration.

Perhaps the most important issue surrounding true sustainable development is providing food to growing populations (Ko et al., 1998). There are currently 800 million people in the world without proper food availability (FAO, 2015a) and the level of undernourishment in SSAF is 23% (FAO, 2015b). This means that approximately 28% of the world's undernourished population is in this region. Though concerns of food and nutrition have been at the forefront of development goals in SSAF, little interdisciplinary connectivity exists in the relation of water scarcity and food security (Mabhaudhi et al., 2016). SSAF has an abundance of arable land and water resources, making the region attractive for international agricultural investment (Williams, 2015). Climate change has been historically linked to changes in agricultural yield in SSAF, showing positive correlation with increased rainfall (Buhaug et al., 2015). Again the IPCC projections for rainfall in SSAF indicate that some parts of SSAF will experience increased rainfall and others less (Pachauri et al., 2014).

Nobel Laureate Richard Smalley (2005) compiled a list of the top ten most pressing concerns for humanity. Included on his list were population (#10), education (#8), environment (#4), and food (#3). The most important issue that Smalley assigned to the world today was energy. It was his hypothesis that solving the energy issue would result in a significant lessening of all of the other issues. Our study supports the notion that energy availability may be a root solution to many issues in SSAF, highlighting the necessity for that energy to come in the form of climate-friendly renewable energy. Investment from the developed world could prove a worthwhile investment in both alleviating projected population growth (and thus aid in the future) as well as moving the global energy infrastructure towards renewable energy, and thus sustainability.

In conclusion, we have two primary recommendations: 1) per capita energy consumption in SSAF should be grown via renewable energy infrastructure and 2) SSAF takes immediate action to prevent the population growth projected by the UN (2015b). In the first recommendation, we agree with the late Dr. Smalley's conclusion that energy is the means to easing the other issues facing the world today. We expand on that conclusion to add that the world will require a bulk-renewable energy infrastructure by the end of the century (Jones and Warner, 2016; Warner and Jones, in review). SSAF is currently a net energy exporting region; however, as we have shown here, that energy surplus is a result of extremely low consumption.

Throughout this study we have cited other work that find energy consumption is strongly associated with both economic and social development. It is critical that, either as a unified region or as individual nations, policies are enacted and followed through that begin planning for avoiding catastrophic energy poverty in SSAF beyond 2050. We have suggested that the excess production capacity could be utilised along two paths towards a renewable energy region. First, the countries in SSAF could continue to be net energy exporters for as long as possible (particularly in selling excess uranium reserves to Europe and China) and use the revenue to invest in the renewable energy infrastructure of the region. Second, SSAF could continue to use fossil fuels in-region as a bridge, while diverting the excess capacity as the energy required to produce the physical renewable energy infrastructure. Further research is needed to examine the economic and energy cost-benefit of these two renewable energy paths.

One example of economic challenges to rapid development is the investment and emergence of viable markets. The majority of the population of Sub-Saharan Africa is a part of the 'bottom of the pyramid' section of the global population that earns less than 2

USD per day. Though these individuals are often considered a poor market investment for corporations, there is potential for investment in these areas to alleviate poverty (Karnani, 2007). Alleviating poverty is one goal of investment in these areas; however it is important that the investment in these markets cooperatively ties into larger markets and preserves the identity of the community (Ansari et al., 2012). One promising trend in the challenge of large-scale development is the notion that the Environmental Kuznets Curve is not as relevant as it once was, suggesting that development does not necessarily result in environmental degradation (Stern, 2004).

We concluded that the scale of the problem in SSAF prevents us from utilising an historical analogue. China is the closest we can come to an historical analogue. Unfortunately, China produced as much coal energy over the last fifty years as SSAF has in total non-renewable energy reserves today. The root of the scale issue is the current and projected population of the region. China's population has not quite doubled since 1965, whereas the population in SSAF is projected to more than quadruple by 2100. Our second recommendation is that the region finds a way to reduce fertility rates sufficiently to 'bend' the population projections down to a more manageable figure. As we showed in figure 6, increasing per capita energy consumption may be a means to lower total fertility rates in contrast to the projected fertility rates in the UN projections. Thus, success in recommendation 1 could lead to success in recommendation 2. Neither of our recommendations is particularly novel, though we have quantified the scale of both concerns using a different approach. More specific quantitative studies on the details of our recommendations are needed.

CHAPTER VI

THE 21ST CENTURY COAL QUESTION: THE UNITED STATES, RUSSIA, THE EUROPEAN UNION, AND THE TRANSITION FROM COAL TO RENEWABLE ENERGY

Introduction

The role of energy in climate change has been a major focus of the work in this dissertation. The next two chapters focus on the climate change contribution of fossil fuel energy production, particularly coal. In 1865, WS Jevons published The Coal Question: An Inquiry Concerning the Progress of the Nation, and the Probable Exhaustion of Our Coal Mines (Jevons, 1865). The coal question in his work related to the possibility that the United Kingdom might someday run out of coal to fuel the ongoing Industrial Revolution. Though coal is a non-renewable and finite resource, the modern coal question may better be focused on the climate change implications of combusting fossil fuels. Coal is the most carbon intensive globally-utilised fuel. Based on the standard global average conversion factors, carbon dioxide emissions from coal combustion are estimated 3.96 tonnes/TOE for coal, compared to 3.07 tonnes per tonne of oil equivalent (TOE) for oil and 2.35 tonnes/TOE for natural gas (BP, 2015).

In the 21st century, as more and more detailed understanding of these emissions develop, serious concerns continue to arise (Andres et al., 2012). From 1870-2010, 1,890 GtCO2 were emitted globally (Pachauri et al., 2014). Another 140 GtCO2 were emitted from 2011-2014 (BP, 2015). The Intergovernmental Panel on Climate Change (IPCC) warns that catastrophic climate change impacts are likely if these emissions surpass 2,900 GtCO2. (Randalls, 2010). The December 2015 UN climate summit in Paris (COP21) was a major step towards binding agreements to limit global climate change to 1.5-2.0°C by limiting the use of fossil fuels. Prior to the summit, every nation submitted an intended nationally determined contribution (INDC) stating the goals of the country for reducing greenhouse gas emissions. However, the majority of INDCs only cover the time period of 2015-2030. Because we are interested in the entirety of the 21st century, we use an energy production plan in this chapter that is based on the declaration made by the leaders of the G7 countries (five of the seven countries are examined in this study) to transform the energy sector by 2050 and to decarbonise the global economy throughout the century (G7, 2015).

Yet, the most powerful nations and economies in the world have been built on cheap fossil fuel energy (Wrigley, 2013) and it is important to examine the transitions of these nations as they move from fossil fuels to renewable energy. The threat of global climate change and the population growth expected around the world will require the development of careful energy strategies and policies. We have chosen two areas of focus for the 21st century coal question: this chapter examines the developed countries that industrialized in the 18th, 19th, and early 20th centuries, the United States, the Russian Federation, and the European Union. The next chapter examines the two largest developing countries in the world, China and India.

The Industrial Revolution began in England, eventually spreading to Europe and North America by the turn of the 20th century (Voigtlander and Voth, 2006). These countries fuelled their industrial revolutions with the coal that was deposited when these countries were part of Pangaea during the Carboniferous and Permian periods (359-252 million years ago) (Ziegler et al., 2003). It is estimated that from 1820-2000, 110 billion tons of coal were extracted from the European continent (not including the Former Soviet Union) (Rutledge, 2011), emitting approximately 220 gigatonnes (1.89×10^{15} kilograms) of carbon dioxide equivalent ($GtCO_2$) into the atmosphere. The same analysis yields 120 and 48 GtCO2 emitted from coal in the United States and the Russian Federation/Former Soviet Union, respectively. As of year-end 2014, the United States and Russia combine to hold 43% of global proven coal reserves (BP, 2015). Based on the estimated carbon emissions of coal from BP (2015), these reserves have the potential to emit 806 gigatonnes of carbon dioxide equivalent ($GtCO_2$).

Per capita energy consumption is well above the global average (76 GJ/person in 2014) in the United States (302 GJ/person), Russia (200 GJ/person), and the European Union (134 GJ/person) (BP, 2015; UN, 2015b). Fossil fuel reserves are abundant in the United States and in Russia; however, the European Union is not an energy-rich set of countries (BP, 2015). Estimates of energy reserves can be found in table 13. Renewable energy is used to different extents in these countries, with the 28 European Union countries generating 13 percent of total energy consumption from renewable energy, Russia generating six percent, and the United States generating five percent (BP, 2015). Table 14 displays each country/region's 2014 energy consumption by source.

Table 13: Estimated year-end 2014 reserves of non-renewable energy resources (exajoules) used in this study. Data from BP (2015); WNA (2013). Units converted to exajoules (EJ) using approximate conversion factors in BP (2015). Uranium reserves from 2013 adjusted to 2014 using domestic production values from BP (2015). All values rounded to the nearest exajoule.

	Oil	**Coal**	**Natural Gas**	**Uranium***	**Total**
United States	247	4,842	369	65	*5,523*
European Union	33	854	56	12	*955*
Russian Federation	594	2,885	1,234	177	*4,890*

Table 14: Energy consumption (exajoules) by source, 2014. Includes total energy production, consumption, and energy balance. Negative values indicate net energy importation. All values rounded to the nearest exajoule. Data from BP (2015).

	United States	**European Union**	**Russian Federation**
Oil	22	3	22
Coal	21	6	7
Natural Gas	28	5	22
Nuclear	8	8	2
Hydropower	3	4	2
Wind	2	2	0
Solar	0	1	0
Other RES	1	2	0
Total Production	*85*	*31*	*55*
Total Consumption	*97*	*68*	*29*
Energy Balance	**–12**	**–37**	**26**

The United States consumed 97 exajoules (EJ, 10^{18} J) of energy in 2014 (BP, 2015). The United States is the third most populated country in the world behind China and India: the 2014 population of 319 million people is projected to increase to 450 million by 2100 (UN, 2015b). The 2014 average per capita energy consumption was 302 gigajoules (GJ). In addition to being the third most populated country, the United States is one of the largest per capita energy consumers in the world (BP, 2015; UN, 2015b). The year-end 2014 proven fossil fuel reserves total 5,458 EJ (BP, 2015) and uranium reserves total 65 EJ (OECD and IAEA, 2014). At the 2014 energy consumption rate, these non-renewable reserves would sustain the country for 57 years. As it were, the United States was a net energy importer of energy (12 EJ) in 2014.

The European Union is comprised of 28 countries. The population of the European Union was 505 million in 2014 and is projected to peak at 509 million in 2028 and decline to 463 million people in 2100 (UN, 2015b). Among European Union nations with a population greater than one million, the highest consumer was Sweden and the lowest was Romania (BP, 2015; UN, 2015b). The European Union countries were an overall net importer of 37 EJ of energy and carbon emissions (2.6 $GTCO_2$) (BP, 2015). The EU appears to have peaked in total energy production at 42 EJ in 1986. Remaining fossil fuel reserves in the European Union total 942 EJ (BP, 2015). European Union reserves of uranium total 12 EJ (OECD and IAEA, 2014); however, nuclear energy comprises 12% of total energy consumption. At the 2014 energy consumption rate, these non-renewable reserves would sustain the European Union for only 14 years.

