Projecting Long–Term Primary Energy Consumption with Error Correction Models [*]

Z. Csereklyei[†] **S. Humer**[‡]

Department of Economics, Vienna University of Economics and Business (WU)

February 27, 2013

Abstract

In this paper we use the long–term empirical relationship among primary energy consumption, real income, physical capital, population and technology, obtained by averaged panel error correction models, to project the worldwide long–term primary energy consumption up to 2100. In forecasting long-term primary energy consumption, we work with four different Shared Socioeconomic Pathway Scenarios (SSPs) developed for the Intergovernmental Panel on Climate Change (IPCC) framework, assuming different challenges to adaptation and mitigation. We find that in all scenarios, China, the United States and India will be the largest energy consumers, while highly growing countries will also significantly contribute to energy use. We observe for most scenarios a sharp increase in global energy consumption, followed by a levelling–out and a decrease towards the second half of the century. The reasons behind this pattern are not only slower population growth, but also infrastructure saturation and increased total factor productivity. This means, as countries move towards more knowledge based societies, and higher energy efficiency, their primary energy usage is likely to decrease as a result. Global primary energy consumption is expected however to increase significantly in the coming decades, thus increasing the pressure on policy makers to cope with the questions of energy security and greenhouse gas mitigation at the same time.

JEL Classification: C53, Q43, Q47.

Keywords: Primary Energy Demand, Projections, Panel Cointegration, Model Averaging

1 Introduction

The purpose of this paper is to project the long–term worldwide primary energy consumption up to 2100, based on averaged panel error correction estimates, designed to decrease the inherent

---

[*] The authors are grateful to Jesús Crespo Cuaresma and Helmuth Böck for advice and suggestions. All remaining errors are ours.

[†] Address: Simmeringer Hauptstr. 215/301, 1110 Vienna, Austria, [✉] *zsuzsanna.csereklyei@acceron.at.*

[‡] Address: Augasse 2–6, 1090 Vienna, Austria, [✉] *shumer@wu.ac.at.*

uncertainty in modelling energy demand. We utilise the results of our earlier study (Csereklyei and Humer 2012), in which we estimated various panel error correction models to determine the main drivers of primary energy consumption. These models estimated the long–term empirical relationship for 64 countries between 1965–2009, allowing for world, regional and wealth level differences. We applied simple model averaging techniques to the estimated coefficients, which led to a significantly better predicting ability than by any single individual model, therefore we will use these averaged results for our long–term energy projections.

When projecting future energy consumption, most organisations and researchers work with general equilibrium models, requiring precise assumptions about demand and supply inputs that are very difficult to make. We decided to use the cointegrating relationship present between primary energy consumption, physical capital, population, real income and total factor productivity. Therefore, our study takes a radically different approach to energy consumption projections as compared to the prevailing integrated models.

The challenge of producing long–term energy forecasts has been mostly met by international, academic and governmental organisations, such as the International Energy Agency (IEA), International Atomic Energy Agency (IAEA), the European Union (EU) and Eurostat in the past. The best–known of these studies is the annual World Energy Outlook of the International Energy Agency (2011), which uses a number of general algebraic modelling systems and a bottom–up modelling approach for both the demand and supply side to forecast energy consumption for the next 25–30 years. A prestigious non–governmental study comes from the British Petrol (2011a), projecting energy consumption until 2030. The Massachusetts Institute of Technology (MIT) has also conducted during the past ten years a number of interdisciplinary studies about the future of coal (Massachusetts Institute of Technology 2007), natural gas (Massachusetts Institute of Technology 2010), geothermal energy, nuclear energy (Massachusetts Institute of Technology 2003) and of the nuclear fuel cycle (Massachusetts Institute of Technology 2011). These studies offer the most comprehensive future technological reviews and resource estimates at the time of this study. Energy modelling in the context of climate change and greenhouse gas mitigation has been also addressed by the Stern Review (Stern 2007), the report of the Intergovernmental Panel on Climate Change (IPCC 2011), and by various energy modelling forums, among others but not exclusively by Stanford, the Potsdam Institute, and the IIASA Global Energy Assessment (GEA) Report (IIASA 2012a). Most sovereign governments carry out strategic national mid-term energy projections such as the United States Energy Information Administration (2012), the United Kingdom Department of Energy and Climate Change (2012), the Australian Government Bureau of Resources and Energy Economics (2011), or the Umweltbundesamt in Austria (Umweltbundesamt Österreich 2011) focusing on their national needs.

The majority of these projections include usually some assumptions about the abatement of greenhouse gases, and government subsidies. Few take however — due to their relatively short time horizon — into account the constraints caused by the availability of fossil resources. One exception here is IIASA's GEA Scenario System running up to 2100, which takes into account the resource base of all conventional and non–conventional fossil fuels, and allows for a large selection of macroeconomic variables including primary energy, secondary energy, population, GDP, energy security to be projected on the long–run. Besides the economic variables, IIASA projects the key environmental variables such as air pollutants, greenhouse gas (GHG) emissions and radiative forcing with the help of the MESSAGE and IMAGE modelling systems. Interestingly, the International Monetary Fund's World Economic Outlook (International Monetary Fund 2011) also deals with resource constraints and considers the impacts of oil scarcity on economic output.

Forecasting energy consumption is a highly important task that — in any case — is carried out with high uncertainty. Therefore most of the forecast do not venture beyond a scope of 20 maximum 30 years, giving thus little insights about longer term implications. This paper attempts a longer horizon energy projection up to 2100, allowing for different scenarios based on the shared socioeconomic pathways (SSPs) developed by the IPCC working group (Kriegler et al. 2010) for population and real income. We also conduct a geopolitical analysis of energy, and review potential future technologies for energy production. The effects of greenhouse gas emissions from increasing energy consumption might, according to various studies (Stern 2007) contribute to increased famine, adverse weather conditions, increasing sea levels and the associated economic costs. Therefore the right choice of energy sources used to meet growing energy demand will be of crucial importance, especially if energy use patterns are identifiable and connectible to a given level of economic development (Jakob, Haller, and Marschinski 2012).

In comparing our projections with the major studies from above, we receive very similar mid–term results as the International Energy Agency (2011), or IIASA, projecting up to 45% increase of primary energy consumption by 2035. We do find that after a previous increase in energy consumption, primary energy demand for our sample set is likely to level and to slowly decrease in the second half of the century. This is not only attributable to lower population growth, but also to infrastructure saturation, and to increased total factor productivity. We also find that presently developing countries are likely to go through similar patterns of energy consumption as industrialized countries did, and a decrease in energy consumption levels is only likely after a change in the structure of the economy. Therefore, in order to cope with the challenges caused by the high energy usage, shifting to cleaner (reduced or no greenhouse gases and particle emissions), economic and concentrated energy sources, such as natural gas, renewables or nuclear energy would be advisable.

This paper is organised as follows: Section 2 gives a short technological overview of the main energy sources, Section 3 introduces the data and the applied methodology. Section 4 elaborates on the results, while Section 5 concludes. Detailed energy projection tables can be found in Section 6, the Annex.

2 Resources and technological outlook

In order to be able to analyse the future role of different energy forms, we give here a short prospective technological review, including next to the resource base[1], the advantages and potential hazards of different energy technologies.

2.1 Fossil resources and technology

First we start with fossil fuels, including conventional and non–conventional oil, gas and coal reserves throughout the world. Wood is excluded from this study, although it is still extensively used in developing countries for cooking and heating, at the same time its total share of primary energy supply is negligible. Conventional and nonconventional oil reserves are reported annually by the IEA's World Energy Outlook (International Energy Agency 2011), but also by the Oil and Gas Journal. By definition, conventional oil includes crude oil and natural gas liquids. Unconventional oil includes extra-heavy oil, natural bitumen (oil sands), kerogen oil, gas-to-liquids, coal-to-liquids and additives (International Energy Agency 2011, p.120). The total proven oil reserves are reported by the International Energy Agency (2011) to range between 1470 billion barrel (O&GJ) and 1526 billion barrel (BP 2011). The reported reserves have a history of constant increase due to newly reported and confirmed discoveries, despite of continuous oil consumption.