Russia consumed 29 EJ in 2014 (BP, 2015).The 2014 population of 143 million is expected to decline to 118 million by 2100 (UN, 2015). Average per capita energy consumption was 200 GJ/person. The year-end 2014 proven fossil fuel reserves total 4,713 EJ (BP, 2015) and uranium reserves total 177 EJ (OECD and IAEA, 2014). At the 2014 energy consumption rate, these non-renewable reserves would sustain the country for 171 years. Russia was a net exporter of 26 EJ of energy in 2014 (BP, 2015). Russia is in a unique position in that the Former Soviet Republics have been projected to be in a position of strength in the international energy market throughout the 21st century (Warner and Jones, in review).

The developed nations of the world have three main options concerning the future of global coal exploitation: 1 – Use the coal for domestic purposes, delaying/reducing the need to incorporate renewable energy options and exporting whatever remains; 2 – Incorporate renewable energy technologies and use coal as a bridge fuel and then export the remaining coal to less-developed nations; 3 – Take the lead in climate change action and leave as much of the coal as possible in the ground, sparing the atmosphere as much carbon dioxide as possible. We will investigate several potential avenues that these countries could employ in the world after the COP21 climate summit in Paris.

Data and Methods

There will be six scenarios in our study. Each of these scenarios is based on energy production. Table 15 describes each model scenario. We aim to determining the energy demand that cannot be satisfied with domestic non-renewable energy reserves, and must therefore be derived from either imported energy or domestic renewable energy production. Per capita energy production in all six scenarios is set at the 2014 level and will not vary throughout the remainder of the century. The first of these scenarios (US1, EU1, RF1) assume a business-as-usual approach where non-renewable energy in the

United States, Russia, and the European Union are modelled in a traditional manner, without regard to carbon emissions.

Table 15: Description of the six scenarios used in this study. Standard Hubbert NRES model use implies growth peak and decline of non-renewable energy sources according to geologic constraints, modelled via Hubbert (1982). G7 NRES model use indicates that each non-renewable energy resource was forced to peak in 2050 and each non-renewable energy resource was forced to less than one exajoule of production by 2100.

Scenario	NRES Model
US1	Standard Hubbert Model
US2	G7 Model
EU1	Standard Hubbert Model
EU2	G7 Model
RF1	Standard Hubbert Model
RF2	G7 Model

The second set of scenarios (US2, EU2, RF2) models an optimistic energy production plan for the remainder of the century. This energy production plan will be referred to as the G7 plan. Fossil fuel use will mirror that of the first set of scenarios until 2050. We assume that the G7 commitment to decarbonise the global economy throughout the century implies that there will be no fossil fuels used from the 22nd century on. Beginning in 2050, oil, coal, and natural gas production is Hubbert modelled to phase out fossil fuel production by 2100.

The United States is the second largest consumer of energy in the world, behind China (BP, 2015) and per capita energy consumption is among the highest in the world. The shale revolution (Manescu and Nuno, 2015) and recently lifting its ban on the export of petroleum to the global market (Snow, 2015) has bolstered the nation's position in the global energy market. As a result, the United States is importing much less energy from the Middle East, eroding Russia's market control over the European Union (Kim and Blank, 2015). Recently, Jacobson et al. (2015) presented plans for all 50 states to achieve 100% renewable energy production by the year 2050.

The Russian Federation was the #2 oil, #2 natural gas, and #6 coal producer in the world in 2014 (BP, 2015). As US unconventional oil and gas production threaten Russia's supremacy in the western oil and gas trade, Russia is increasingly looking to export to northeast Asia (Shadrina, 2014). The Russian Federation has billed its conventional production methods as more reliable, stable, and environmentally-friendly than unconventional producers such as the United States (Ocelik and Osicka, 2014). The decline in Soviet oil production in the late 1980s has been suggested as contributing to the ultimate dissolution of the Soviet Union (Reynolds and Kolodziej, 2008). From 1988-1997, per capita energy consumption in the Russian Federation declined 32% (from 252 GJ/person to 171 GJ/person) before beginning to recover to 79% of the Soviet-era peak by 2014 (BP, 2015; UN, 2015b).

The economies of the European Union are dependent on Russian energy imports, complicating the efficacy of the sanctions resulting from Russia's annexation of the

Crimea from Ukraine (Tsakiris, 2015). Though the European Union is among the world leaders in renewable energy implementation, that implementation is far from ubiquitous (Parobek et al., 2016). Per capita energy consumption in the European Union peaked at 149 GJ/person in 1989 and consumed 134 GJ/person in 2014. The region has consumed between 130-150 GJ/person since 1973.

Though there are many net energy exporting nations in the world today, it is projected that most of these countries will become net energy importers after 2050 (Warner and Jones, in review). As previously stated, the EU has long been a net energy importer. Over 50% of total energy consumed in the 28 countries is imported. Russia is both a net energy exporter and a lower overall consumer of energy than both the United States and the European Union (though per capita energy consumption is higher in Russia than in the EU as a whole).

Each scenario is built from a base model for each country. The modelling technique is the same as in Jones and Warner (2016) and Warner and Jones (in review). The base model is built using energy production and consumption values from various sources (ASPO, 2006; BP, 2015; Laherrère, 2004; OECD and IAEA, 2014; Rutledge, 2011). Historical and projected population for each country is added from UN (2015b) in order to determine per capita energy consumption. We project oil, coal, natural gas, and nuclear energy using the single-cycle Hubbert logistic curve (Hubbert, 1982). These figures only represent energy from domestic reserves and do not account for imported energy. The IPCC estimates that the global total hydropower potential is 52.5 EJ (Seyboth et al., 2011). This estimate is further broken down to world region hydropower potential estimates. We allocated the United States and the Russian Federation with a portion of the regional estimate based on the 2014 percentage of hydropower produced within the IPCC region. The European Union was assigned the hydropower potential of continental Europe. Each hydropower potential was modelled to be reached in the year 2100.

We multiplied the per capita energy trend in each scenario by the UN (2015b) medium fertility population projection to determine total yearly energy demand throughout the remainder of the 21st century. From the total demand figure, we subtracted non-renewable plus hydropower production (NRES+H) for each year. The remainder in each country/region is either the export potential (positive value) or the import/renewable energy requirement (negative value).

Results and Discussion

The results of the standard energy modelling indicate that fossil fuel production peaks in 2014 in the United States (figure 33) and declines to 42% of the 2014 production by 2100. This is due to the imminent peaks in oil and natural gas production based on the reserve estimates in BP (2015). The reserve estimates require the reserve to be economically viable at the time that the estimate is made. According to the EIA, oil production in the United States has been in decline since May 2015 (EIA, 2016b) and natural gas production has plateaued since the highest monthly production March 2015

(EIA, 2016c). Coal peaks at 1.6 times the 2014 production value in 2071. Total non-renewable energy production in 2100 is projected at 30 EJ. Hydropower contributes another 5 EJ, resulting in a total of 35 EJ of non-renewable plus hydropower production (NRES+H) in 2100.

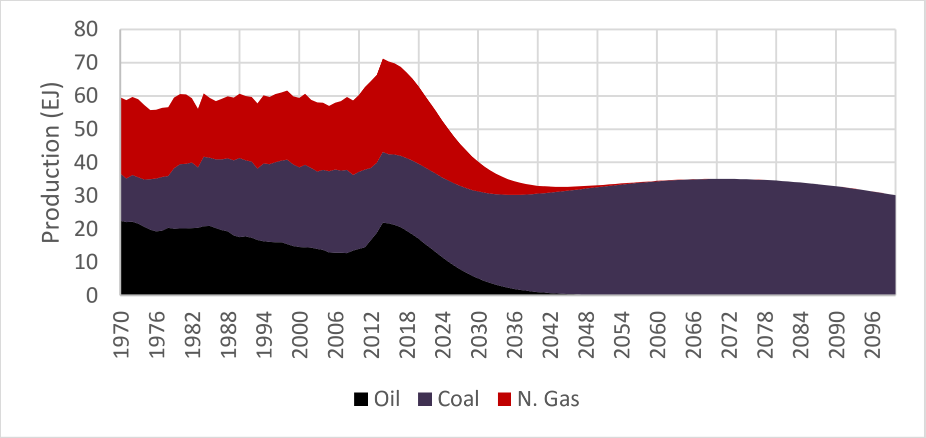


Figure 33: Standard Hubbert fossil fuel energy modelling results, 1970-2100. United States.

Fossil fuel production peaked in the European Union in 1983 (figure 34) and declines to 32% of the 2014 production by 2100. Oil production peaked in 1999 and natural gas peaked in 2001. The decline in coal production from the 1980s peak is slowed in the model, allowing the remaining reserves to be used. Total non-renewable energy production in 2100 is projected at 4.5 EJ. Hydropower contributes another 3.7 EJ, resulting in a total of 8.2 EJ of NRES+H in 2100.

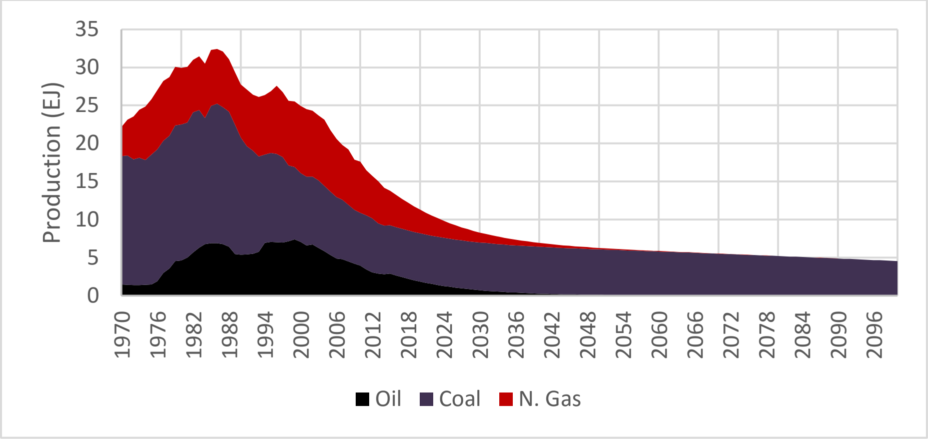


Figure 34: Standard Hubbert fossil fuel energy modelling results, 1970-2100. European Union.

Fossil fuel production peaks in 2016 in the Russian Federation (figure 35) and declines to 50% of the 2014 production by 2100. Oil and natural gas production declines slowly throughout the model and coal continues to rise until peaking at 3.1 times the 2014 production value in 2102. Total non-renewable energy production in 2100 is projected at 26 EJ. Hydropower contributes another 3 EJ, resulting in a total of 29 EJ of NRES+H in 2100.