Extraction of non–conventional reserves, as well as resources that were thought to be economically non–viable in the past however did become viable during the recent years due to increasing oil prices. The IEA estimates remaining recoverable conventional and unconventional oil resources[2] at around 5500 billion barrels including proven conventional reserves and approximately 2700 billion barrels unconventional resources[3]. Crude oil products are predominantly used for the transportation sector worldwide, and constitute approximately 27.7% (British Petrol 2011b) of total worldwide primary energy consumption.

We compiled the conventional and nonconventional gas resources from the International Energy Agency (2011), the Massachusetts Institute of Technology (2010), and from the British Petrol (2011b) World Statistical Review. The role of natural gas has gained increasing importance during the last decades, and currently about 11.2% of the world primary energy consumption is covered by natural gas (British Petrol 2011b). These levels are considerably higher for North-America (27.6%) and for Europe and Eurasia (34.4%). Nearly all studies (International Energy Agency

---

[1] Many current studies neglect the difference between reserves and resource bases. Depending on definition, reserves are explored and reported amounts of natural resources, which might however constitute only a small part of the existing and recoverable resource base. In this paper we work with the resource base, which includes not only the reported, but also the scientifically assumed recoverable resources.

[2] Ultimately recoverable resources are latest estimates of the total volume of hydrocarbons that are judged likely to be ultimately producible commercially, including initial 1P reserves, reserves growth and as yet undiscovered resources. (IEA: WEO 2010, p116)

[3] The conversion factor of million barrels of oil equivalent to million tons of oil equivalent (BOE) varies slightly by different definitions, normally between 7.11–7.4 BOE = 1 TOE. We use for the purpose of this paper the conversion factor proposed by the British Petrol report British Petrol (2011b) that is 7.33 MBOE =1 MTOE, or 0.1364 MTOE/MBOE

2011; Massachusetts Institute of Technology 2010) expect the share of natural gas to increase in the primary energy mix in the future. Natural gas plants have at the moment the lowest CO_2 footprint of all fossil resources, and are therefore in many cases preferred by policy makers. During the last decade, technology advancements allowed large discoveries of non–conventional gas reserves. Non-conventional gas includes coalbed methane, tight gas, and shale gas. Presently, the International Energy Agency (2011) estimates conventional recoverable resources to be around 400 trillion cubic meter (tcm), and non–conventional resources a bit higher than 400 tcm. These numbers are significantly higher than the reported reserves, and would be equal jointly to approximately 250 years of production at 2010 levels[4]. The Massachusetts Institute of Technology (2010) also estimates the global supply of conventional natural gas with a remaining resource base of about 16.200 trillion cubic feet (a mean projection between 12,400 tcf and 20,800 tcf, which constitutes a 90% confidence interval). This converts to around 538 tcm, thus slightly higher than the IEA estimate. For the purpose of this paper we take uniformly the IEA resource estimates for fossil fuels.

Non-conventional gas sources have the advantage that they can be extracted with the similar technology developed for conventional gas and transported in the existing gas transportation and pipe system, which in fact greatly reduces the short-run infrastructure investment requirements. Another advantage from an energy security point of view is that unconventional gas resources are geographically more evenly distributed. According to Massachusetts Institute of Technology (2010) next to shale gas, methane hydrates which are mostly found in ocean sediments could also constitute a significant long–term resource option. Shale gas seems to be gaining momentum in the US energy landscape since the last few years. As of 2010, approximately 23% of the United States gas production was shale gas (United States Energy Information Administration 2012). The reasons for such a rapid increase in shale gas production are found not only in economics, but in the ownership structure of resources in the United States, where resource ownership belongs to land owners, unlike in many other countries, where governments claim resources. This potentially leads to investments, and to open attitude from land owners and the industry. Free markets, an open economy, as well as the technical advances of the past years also contribute significantly to the North American success.