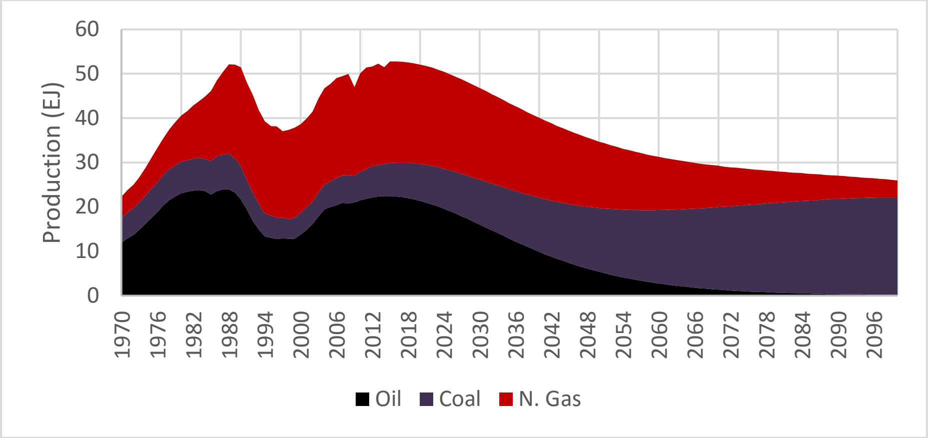


Figure 35: Standard Hubbert fossil fuel energy modelling results, 1970-2100. Russian Federation.

The G7 plan fossil fuel production models are shown in figure 24. In each case, the production models are not altered from the standard model until the year 2050. Oil and natural gas projections do not change in either the United States (figure 36) or the European Union (figure 37). Coal is the only energy source that is altered. Total fossil fuel carbon emissions in the United States is 289 $GtCO_2$ without climate restriction and 165 $GtCO_2$ in the climate-limited model (43% decrease). The European Union produces 52 $GtCO_2$ in the standard model and 37 $GtCO_2$ in the climate-limited model (29% decrease). In the Russian Federation, coal and natural gas are altered from the standard model (figure 38). Total fossil fuel carbon emissions in the Russian Federation is 234 $GtCO_2$ without climate restriction and 152 $GtCO_2$ in the climate-limited model (35% decrease). In both the standard energy model and the G7 energy model conventional nuclear energy is projected to continue to generate energy but be phased out in the United States by 2050, 2017 in the European Union without imported uranium, and remains a low-energy producer throughout the century in the Russian Federation.

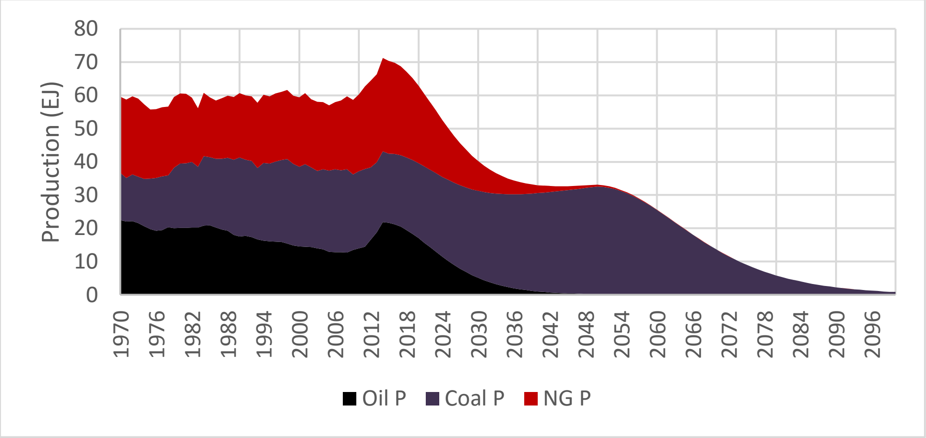


Figure 36: G7 fossil fuel energy modelling results, 1970-2100. United States.

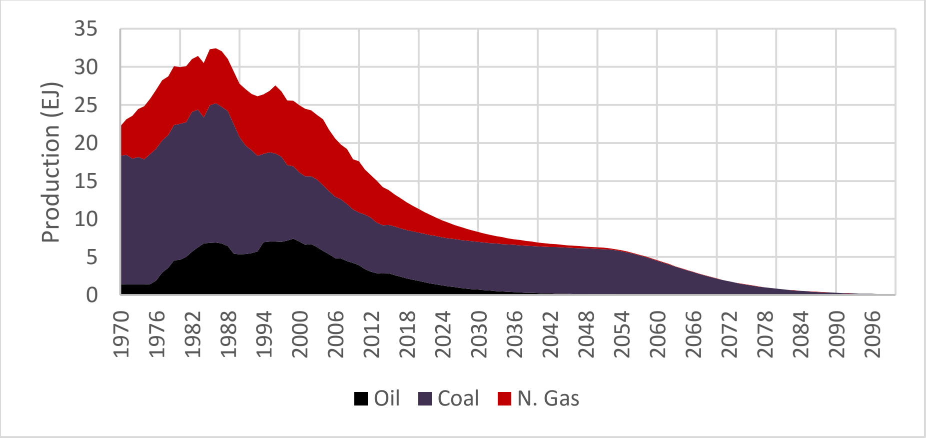


Figure 37: G7 fossil fuel energy modelling results, 1970-2100. European Union.

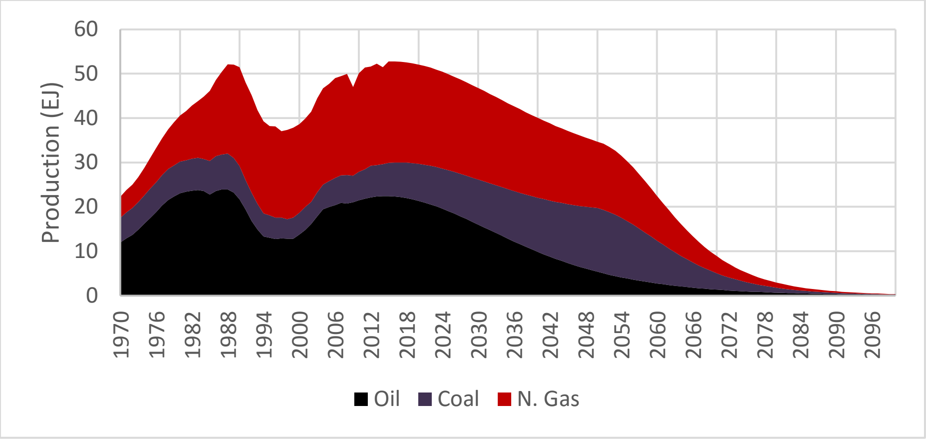


Figure 38: G7 fossil fuel energy modelling results, 1970-2100. Russian Federation.

The standard energy production model results in a global total of 2,605 $GtCO_2$ emissions from 1870-2100 (figure 39). This leaves only 295 $GtCO_2$ to be emitted by the 87% of the 2014 global population not examined in this paper. The climate-limited model reduces that figure to 2,408 $GtCO_2$. The saved carbon emissions are due to the capped coal production in the United States and in Russia.

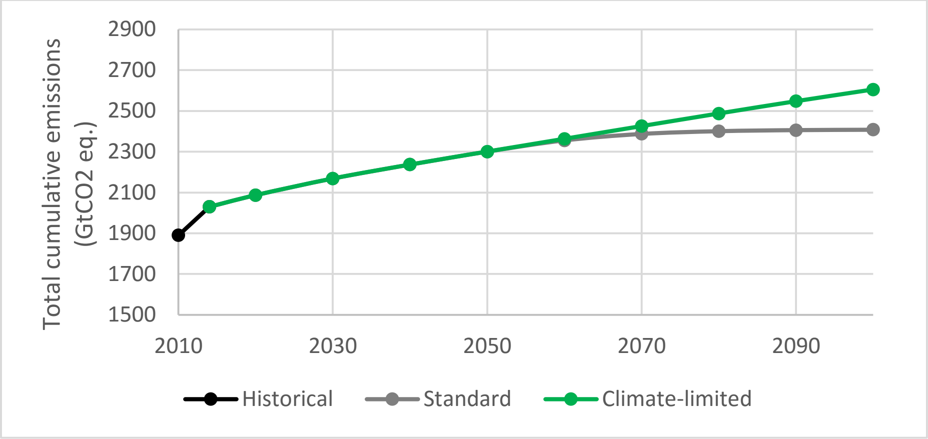


Figure 39: Total cumulative global carbon emissions, 2010-2100. This figure includes only the modelled contribution of the United States, the European Union, and the Russian Federation. Limiting global warming to less than 2°C above preindustrial levels requires the total emissions to remain below 2,900 gigatonnes of carbon dioxide equivalent. Our climate-limited energy production scenarios result in an extra 197 $GtCO_2$ of emissions allowed throughout the rest of the world.

In December 2015, the Paris Accords were unanimously agreed to by all 195 UN countries, promising efforts to reduce greenhouse gas emissions and to keep global warming <2°C above preindustrial levels (UNFCCC, 2015). Climate deals are dependent on both the producers of carbon intensive fuels and the consumers of this energy. Given the global distribution of fossil fuels, climate change mitigation must include the cooperation of the former Soviet republics, the Middle East and North Africa, China, and India (Warner and Jones, in review) . Due to extensive fossil fuel reserves, the Russian Federation has been historically slow to develop renewable energy infrastructure, though Russia's energy strategy 2030 has shown promise for the development of renewable energy (Pristupa and Mol, 2015).

Nuclear energy is often proposed as a bridge fuel to a renewable energy infrastructure. There are concerns over the long-term viability of uranium reserves and nuclear energy production (Dittmar, 2012). The uranium reserves used in this model are those considered reasonably assured (<$130 USD/tonne). The reserves in this study also do not include those currently in the form of nuclear weapons (see Grape et al., 2014). There are uranium reserves in countries around the world that do not have nuclear power production. This includes major uranium exporters such as Australia and several countries in Sub-Saharan Africa. There are nine countries in the European Union that receive at least 10% of total energy consumption from nuclear energy, and the region as a whole consumes 12.3% nuclear energy (BP, 2015). Competition for global uranium reserves figures to intensify, as the majority of China's growing demand for uranium is expected to come from foreign sources as the country plans a large scale-up of nuclear power production by mid-century (Zhang, 2015).

"It is true that where fuel is cheap it is wasted, and where it is dear it is economised"(Jevons, 1865). Energy efficiency is another proposed "fuel" to mitigate carbon emissions. Jevon's Paradox suggests that increased efficiency leads to increased consumption. For example, though the carbon intensity of the United States decreased from 1963-1997, the overall carbon emissions increased (Clement, 2011). We do not subscribe to either the likelihood, or the efficacy of increased energy efficiency toward mitigating climate change.