Shale gas can be best described as gas trapped in mud stones, which do not migrate as conventional gas reserves. Mud stones or shales do not easily give up the contained hydrocarbons, as their pores are approximately 1,000 to 20,000 times smaller than those of sandstones. Therefore, to gain these hydrocarbons, the so called hydraulic fracturing (commonly known as fracking) procedure is applied, during which about 3–5 million gallons of high pressure water (Potter 2012) and sand are pumped several thousand feet below underground, cracking the rocks with the help of water, whereas sand is used to prevent the rocks from closing again. Fracking causes microseismic events, heard as the small cracking of rocks. During recent research it was found that most gas flows constitute a rectilinear network of fractures (Patzek 2012). At the same time, it should be considered that each mud stone system is unique and thus calculations for one field cannot be

---

[4] We use the conversion ratio proposed by BP (2011), 1 bcm=0.9 MTOE, or 1 tcm= 900MTOE.

generalised (Patzek 2012). When a shale gas field is explored, the fracture lines give normally an organised system, where gas flows towards low pressure points. It is expected that at some point, approximately ten-twelve years into the lifetime of the well, these fractures may interact with each other (Patzek 2012), thus the lifetime of a well is generally taken as ten years. The approximate number of fractures per well are different, and estimated between five to twenty. The most important geological factors determining shale economics are porosity thickness, carbon richness, brittleness, thermal maturity and pressure (Potter 2012).

The environmental concerns around shale gas, or more precisely the fracking procedure contain among others the provision and disposal of water, issues in groundwater protection, fracture fluids chemistry, surface disturbance and induced seismicity (Kleinberg 2012). Possible earthquakes have been also mentioned by Rubinstein, Ellsworth, and McGarr (2012), triggered by the wastewater, which is injected back to the ground to be disposed of. Such triggered earthquakes have been however also attributed to coalbed methane production and carbon dioxide sequestration (CCS). The most pressing and publicly debated issue is the possibility of groundwater contamination, through the fracking procedure. This would be either possible through bad cementing (Kleinberg 2012) and engineering work around the wells, or through upward cracking fractures (vertical fractures). Normally however, vertical fractures are several thousand feet below the water reservoirs. One known exception was a Wyoming accident, where shale reservoirs were too close to the water reservoir, which resulted in groundwater contamination. The presently recorded accidents had been attributable mostly to bad engineering such as gas escape, gas pollution, water well explosion, and wastewater discharge (Kleinberg 2012). The handling of the mildly radioactive wastewater is also an issue to be addressed. Present calculations indicate that the reuse of water is always more economic than the disposal of wastewater. At the same time saline compatible technologies are being developed that will allow the usage of salt water instead of the excessive use of freshwater reserves. Another claim against shale gas that is currently debated among different stakeholder groups is the release of methane gas into the atmosphere. Methane has much higher global warming potential than CO_2 over a mid-term horizon, as it traps heat in the atmosphere. Carbon dioxide on the other hand accumulates, and stays longer in the atmosphere.

Mostly due to their low cost and the questions of energy security, unconventional oil and gas are expected to provide the bulk of the United States energy supply for the next decades (ExxonMobile 2012). Whether shale gas and oil extraction can be as successful in other countries as in the United States is a question for the future. Next to China, Australia, also European countries such as Poland and France are likely to possess large shale reserves.

Coal resources, including brown coal, black coal (hard coal) and peat constitute the largest bulk of fossil resources. Presently reserves are estimated around 1 trillion metric tons (MT), while resources are much larger, presently estimated around 21 trillion MT (International Energy Agency 2011). How much of these resources could be eventually accessed in the future is not only a function of costs and economics, but also of environmental policy around the world. Coal has of all fossil resources the highest greenhouse footprint, but also the highest polluting particle emissions. At the same time coal is highly abundant, as well as fairly cheap and often subsidised by developing country governments, in order to keep the price of coal low for the industry, but also to preserve mining jobs (International Energy Agency 2011). As the International Energy Agency (2011) notes, China is responsible for about half of the coal use as of 2009, followed by the USA and India, whereas by the mid 2030s India is by all scenarios likely to overtake the USA in coal consumption. The fact that coal is cheap, widely available and stands at the lower part of the energy ladder (Burke 2011) has caused the share of coal in the energy mix to increase significantly during the last decade. As the International Energy Agency (2011) claims, its importance is the highest since 1971.

Coal consumption is driven thus, not only through prices and subsidies, but also by the existing coal plant structure (lock-in), easy transportability, and energy security considerations. This lock-in effect is also considerable, and the type of plant built is largely determining emissions of the next 20-40 years. Presently used plant technologies (International Energy Agency 2011) include subcritical, supercritical, ultra-supercritical plants and integrated gasification combined cycles. Criticality here relates to the state of water under very high pressures and temperature. The outlook for future industry efficiencies is limited, although some improvements may be possible. The future of coal lies among others, with the question whether carbon capture and storage (CCS) technologies will prove to be a viable solution of the future. At the moment there are no large scale experiences from CCS plants that operate on the principle of capturing carbon and storing it underground (in depleted gas fields for example). Besides the problem that CCS reduces the efficiency of coal plants and raises the levelised costs of electricity considerably (between 39-64%) (International Energy Agency 2011), the largest hurdle CCS may face lies within its hazard of inducing earthquakes, as argued by Zobak and Gorelick (2010). While these induced earthquakes may not result in significant property or human damage, they may corrupt the integrity and seal of the carbon storage, resulting in the release of the trapped greenhouse gases. While these concerns are relevant for the future of coal, presently they are unlikely to influence the short term development of coal consumption, which is driven mostly by non–OECD developing countries, deploying older technologies.

2.2 Nuclear resources and technology

Nuclear resources are perhaps the most abundant of all non–renewable energy sources on earth, practically unlimited. The usage of civilian nuclear power had its beginnings in the 1950s and the number of newly built nuclear power plants peaked around 1980. In case of uranium it would be a mistake to think with proven reserves (estimated around 5.5 million metric tons (Massachusetts Institute of Technology 2011), as due to the falling prices of the last years, there was little economic incentive behind exploring and reporting new uranium reserves. The resources (about 13 million metric tons) reported refer to ore extractable below 130 USD/metric ton normally. Presently technologies exist to gain uranium from seawater and from lower ore grade material. With a higher uranium price, both reserves and resources would be estimated much higher, as alone saltwater contains about 4 billion tons of uranium. The distribution of uranium on earth was first described by Deffeyes & MacGregor (Deffeyes and MacGregor 1980) and is known as the Deffeyes log-normal frequency of distribution of uranium, displaying the approximate amount of uranium resources found in different formations. One clear advantage of nuclear produced electric energy, is that uranium has only a little share (about 4%) in the total price of electricity. Therefore even seawater uranium extraction at 300–400 USD/ton would lead only to an estimated maximum busbar cost increase of 12% (Massachusetts Institute of Technology 2011, p.37). Thorium, which is another option for nuclear fuel, is more energy dense in a thermal spectrum than uranium. Due to the fact that commercial power plants do not use thorium on large scale at the moment, the reserve and resource estimates are very uncertain. The International Atomic Energy Agency (2005) estimates reserves (reasonably assured and additional estimated reserves) under 80 dollar/ton around 4–5 million metric ton. Similarly to uranium, the resource's share in the price of electricity is very low, therefore fluctuations have little impact on consumer energy prices.

The rate of the resource use is dependent on the nuclear technology used, and is thus not easily comparable to fossil energy use. The most widespread nuclear technology is the usage of light water reactors (LWR), that use low enriched (4–5% U235) uranium as a fuel. The usual burnup of a light water reactor is around 45–50 GWd/MTHM (gigawatt-days/metric ton of heavy metal), meaning that using 1 ton of 4–5% enriched nuclear fuel, about 45–50 kg U235 is fissioned to produce about 400 million KWh electricity, assuming a thermal conversion efficiency of 34%. To produce the one ton of low enriched nuclear fuel we need approximately 10–11 tons of natural uranium ore (U308). In a usual light water reactor the energy comes from the fission of mainly U235 and Pu239. Pu239 is created from U238 by a neutron capture and a successive beta decay (Villa 2008). The full use of the fuel in a reactor is usually not limited due to fuel exhaustion but due to the progressive build up of (parasitic) neutron absorbers (short lived fission products) in the cycle[5]. As the Carbon Mitigation Initiative in Princeton University notes, doubling the number of worldwide nuclear capacity and replacing coal-fired power plants would have the capacity of reducing 1 billion tons of global carbon emissions each year by 2060, or by one wedge (Princeton University 2011).