Population and per capita energy consumption determine overall energy demand. In our study we used the UN (2015b) medium fertility population projections. Total fertility rate in the United States (1.89), all European Union countries (1.28-2.01), and Russia (1.66) were below replacement (2.10) in 2014 (UN, 2015b). Despite below-replacement fertility, the population in the United States and the European Union is projected to grow via immigration (UN, 2015b). The declining population works in the favour of Russia within the confines of the model; however, there are other concerns associated with a nation that reproduces below replacement, including demographic marginalization, age structure shifts, and a reliance on immigration to subsidize otherwise declining citizenry (Demeny, 2015). These issues suggest an increase in the likelihood of economic stress from a declining workforce, shifting of voting trends towards increasingly senior-age interests, and the diversion of public funds to retirement benefit policies (Demeny, 2015).

Conclusions and Policy Implications

In all, coal accounted for 20% of energy consumption in the combined United States, 17% in the European Union, 12% in the Russian Federation, yet 30% of total global energy consumption in 2014 (BP, 2015). Overall, the impacts of resource scarcity issues are not limited to national or regional policies. We examined coal production and per capita energy consumption among the most influential countries (China and India are examined in the next chapter) in global energy policy. These countries industrialized throughout the

18th, 19th, and 20th centuries and stand poised to determine the course of energy policy and climate change in the 21st.

The current lifestyle of the developed nations are often seen as the end goal for less developed nations (Wolfram et al., 2012). Sustainability and global equality are not achievable by simply raising the underdeveloped countries to the level of developed economies; rather, the highest consuming countries must reduce their impact as well (Daily and Ehrlich, 1996). As it stands, the lifespan of current fossil fuel infrastructure would impact the climate for upwards of 40 years even without adding new power plants or internal combustion engine vehicles (Davis et al., 2010). Both decarbonisation and a transition to a renewable energy infrastructure do not necessarily impede economic or social development (Lotfalipour et al., 2010; Schandl et al., in press).

The coal question of the 21st century is not one of geologic supply, but of atmospheric capacity. European countries have small coal reserves and major producers peaked in the 20th century (Höök et al., 2010). American coal production could peak as soon as 2030 (Höök and Aleklett, 2009), though coal reserves may actually be overestimated in the United States (Reaver and Khare, 2014). In order to limit global warming to 2°C above preindustrial levels, over 80% of coal reserves must remain unburned (Jones and Warner, 2016; McGlade and Ekins, 2015). As anthropogenic forcings continue to significantly influence the global climate, policymakers have a responsibility to take the actions necessary to protect the world for current and future generations (Hansen et al., 2013). As such, we recommend that, at the least, nations such as the United States, the Russian

Federation, and those in the European Union take the lead in reducing the emissions of greenhouse gases, starting with the transition away from coal as soon as possible.

CHAPTER VII

THE 21ST CENTURY COAL QUESTION: DEVELOPING ECONOMIES AND CLIMATE CONCERNS IN CHINA AND INDIA

Introduction

This is the second chapter of the dissertation that reintroduces WS Jevons' coal question to the 21st century. The previous chapter examined the transition to renewable energy and climate change concerns in the United States, the European Union, and the Russian Federation. Those countries were the first to industrialize (Voigtlander and Voth, 2006) and are in a favourable position to transition away from coal. This chapter focuses on China and India, the two most populated and fastest developing countries in the world. In 2014, the two nations' 2.69 billion population represented 37% of the world total (UN, 2015b), they consumed 152 exajoules (EJ) of energy, or 28% of the world's total consumption (BP, 2015), and they emitted 12 gigatonnes of CO_2 equivalent, or 34% of global emissions (BP, 2015). It is clear that any discussion of global sustainability must include an analysis of these two nations. This paper is an evaluation of the world's two most populous nations' potential role in 21st century energy demand. Our approach is similar to that of Jones and Warner (2016), scaled now to a national-level.

Our primary interest is in the per capita energy consumption of these large populations. In 2014, per capita energy consumption was 92 gigajoules (GJ) per person in China and 21 GJ/person in India. The 2014 world average consumption was 76 GJ/person. In the previous chapter, the coal question was examined in terms of climate change. We also evaluate carbon emissions resulting from their energy production and consumption. We remain interested in the carbon dioxide emissions related to energy demand; however, not necessarily those limited to the 2015 Paris climate accords and the associated individual intended nationally determined contributions (INDCs), or the 2015 G7 leaders' declaration.

China is both the most populous and the most carbon emitting country in the world (BP, 2015; UN, 2015b). India is primed to overtake China's population by 2022 (UN, 2015b) to 2030 (Gerland et al., 2014). Both China and India are members of the Group of Twenty (G20) major economies forum. These twenty nations represent the largest economies in the world and account for roughly 90% of global GDP and 80% of global trade (OECD, 2016). The countries are also members of the BRICS nations (Brazil, Russia, India, China, and South Africa). These nations are characterized by large populations, relatively rich resource reserves, and development toward becoming more influential in world economic affairs (Wilson, 2015). Inclusion in both of these groups indicates that the two nations are among the closest to achieving developed economy status.

Energy security is a global concern. According to BP (2015), China became a net energy importer in 1992 and India has been a net importer since before 1970. China produced 105 EJ (82% of energy consumption) in 2014 and India produced 15 EJ (57%). In 2014, Chinese energy consumption was fuelled by 89% fossil fuels, 1% nuclear, and

10% renewable energy (BP, 2015). India’s consumption was 92% fossil fuels, 1% nuclear, and 7% renewable energy (BP, 2015). The two most competitive sources of (relatively) carbon-free energy are nuclear and hydropower. Combined, these sources provide 11% of total global energy consumption, 9% in China, and 6% in India (BP, 2015).

The following statistics are sourced from the *2015 BP Statistical Review of World Energy* (BP, 2015). The proven reserves of fossil fuels in China total 3440 EJ (3203 EJ of which is coal). The reserves-to-production ratio (R/P) of oil is 12 years, 30 years for coal, and 26 years for natural gas. Proven fossil fuel reserves in India are estimated at 1721 EJ. Coal reserves are estimated at 1634 EJ. The R/P of oil is 18 years, 94 years for coal, and 45 years for natural gas. At current energy consumption rates, making no allowance for population growth, these reserves would last China 28 years and India 64 years. The problem with R/P estimates is that they do not alter the rate at which the reserve is drawn down, such that when the reserve runs out, production declines instantly from the current value to zero. The logistic decay curve depicts a more realistic slowdown of production as the reserve is produced.

Independently derived estimates published by the German Federal Institute for Geosciences and Natural Resources (BGR) in 2014 are similar to the BP reserve estimates (BGR, 2014). The 2013 BGR estimates are 3482 EJ of coal in China and 2360 EJ in India. Global fuel source reserves were estimated at 37,646 EJ in 2013 (BP estimated 36,969 for 2014). The BGR also publishes estimates of total resources. These estimates include speculative and potential sources of energy fuels not yet technically or economically exploitable, a maximum estimate that is much larger than the proven reserve estimates reported by BP. These estimates multiply the available coal for China by a factor of 44, and India by 2.3. The coal ultimate recoverable resource (URR) estimates from each of the three data sources are displayed in table 16. Proven reserves are those that are confirmed to exist and have a 90% chance of being exploited (abbreviated as 1P). Probable reserves are those that have at least a 50% likelihood of production (abbreviated as 2P). Possible reserves are the remainder of the resource estimate that may or may not exist (abbreviated as 3P). These reserves are assigned a 10% chance of being exploited.

Table 16: Ultimate recoverable resource (URR) estimates for China and India by reserve estimate. Reserve estimates sourced from (BGR, 2014; BP, 2015). URRs calculated using historical production per (BP, 2015; Rutledge, 2011).

Reserve Source	China Coal URR (EJ)	India Coal URR (EJ)
BP 2015	4,699	1,894
BGR 2014	4,978	2,621
BGR 2014 Resource	155,703	5,698

Coal is the primary energy source for both of the focus nations. China derives 66% of its total energy consumption from coal and India, 57% (BP, 2015). In 2014, 260 tonnes of coal were mined around the world every second (BP, 2015). Coal production has increased six-fold in China since 1981 and 2014 was the first year during which coal production did not grow (-2.6%) from the previous year (BP, 2015). China was the number one coal producer in the world in 2014 (at over 3.5 times the production of number two, the United States) and India was the number five producer (BP, 2015). Carbon dioxide emissions from coal are estimated at 94.6 tCO_2 per terrajoule (10^{12} J) produced (BP, 2015). Emissions from coal totalled 15.6 GtCO2 globally in 2014, with China and India contributing 53% of that total. The United States, European Union and Russian Federation were responsible for an additional 24%.

Estimates (Jones and Warner, 2016; Maggio and Cacciola, 2012; Mohr et al., 2015) suggest that global fossil fuel production will peak and begin to decline between 2030 and 2050. Coal is the most abundant of the non-renewable fuels; however, Wang et al. (Wang et al., 2013a) reviewed eight estimates of peak coal in China (ranging from 2010-2039) and derived their own estimate that production will peak in 2027. India produces much less coal than China; however, production has been increasing at about four percent per year since 1950 (BP, 2015). Warner & Jones (in review) projected that coal production in the South Asia region (in which India is the only major coal producer) will peak near 25 EJ in 2057 .

The 12th five year plan (2011-2015) in China was the first to incorporate economic development plans that consider carbon emissions (Meng et al., 2012). In response to the 2009 COP15 meeting in Copenhagen, China set a goal of 40-45% reduction of greenhouse gas emissions from the 2005 level by 2020 (Wei, 2010). According to BP (2015) the 2014 emissions were 54% higher than 2005. China's economic growth and development is limited by the availability of cheap energy (Wang, 2015). China's intended nationally determined contribution (INDC) for the 2015 COP21 climate summit in Paris stated an understanding of the risks of climate change and stated the goal of peaking in carbon emissions while achieving 20% non-fossil fuel share of energy consumption by 2030 (China, 2015).

The government structure of India creates a more complex geo-economic transition focused more on securing future energy supplies than on cooperating towards global goals (Chacko, 2015). India’s INDC stressed the difference between consumption and emission rates in India and the developed world, noted the importance of energy consumption to improving a nation’s human development index (a statistic that factors in life expectancy, income, education etc., HDI), and repeatedly noted the pressures of providing a “dignified life” for its populace (India, 2015). It is important to note that the INDCs from both China and India stress the responsibility of the developed nations and their own status as developing economies. In all, realistic climate concerns dictate that carbon emissions in China will have to peak by 2030 and by 2040 in India (van Ruijven et al., 2012).

In addition to domestic energy production, development and population have an impact on energy consumption. Increasing GDP alone is not sufficient for improving the quality of life at the national or global level (Kubiszewski et al., 2013). A recent study suggests that for every percent of GDP growth in Hebei Province, China, electricity demand grows 0.84% (Zhao et al., 2015). The electrification of non-agricultural homes was found to increase household incomes in India by nearly 30% from 1994-2005 (Chakravorty et al., 2014).

The demographic transition theory suggests that underdeveloped economies benefit from unrestricted population growth and eventually develop to an economy that benefits from restricted population growth (Caldwell, 1976). The result of the demographic transition is a slowing of the population growth rate toward an equilibrium or declining trend in the fertility rate to the replacement level of 2.1 births per woman (Hussain, 2002). It is evidenced in India that there has been a trend towards "quality over quantity" in regard to ensuring education for children over family size (Bhat, 2002). The female literacy rate is estimated at 92.7% in China (total fertility rate of 1.55 births per woman in 2014) and 59.3% in India (2.48 births per woman in 2014) (WB, 2015).

Data and Methods

In this paper we examine four per capita energy consumption benchmarks for the year 2100: 25 and 50 GJ/person for India, and 100 and 130 GJ/person for China. The 130 GJ/person benchmark for China is close to the 2014 European Union consumption rate of 134 GJ/person. It has been suggested that one means of increasing a nation's quality of life indices is to increase per capita energy availability. Lambert et al. (2014) suggested an ideal range of 100-150 GJ/person, citing significant increases in national quality of life indices at consumption rates greater than 100 GJ/person and no significant improvements at rates greater than 150 GJ/person.

We begin by identifying some basic model parameters. The 2015 UN population projections provide high, medium and low fertility estimates for each year from 2015-2100 (UN, 2015b). We use the medium fertility estimates in our models. Next we project the trends for each of the four benchmark per capita energy consumption scenarios from China and India's current values. We used the von Bertalanffy growth curve (von Bertalanffy, 1934) rather than the full logistic growth curve used in Jones and Warner (2016) to provide yearly estimates from 2015-2100. We use the von Bertalanffy growth rather than the logistic in order for a smooth rise in per capita consumption rather than the abrupt initial growth and saturation of the logistic s-shaped curve. The growth rates for each scenario were adjusted such that the scenario values were reached at the year 2100. Energy demand throughout the century was estimated by applying the projected per capita energy consumptions to each year's UN population estimate. The projections of per capita energy consumption in China and India can be found in figure 40.

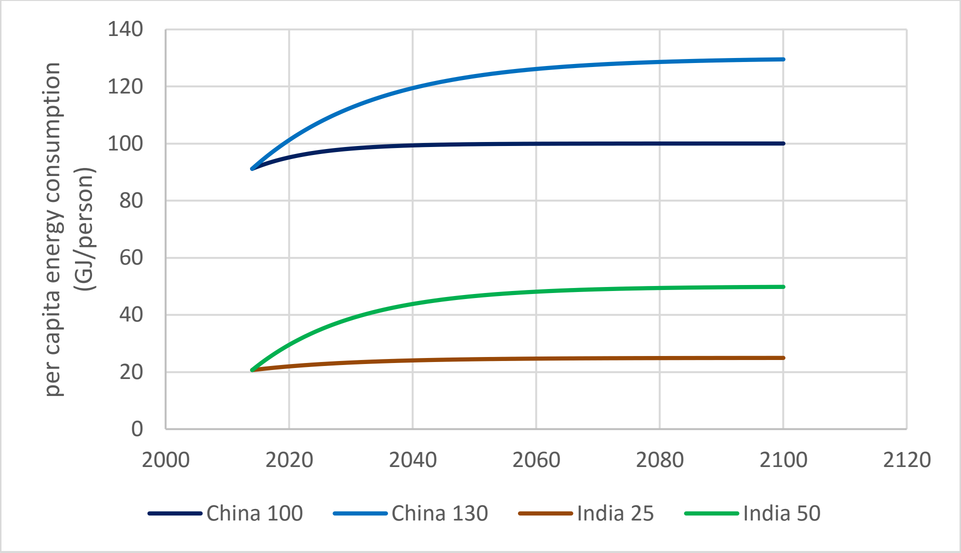


Figure 40: Per capita energy scenario projections, 2014-2100. Per capita energy consumption measured in gigajoules per person (GJ/person).

Next we examined the internal resources, available and necessary, of both countries to meet the projected energy demand. The coal production models are based in the statistics found in BP (2015). These coal production values extend back to 1981. Coal production values from before 1981 were filled in by using Rutledge (2011). Future Production of coal was modelled using the standard logistic function (Hubbert, 1956 and 1982), and assuming that every exajoule of proven coal, oil, and natural gas is used. We utilize the BP proven reserve estimates and the BGR reserve estimates. These estimates are combined with production data from BP (2015) and from Rutledge (2011) to generate estimates of the ultimate recoverable resource (URR) and model coal production throughout the century. CO_2 emissions were calculated for each using the emissions values provided in BP (2015).

Next, we applied two speculative CO_2 emissions plans: the remaining allowable CO_2 emissions weighted via the 2015 and the 2100 populations. Again, from 1870-2010, 1,890 $GtCO_2$ were emitted (Pachauri et al., 2014). According to BP (2015), from 2011-14 another 140 $GtCO_2$ was released. This leaves 870 $GtCO_2$ global emissions to be released from 2015-2100 in order to remain below 2°C warming. Oil and natural gas production was left unchanged from the base model and coal production was curbed to the maximum allowable CO_2 emission level for each year. Coal production curves were checked against historic data and run from 1900 to 2200 to ensure that the model did not eventually overdraw the reserve estimates. The model continues by examining the RES growth required to satisfy the climate-based coal limitations. Oil, natural gas, nuclear, and hydropower production were modelled using the same techniques as Jones & Warner (2016). Potential energy imports were not added to the mixture of energy for these countries.

Results and Discussions

The medium fertility population projection estimates that 1.00 billion people will live in China in 2100 and that 1.66 billion people will live in India. The population projections range from a 2100 population of 613 million to 1,555 million in China and 1,011-2,588 million in India (UN, 2015). The resultant energy demand projections are in figure 27. Chinese energy demand in 2030 ranges from 113–181 EJ and from 46–232 EJ in 2100. Energy demand is between 79 and 160 EJ in 2030 and 76–386 in 2100 for India. Figure 27 charts the energy demand for China (figure 41) and India (figure 42).

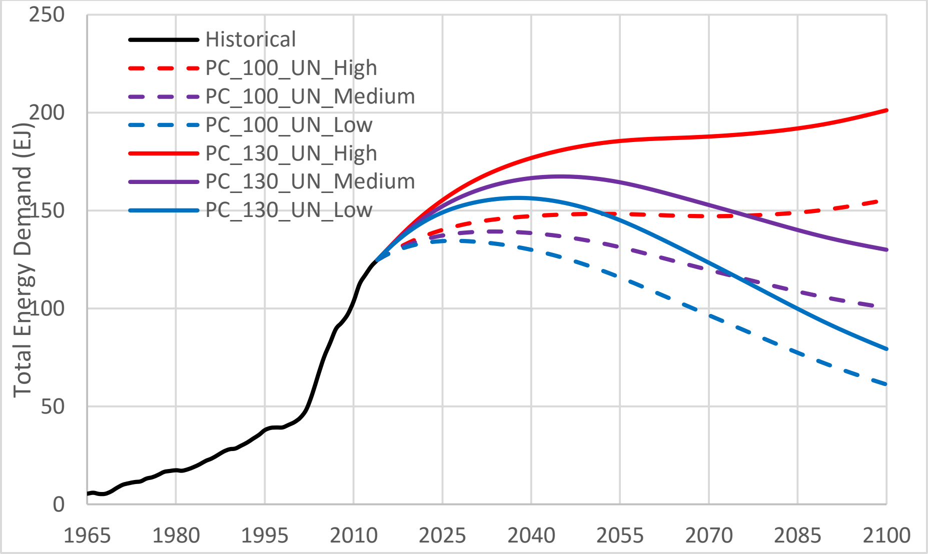


Figure 41: Total energy demand in each population/consumption scenario for China. Demands are based on the three 2015 UN estimates (UN, 2015b). These estimates cover the entire population projection range.

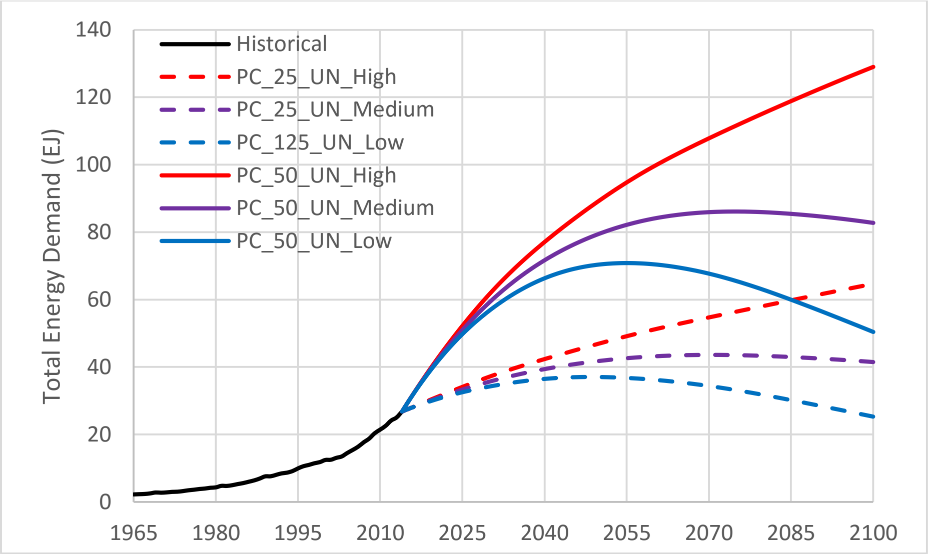


Figure 42: Total energy demand in each population/consumption scenario, India. Demands are based on the three 2015 UN estimates (UN, 2015b). These estimates cover the entire population projection range.

There is little discrepancy in the proven reserve estimates for China, however there is for India. The estimated potential CO_2 emissions from these URRs range from 303 to 329 $GtCO_2$ from China and from 180 to 540 $GtCO_2$ from India. From 1870-2014 China emitted 608 $GtCO_2$ and India emitted 25 $GtCO_2$ from coal production alone. If fully utilized, the lower reserve estimate emission from coal in these countries could total 1,724 gigatonnes. That is 60% of the 2,900 gigatonnes allowable under the <2°C climate goal and the lowest-estimate remaining proven reserves are enough to surpass 2,900 $GtCO_2$ globally.

In order to emit fewer than 2,900 $GtCO_2$ from 1870-2100, total global emissions must remain below 870 $GtCO_2$ from 2015-2100. According to the most recent UN population projections, China comprises 18.7% of the 2015 population and, in the medium variant, it is expected that China will represent 9.0% of the population in 2100. The same conditions indicate 17.8% of the 2015 population and 14.8% of the 2100 population in India. This means that China is allowed 163 $GtCO_2$ in the 2015 population allowance and 78 $GtCO_2$ in the 2100 population-based allowance. India is allowed 155 $GtCO_2$ in the 2015 population allowance and 129 $GtCO_2$ in the 2100 population-based allowance (figure 43).