Future options could be fast reactors that operate in a fast neutron spectrum with electrons having a kinetic energy over 1,1 MeV (Massachusetts Institute of Technology 2011), and give thus an option of fissioning (or utilising) all parts of the nuclear fuel, including U238, Pu240 and other high level nuclear waste produced by light water reactors. Fast reactors could be set either as burners (to burn more fissile material than they create), self-sustaining reactors (1:1 conversion ratio) or as breeders (create more fissile material than it uses). When fast reactors are set as burners they can present a viable option to reducing nuclear waste created by the LWR technology. Using them as breeders would present an option to extend the uranium reserves instead of reducing the amount of spent high level waste (HLW). As fast reactors need the spent fuel and transuran elements (TRUs) from LWRs to startup, the number of fast burners that can be built

---

[5] One option for conversion is the method of British Petrol (2011b), citing 1 TOE= as 11.63 MWh calorific equivalent, but noting that after conversion, one million tons of oil produces about 4400 gigawatt-hours of electricity in a modern power station. This converts to 4400 million kWh electricity. Therefore depending on the burnup reached in a reactor, 10 tons of 4–5% enriched uranium fuel roughly produces the same electricity as 1 million tons of oil, but without greenhouse gas emissions.

is a function of the number of operating and built LWRs (Massachusetts Institute of Technology 2011). Fast reactor burnup is assumed by Massachusetts Institute of Technology (2011) around 100 GWd/MTHM.

Another often discussed option to nuclear energy would be the use of thorium fuel and the U233 cycle. Presently thorium technologies are in research phase, as uranium is abundant, and there is little economic incentive to invest high research sums into thorium powered reactors. Thorium research is primarily carried out at the moment in India, which owns a large share of the world's thorium reserves, and in China, which is experimenting with German-designed pebble-bed reactors. An advantage of thorium over uranium is that it is more "energy dense", almost all Th232 could be theoretically converted to U233 to fission it. Some thorium technologies (Radkowsky reactor, pebble bed reactors, heavy water reactors with thorium, molten salt reactors), focus on the reduction of waste (no TRUs), others on non–proliferation. As the International Atomic Energy Agency (2005) notes, the use of thorium-based fuels in combination with plutonium has two-fold advantages: on the one hand the production of plutonium and higher actinides are reduced, on the second hand already stockpiled plutonium can be burned effectively in the cycle. Problems with present thorium technologies are the presence of U232 isotopes in the process, which require extremely heavy radiation shielding due to their gamma emissions (International Atomic Energy Agency 2005), but also the smaller fraction of delayed neutrons than in case of the U235 process (Villa 2008), which make reactor controllability much more sensitive and difficult.

Next to the fear of accidents, opponents of nuclear technology are mostly concerned about the problem of nuclear waste and the possibility of nuclear proliferation. Nuclear energy is thus facing in many countries massive public opposition, which tends to be however lower in countries with existing nuclear power (Goodfellow, Williams, and Azapagic 2011). It is notable that perceived risk in case of nuclear power is exorbitantly higher than the true risk of the technology (Slovic 1987). In many cases, anxieties arise from a not-well understood technology, despite the large number of built-in safety measures. Presently, a number of technical possibilities exist to deal with nuclear waste (including transmutation, or burning them in fast reactors) that could be further researched and applied at a large scale, significantly reducing both the lifetime and the radiotoxicity of high level waste (HLW). Currently, most regulators chose the option of storing nuclear waste, either above ground in a temporary storage to allow extraction of the material for the future (US), or are planning deep final repositories (France, Switzerland). The question of nuclear proliferation is a more serious one, as presently available nuclear technologies do not effectively hinder the extraction of weapon-grade material from commercial or research reactors. Fuhrmann (2012) notes however that enrolling in civilian nuclear activities does not imply sinister intention from the beginning.