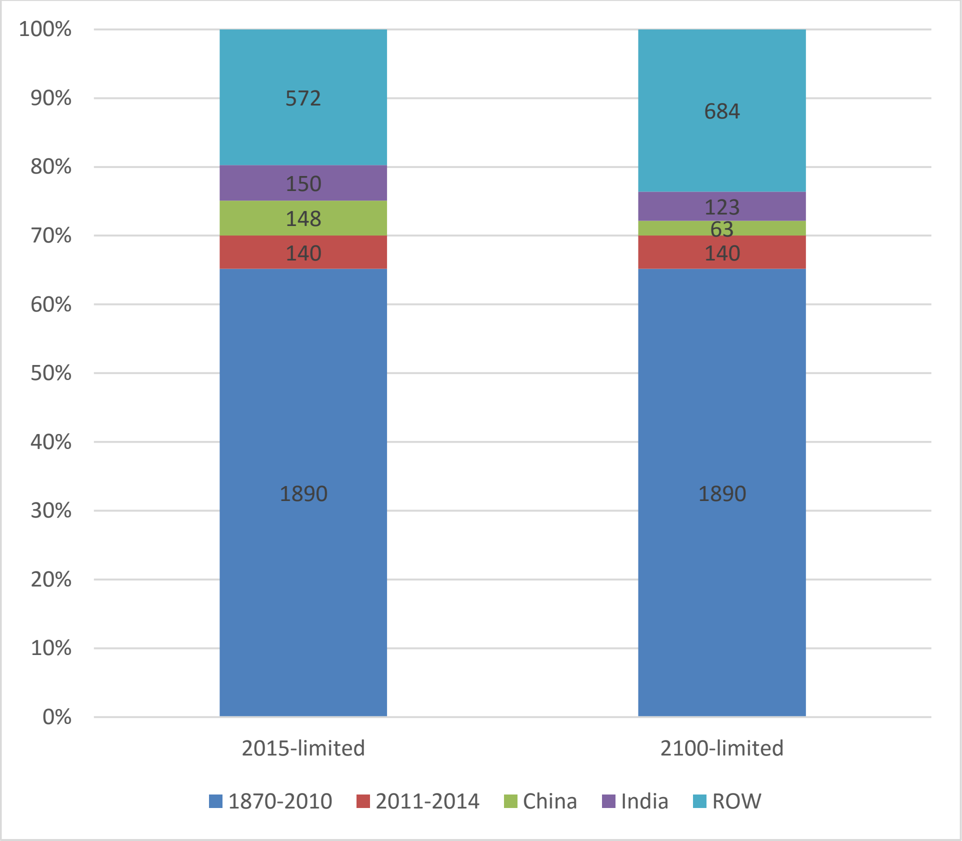


Figure 43: Share of total carbon emission, limited to <2C goal, 1870-2100. Includes 2015 population share-based (2015-limited) and 2100 population share-based (2100-limited) models. Climate goal limits carbon emissions to 2,900 gigatonnes of carbon dioxide equivalent ($GtCO_2$) from 1870-2100, with 1,890 of those emitted from 1870-2010 (Pachauri et al., 2014). Global emissions from 2011-2014 totalled 140 $GtCO_2$ (BP, 2015). Remaining 21st century carbon emissions partitioned by country based on percent of population in either 2015 or 2100, as per the medium fertility population projections (UN, 2015b). ROW indicated the rest of the world.

Future oil and natural gas emissions are estimated at 15 $GtCO_2$ in China and 5 $GtCO_2$ in India. Based on these allowances, China's allowable coal emission are emissions adjusted to 148 and 63 GtCO2. India's allowable coal emissions are adjusted to 150 and 123 GtCO2. As such, China is restricted to using less than half of its remaining proven reserves of coal; however the restrictions on India are much less severe in the climate-constrained scenarios. The coal production parameters are shown in table 17.

Table 17: Coal reserves, carbon emissions, and population per reserve scenario, year-end 2014. Coal reserves have been converted from source units into exajoules. CO_2 is measured in gigatonnes of carbon dioxide equivalent. Share of population in each country is based on the UN (2015b) medium fertility population projection. Note the BGR (2014) coal resource estimate and carbon dioxide equivalent for China is too large for practical modelling purposes.

China, 2015-2100				
	BP	*BGR*	*2015-limited*	*2100-limited*
Coal (EJ)	3,203	3,482	1,562	78
CO_2 ($GtCO_2$)	303	329	148	63
% Population	-	-	19	9
India, 2015-2100				
	BP	*BGR*	*2015-limited*	*2100-limited*
Coal (EJ)	1,634	2,360	1,584	1,305
CO_2 ($GtCO_2$)	155	223	150	123
% Population	-	-	18	15

The projections for coal in the absence of climate restrictions indicate national Chinese peaks in 2024 (BP), and 2025 (BGR reserves). India's coal production peaks in 2054 (BP), and 2068 (BGR reserves) for India. The population-based coal scenarios result in China's coal production peaking in 2013 in both the 2015-limited and the 2100-limited scenarios (figure 44). India's production under the two scenarios peaks in 2052 (2015-limited) and 2046 (2100-limited) (figure 45).

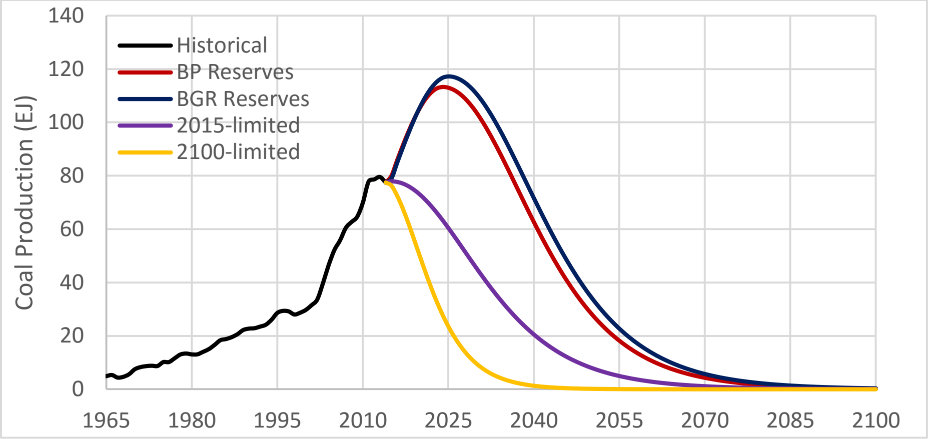


Figure 44: Modelled coal production in China, 1965-2100.

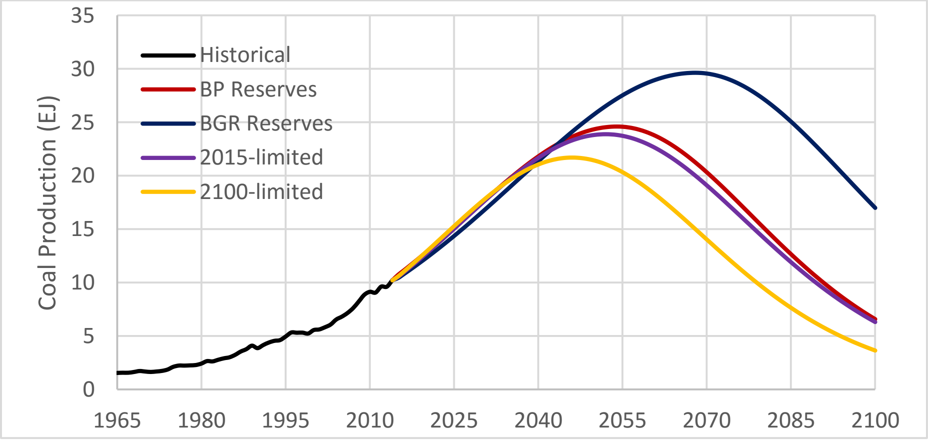


Figure 45: Modelled coal production in India, 1965-2100.

Based on the BP (2015) proven coal reserves, import/RES demand for China and India from 2000-2100 are depicted in figure 30. There is a period from 2019–2033 that China has the potential to be an energy exporter again (figure 46). These cases preclude climate-based coal limitations *and* per capita energy consumption to be limited to 100 GJ/person.

There is no period in the model during which demand in India does not require RES and/or imported energy to meet demand (figure 47). Figure 31 breaks down the difference in import/RES demand differences as a result of the four coal scenarios for China (figure 48) and the five coal scenarios for India (figure 49).

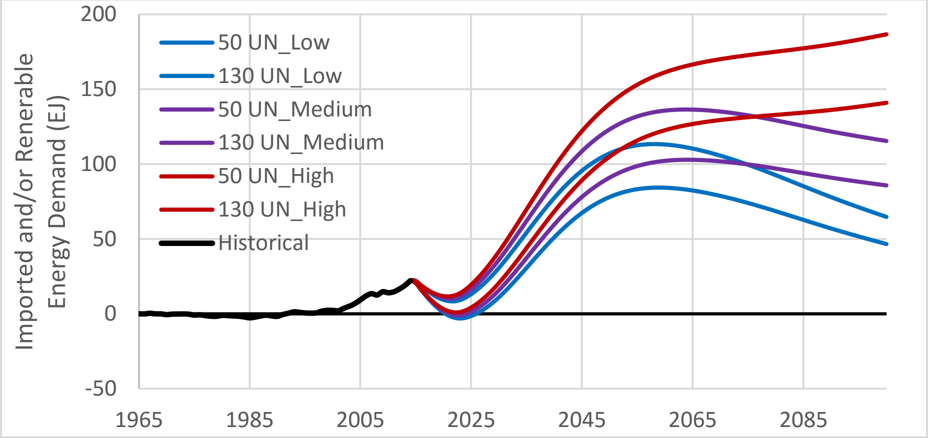


Figure 46: Imported and/or non-hydro renewable energy demand, China 1965-2100. These curves represent the modelled dependency upon imported and/or on-hydro renewable energy in China. Note that there is one condition under which China could theoretically become a future net energy exporter.

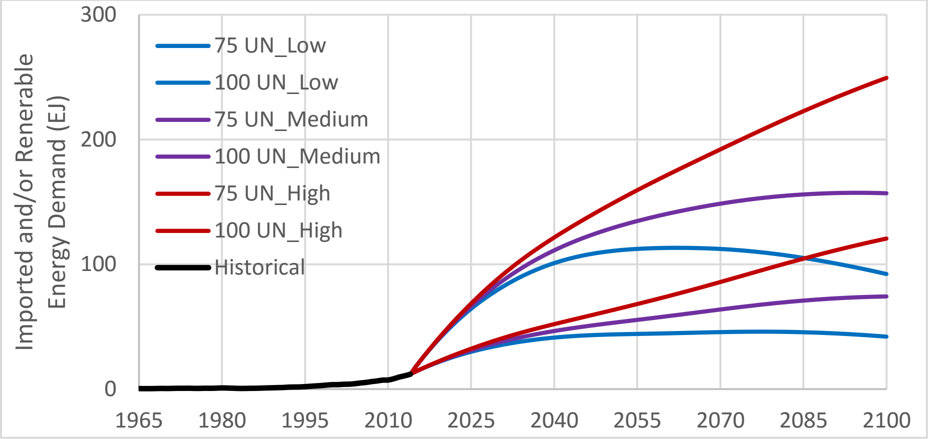


Figure 47: Imported and/or non-hydro renewable energy demand, India 1965-2100. These curves represent the modelled dependency upon imported and/or on-hydro renewable energy in China.

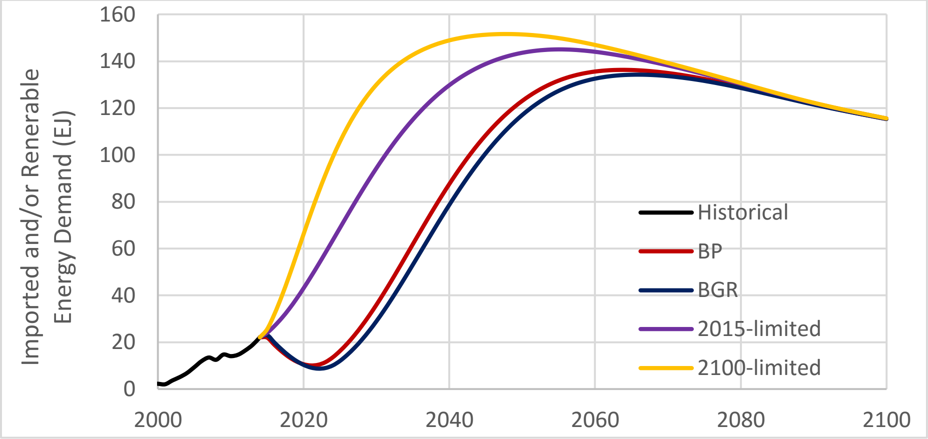


Figure 48: Imported and/or non-hydro energy demand by coal reserve condition, China 2010-2100. The sample scenario for China is 130 GJ/person and the UN medium fertility population projection.

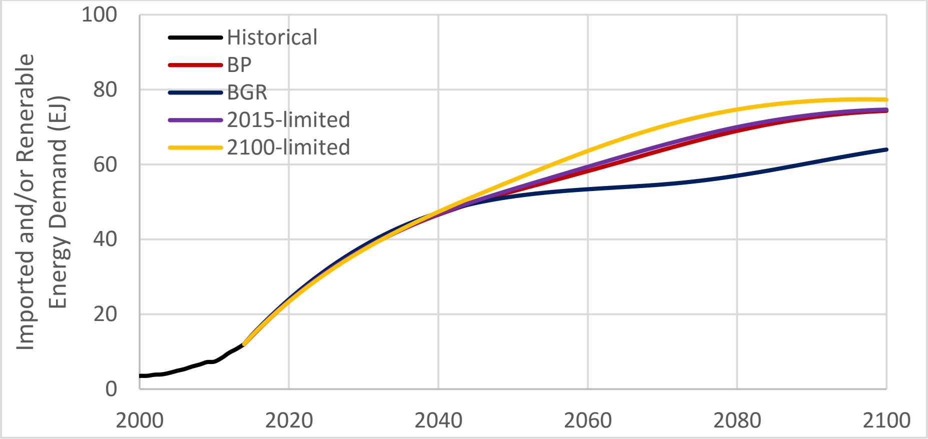


Figure 49: Imported and/or non-hydro energy demand by coal reserve condition, India 2010-2100. The sample scenario for India is 50 GJ/person and the UN medium fertility population projection.

Coal production in China peaks in this model sometime between 2013 and 2024. This result is similar to the range in Wang et al. (2013a) of 2010-39. That range does not include climate concerns in any way. Production of the more climate-friendly natural gas (often considered a more clean bridge fuel to a renewable infrastructure) is projected in our model to peak in 2019 and in Lin and Wang (2012) to peak in 2022. Wang et al. (2013b) detail the extent to which China will rely on imported natural gas to meet the fast-growing demand. India has already peaked in natural gas production and is expected to be one of the fastest growing markets for imports (Darda et al., 2015).

In the previous chapter, we found that the United States, the European Union, and the Russian Federation alone are likely to push the 1870-2100 carbon emissions over 2,400 $GtCO_2$ in the more optimistic G7 plan model. If China and India emit the BP modelled

481 additional $GtCO_2$, the total emissions from 32 or the 195 UN countries from 1870-2100 would total 2,889 $GtCO_2$. Without climate limits, China does not face an immediate problem; however, China is only an energy exporter if population growth is lower than expected and they do not increase per capita energy consumption much above the most recent value. Growing the per capita energy consumption in China and India will require significant energy beyond the domestic non-renewable reserves in each country by mid-century. In this case (and all model results for India) China and India must rely on exploiting their domestic coal reserves *and* securing additional energy resources. As the global energy market dwindles throughout the century (as suggested in Warner and Jones (in review)), these energy resources will become increasingly reliant on a renewable energy infrastructure.

In order to abide by climate limitations both China and India will have to grow renewable energy infrastructure at unprecedented rates in order to support both population growth and development goals. Climate goals will require China and India to shift focus from economic growth to social and environmental awareness (Piovani and Li, 2013). Walsh et al. (2011) identified four issues that would influence China and India's negotiation agendas surrounding the 2009 Copenhagen Accords: first, should developing nations prioritize the alleviation of emissions or poverty; second, involved the statistical methods used for negotiations; the third issue was the financing for mitigation projects; the last issue was the repercussions for countries that had failed to abide by their Kyoto protocol commitments. These issues are still unresolved as of COP21. China and India recognize the need for renewable energy; however, the quality of life of citizens and growth of the economy are more immediate concerns.

Economic development requires expansion of energy availability (Asif and Muneer, 2007). The Nobel Prize winning Chicago School economist Robert Lucas, Jr. defined economic development as "accounting for the observed pattern, across countries and across time, in levels and rates of growth of per capita income" (Lucas, 1988). Biophysical economist Charles AS Hall suggested that the term "development" is merely a euphemism for "industrialization" (Hall, 1992). China and India are described by the United Nations' *World Economic Situation and Prospects* (WESP) as developing economies (UN, 2015a). Developing economies are characterized by rapid economic growth and adoption of a free market system (Hoskisson et al., 2000). In a world of declining energy resources (Jones and Warner, 2016; Maggio and Cacciola, 2012; Mohr et al., 2015), are these countries coming late to the table?

Both nations have a keen interest in the energy market. Since 2000, China's economy has grown at roughly 9% per annum (Shahbaz et al., 2013). Energy consumption during this time has grown in turn at an average of 8.2% per annum (BP, 2015). While many areas of China are well-developed, there is a great inequity in sub-regional economic and social development (Chen et al., 2010). Energy efficiency in non-urban regions of China is variable (Hu and Wang, 2006). The rapid development has relied on unsustainable and high-polluting practices (Zhang, 2010). India has committed to economic development, announcing expectations to double coal consumption by 2020 (Harris, 2014), regardless of climate concerns (Das and Wilkes, 2015).

Any environmental limitations on coal production would be a significant handicap on the efforts of these two nations to assuage growing energy demand. Assuming the 2015 UN medium variant population projection (1.0 billion by 2100) and the 130 GJ/person per capita energy consumption, China will consume a cumulative 13,000 EJ from 2015-2100. There is a clear need in China to address long-term strategies to limit carbon emissions while ensuring energy access (Wang et al., 2016). The same population projection and the more modest 75 GJ/person scenario for India results in 9,350 EJ throughout the remainder of the century. Combined, these estimates would tie up 61% of the BP (2015) and WNA (2013) global proven reserves of oil, natural gas, coal, and uranium on 24% of the global population. China is unlikely to ever again be a non-renewable energy exporter. In calculating the effect of carbon taxes on China and India, Massetti (2011) found that taxation alone will not be enough to reach emissions goals.

There are several concerns within these nations aside from energy demand and climate change. Population is the driving factor in these models. These two nations make up over 36% of the current world population (UN, 2015b). The already monumental task of increasing per capita energy availability in China and India are only exacerbated by population growth. The strong economic and social development of the United States was closely correlated with energy use (Cleveland et al., 1984). Similar development goals in China and India will require similarly available cheap energy options. In China, population projections indicate a peak in population and fertility rates remaining below replacement level (UN, 2015b). The UN medium variant, fertility rates in India do not drop below replacement level until 2030 (UN, 2015b).

It is still common to hear about China's "one child policy." China's post World War II population was rapidly growing while the country was also attempting economic development (Hussain, 2002). China introduced the later-longer-fewer initiative in 1971 to encourage the population to get married later in life, wait longer between the birth of each child, and to generally have fewer children (Bongaarts and Greenhalgh, 1985). Fertility dropped at an unprecedented rate from 6 births per woman pre-1970 to 2.2 births per woman by 1980 (Bongaarts and Greenhalgh, 1985). Despite this reduction in the fertility rate, China is still feeling the effects of population growth. The population in China in 1950 was 544 million, 978 million by 1980, and 1376 million in 2014 (UN, 2015b). However, over time, the effects of population-limiting policies in China are projected to result in a peaking and eventual decline in population by the end of the century (UN, 2015b).

India is expected to continue its demographic transition throughout the 21st century (Kulkarni, 2014). India was one of the first countries in the 20th century to enact family planning policies at the national level (Dreze and Murthi, 2001). Two child families are the most desired in India (Ram, 2012). Individual contraceptive education of married women in India was not shown to significantly increase contraceptive use; however, community-level female education did result in increased contraceptive use (Moursund and Kravdal, 2003). Despite improvements in basic demographic statistics, including fertility rate, child mortality and nutritional quality, India's rate of improvement and lack of cohesive government efforts is not congruous with global quality of life goals similar to the benchmark per capita energy consumptions in this paper (Paul et al., 2011). India's 1950 population was 376 million, 697 million by 1980, and 1295 million in 2014 (UN, 2015b).

There appears to be a difference in community-level education (% of population educated) and individual-level education (duration of schooling per capita) (Caldwell, 1980); community-level education has been shown to lead to a decline in fertility rates faster than individual-level educational statistics (Colleran et al., 2014). Community-level education is correlated with lower fertility desire and increased contraceptive use (Kravdal, 2002). Ideal family size and desired fertility were shown to both decrease as a result of increased education in three Sub-Saharan African countries (Behrman, 2015).

Lowering the fertility rate alone cannot solve population growth concerns. The various population control policies and gender bias toward male children have resulted in unintended consequences. Guilmoto (2012) projected that the gender gap in both countries (at least 50% more males than females) will not begin to shrink until after mid-century, with at least 10% of males remaining unmarried by age 50. On 29 October, 2015 the Xinhua News Agency (XNA) in Beijing announced the replacement of the one child policy with a limit of two children per couple (XNA, 2015). This decision was framed as a means to combat the inverting age structure (aging population) in China.

The Sustainable Energy for All Initiative was commenced in 2012 with the goals of ensuring universal global access to electricity, modern non-solid cooking fuels, and increasing the global share of renewable energy production by 2030 (Banerjee et al., 2013). Though the percent of the world's population using unhealthy solid cooking fuels has decreased, population growth in the developing world has mostly kept pace, meaning that about the same total number of people since 1980 lack access to modern cooking fuels (Bonjour et al., 2013). The same study reports that both China and India have made progress, though between 40-60% of the population still use unhealthy solid cooking fuels. Chen and Feng (2000) found that from 1978-1989, China's high fertility rate was a negative factor toward economic growth. China's population is also rapidly aging. The portion of the population under the age of 15 shrunk considerably between the 2000 and the 2010 census (Mai et al., 2013).

The increasing urbanization of China will make it difficult for China to grow its economy and reduce greenhouse gas emissions at the same time (Liu et al., 2016). Additionally, the development gap between regions of China suggest that carbon emissions resultant of urbanization are linked to income in developed regions and linked to industrialization in less developed regions (Cao et al., 2016). This adds to the difficulties that China will have to overcome in achieving its climate goals, as more region-specific plans must be developed (Cao et al., 2016).

The rate of urban expansion in India has been estimated at 2-3% per year (Gibson et al., 2015). Compared with China, the urbanization of India has not been as organized, leading to underinvested cities (Dobbs and Sanke, 2010). Pandey and Seto (2015) determined that urbanization in the majority rural India over the last ten years has led to small, yet steadily growing loss of agricultural land that could compound if the UN projection of urbanization throughout the 21st century are to be believed. Cities in India and other developing nations are also faced with rapid increase in demand for basic services such as sanitation and piped water access (Das, 2015).

Conclusions and Policy Implications

The question at the beginning of this chapter was whether or not China and India had arrived too late in the fossil fuel era to achieve the economic and social benefits of countries like the United States, the European Union, and the Russian Federation. The United States accounted for 17.8% of total global energy consumption in 2014 (BP, 2015). There is little chance that developed nations will consume less per capita either by choice or via efficiency (Sorrell, 2015). If the 2014 populations of China and India had consumed at the American level (302 GJ/person), they would have consumed 1.5 times the 2014 total global energy production. Even without climate concerns, and using what energy might be available for import, any growth in per capita energy consumption will require immense growth in the renewable energy sector by 2030. Again, most peak energy forecasts estimate that global non-renewable energy production will peak as early as the mid-2030s.

The climate change issue only compounds the dilemma of these two nations. Much like the rest of the world, climate change mitigation is not a viable option for these nations without planned and effective population control combined with aggressive expansion of non-carbon intensive energy infrastructure. In general, though environmental concern exists across income levels, increased wealth usually results in increased valuation of the environment (Dorsch, 2014). Ensuring the success of efforts such as the Sustainable Energy for All Initiative will provide obvious benefits to the less developed nations; also, those benefits will likely serve the environmental and climate efforts of the developed world. If climate change is a result of energy production, then climate change mitigation must also be a function of evolving energy infrastructure.

Similar climate-related energy modelling was performed by Johansson et al. (2015). Their study focused their modelling on per capita carbon emissions and examined the economic effects of achieving emissions plans from the 2009 Copenhagen Accords on China and India. They note that reducing the carbon intensity of the economy is the highest priority in China and that expanding renewable energy infrastructure is more important in India. This conclusion is supported in our study as figures 30 and 31 depict the lower import/RES demand in the near-term for China and the immediate requirement for import/RES in India. Our study is a different approach to the issue, focusing on the energy consumption and availability in each country. Whereas Johansson et al. (2015) seek the economic consequences of limiting climate change contributions from the two countries, our study examines the energy requirements to grow and develop the economies. Both perspectives are necessary for a complete policy framework.

Each of the issues facing nations like China and India can be linked to population and energy. The exacerbating issues associated with urbanization, age structure, fertility policies, energy access, etc. are all fundamentally concerns of population. Cheap renewable energy should be the world's primary concern as many of the other major issues facing the world can be relieved, at least in part, by sufficient access to energy (Smalley, 2005). Ahmed et al. (2014) suggest that up-front investments in RES now will prove more valuable than continuing to import cost-increasing fossil fuels. At any rate, the results of our models cast doubt as to the margin of error for post-2050 population projections (e.g., low, medium, high UN estimates). Implementation of energy into population projections remains an important area for further research. Demographic transitions as a result of increased per capita energy consumption in the developing world are vital to the global transition towards RES infrastructure and climate adaptation in China, India, and the rest of the world.

To reiterate from the previous chapter, the 'coal question' of the 21st century is not one of geologic supply, but of atmospheric capacity. We have now examined 32 countries, the United States, the 28 countries in the European Union, the Russian Federation, China, and India. These countries were responsible for 74% of total global coal production and 81% of total global coal consumption in 2014 (BP, 2015). At the pace of the 12.5 GtCO2 emitted via coal consumption in these countries alone in 2014, the 2°C climate goal would be eclipsed in 2084 without oil or natural gas combustion in these countries and no fossil fuel combustion of any sort in the rest of the world.

The findings of these two chapters lead us to make the following recommendations. Reducing the consumption of coal is a global issue, not limited to economic or social development status. All countries must work towards reducing carbon emissions together. Technology, education, responsibility, etc. should be shared, regardless of national or cultural delineation. Climate goals are unachievable without cooperation from both the high energy consumers and those looking to become high consumers. Providing energy to the global population is going to become a difficult task. A task made increasingly difficult with every year's population increase. Our final recommendation is the same as for every chapter in this dissertation. The transition to a global renewable energy infrastructure must begin immediately. Investing the remaining 870 $GtCO_2$ in the form of the energy required to build out a global renewable energy infrastructure is more than a noble goal or political hot air. Sustainable energy for all is our only hope to limit global warming and to undershoot future population projections.

The final conclusion to the 'coal question' chapters is that both coal and renewable energy will be crucial throughout the 21st century. This is not just a climate change issue, it is a paired issue that requires a focused effort towards providing the energy needed to accommodate increased population and increase per capita energy availability. Developing countries are going to take the measures necessary to provide for their people even at the expense of climate concerns.

CHAPTER VIII

CONCLUSION

The introduction to this dissertation concluded with a quote from Charles Dickens' *A Christmas Carol.* The miserly protagonist has been shown the events surrounding his death should he fail to mend his ways. I do not claim clairvoyance nor do I suggest that the results of my models are definitive. I have taken the data and projections from government and industry sources and applied mathematical models to manipulate the data into projections for the 21st century. The findings of the previous chapters are based on current technologies, as any attempt to predict future breakthroughs would add irresponsible uncertainty to any of my models. In each of the body chapters of this dissertation I have highlighted the course that populations of the world, regions, and countries will take should the current state of policy and technology be continued.

Chapter II modelled energy, population, and climate on a global scale. The primary research focus of this chapter was to determine global peak production dates for the non-renewable energy sources and project the growth of renewable energy demand necessary to ensure a global energy supply in both a climate constrained and an unconstrained 21st century. There were three final recommendation from this chapter. First, that the transition to a renewable energy infrastructure was necessary by 2100, regardless of climate change goal. Second, the likelihood of preventing global warming from eclipsing 2°C above preindustrial levels is small and policymakers around the world should initiate adaptation measures for +2.5-3°C global warming. Third, in order to prevent the majority renewable infrastructure would be required by 2028, whereas the majority renewable energy infrastructure is required by 2054 based on the limitations of proven fossil fuel and reasonably assured uranium reserves.

Chapter III modelled global energy and population at a regional scale. The primary research focus of this chapter was to examine the global model from chapter II to identify and quantify the issues facing each of the nine world regions with respect to changes in per capita energy consumption. This was the most ambitious of the chapters, as the level of detail in each region varied and the global market required a nuanced and impartial approach. This chapter identified the unique challenges in each world region. The only region capable of utilising domestic fossil fuel and uranium reserves throughout the entirety of the model is the Former Soviet Union. Population (particularly projected population growth) is the primary culprit of poor outlook in any region. This chapter also supported chapter II's assertion that limiting global warming to +2°C was unlikely.

The primary research focus of chapter IV was to determine the effect of varying per capita energy consumption and fossil fuel reserves on the outputs of the model from chapter II. In chapter IV we examined different estimates for global fossil fuel reserves and highlighted the importance of changes in per capita energy consumption. The current global population of ~7 billion would demand an extra seven exajoules of energy for every one gigajoule increase in global per capita energy consumption. Given that the total global non-hydropower renewable energy production in 2014 was 13 exajoules, the race to transition away from fossil fuels is falling behind the race to develop economically and socially, rising global population and faces stiff competition from pre-peak fossil fuels.

Chapter V is the first of three chapters that moves from a global focus toward a national focus. This chapter focuses on the challenges of providing the energy required to raise the quality of life of the projected four billion people that will occupy Sub-Saharan Africa by 2100. The primary research focus of this chapter was to quantify some of the efforts needed for development goals in the region and to determine if any suitable analogue can be found in the past 50 years to use as an example for Sub-Saharan Africa going forward. We sought historical analogues over the past 50 years that might give us insight as to how these 51 countries might rise from the current $^1/_6$ of the global average per capita energy consumption in 2014. Though there are several similarities to China, the scale of the problem in Sub-Saharan Africa requires a transformation that is globally unprecedented. Based on the estimates provided here, it is unlikely that the population of Sub-Saharan Africa can reach the projected levels without significant investment and re-organization of the current energy infrastructure.

Chapters VI and VII re-examine the 150 year old ‘coal question’. Cutting carbon emission around the world will not be an easy task. Chapter VI focused on the developed, coal intensive economies of the world: the United States, the European Union, and the Russian Federation. The primary research focus of this chapter was to quantify the difference in carbon emissions projected in these 30 countries in a future unconstrained by climate concerns versus one of more ambitious climate change agreements. These countries industrialized early on and have built complex infrastructures dependent upon fossil fuels. Even achieving both admirable and ambitious climate goals in these countries, while saving approximately 200 $GtCO_2$, would leave precious little carbon available for the rest of the world. Transitioning from coal to renewable energy may well prove as large a challenge for the developed world as transitioning towards developed economies is for the rest of the world.

Chapter VII examines the ‘coal question’ in terms of the per capita energy consumption increase associated with development in China and India. The primary research focus of this chapter was to model and identify the challenges of concurrently developing highly populated countries and achieving global climate goals. These two countries have the highest population in the world. These populations consume energy at lower levels than the developed countries examined in chapter VI. Developing over a billion people in each of these countries is a monumental task made more difficult by the impending peak in global fossil fuel energy production. China and India are indeed coming late to the development table, as adopting climate goals preclude these countries from pursuing the same industrialisation that has allowed the countries in chapter VI to develop in the decades and centuries before China and India.

As the climate debate rages on, sea level is rising faster than it has in at least the last 2,700 years (Kopp et al., 2016); thawing permafrost in the Arctic regions of the world is releasing CO_2 and methane at an alarming and expensive rate (Hope and Schaefer, 2016); and the global warming carbon budget remains an uncertain figure (Rogelj et al., 2016).

At the worst, the recommendations in this dissertation are a starting point to improving numerous global atmospheric, economic, and social conditions, whether or not you believe in climate change, anthropogenic climate change, or peak energy.

To paraphrase Charles Dickens (Dickens, 1843), these models are not shadows of the things that Will be, they are merely shadows of things that May be, only. The status quo course foreshadows certain ends, to which, if preserved in, the models depict, but if the courses be departed from, the ends will change…We make these models to highlight necessary changes because we believe that we are not yet past all hope.

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