On the other hand, uranium and thorium resources can be stockpiled easily and for a very long time, therefore they are the most supply-secure resources. After the tsunami induced nuclear accident at the Fukushima nuclear power plant in 2011, nuclear produced energy numbers have been worldwide revised downwards, and a number of European governments decided to phase out nuclear energy or not to go forward with nuclear expansion. The substitution of nuclear plants with coal or gas plants means not only significantly higher greenhouse gas emissions, potentially expensive carbon capture and storage, but also, in the absence of cheap fossils or other energy source, increased electricity cost impacting on economic performance and thus employment.

2.3 Hydro, geothermal & other renewable sources

Renewable energy sources have been on the rise during the past decades. Global climate change and environmental pollution necessitates the increasing of renewable energy shares throughout the developed world. In spite of the extensive research and development efforts of the past years, there are only a few renewable technologies presently able to compete at the market with conventional energy sources without sufficient government subsidies. Renewable energy sources have the clear advantage of being environmentally friendly with low or no greenhouse gas emissions, or other environmental pollution. The major economic setbacks are the government subsidies required for their market survival. With higher economies of scale however (with the doubling of production) production costs are expected to decline (IPCC 2011), yet the uncertainty involved about the future price of renewables is very high. One major technical setback is the non–constant performance of renewables that requires secure base-load technologies and back-up power plants in case of low performance. Another issue to be considered are the secondary environmental /social impacts such as land use, crop price increase, social problems due to relocation of population (hydropower projects), and loss of habitat. This section is largely based on the IPCC (2011) report's technical summary of renewable energy generation.

The major renewable energy sources can be classified according to the IPCC (2011) into bioenergy, direct solar energy, geothermal energy, hydropower, ocean and wind energy. The joint technical potential of renewable energy sources is estimated by the IPCC (2011) report to be several magnitude higher than the current energy demand. However there is notably a high uncertainty regarding these estimates. It is wiser thus to work with the given minimum (definitely available) technical potential estimates (Table 1), while keeping in mind that transmission, grid, and economic constraints are much likelier to limit the usage of renewable energy. There is a certain inconsistency between the British Petrol (2011b) and the IPCC (2011) reports about the share of renewable energy and natural gas in worldwide primary energy consumption. The IPCC (2011) report estimates global natural gas consumption at 22,1%, and renewable energy at 12,9%, with bioenergy constituting the largest share. The British Petrol (2011b) report does not consider bioenergy, only hydropower and other renewables. The IPCC report uses the „direct equivalent" method for calculating primary energy supply. This includes fossil fuels and bioenergy to be accounted for based on their heating value, while other non–combustible and nuclear energy sources to be accounted for the secondary energy they produce. This leads to an understatement of nuclear energy by a factor of 3, and other non–combustibles to a factor between 1.2–3 compared to bioenergy and fossil resources in IPCC (2011).

While we take note of this inconsistency problem, we shall use the British Petrol (2011b) values for our report for the sake of consistency. Bioenergy, such as wood for cooking and heating is primarily used in the developing world, which countries are at the moment largely excluded from our sample due to lack of data. We do take however the renewable energy resource potential from the IPPC report, while accounting for future reserves/potential[6]. To cope with the large uncertainty, we include only the minimum (absolutely certain) of global technical potential for renewable energy sources.

Table 1: Annual estimated worldwide minimum technical potential (IPCC 2011)

		Unit	MTOE
Renewables for electricity generation	Hydropower	50 EJ	1194.0
	Ocean Energy	7 EJ	167.2
	Wind Energy	85 EJ	2029.8
	Geothermal	118 EJ	2817.8
Renewables for heating	Geothermal	10 EJ	238.8
Renewables other	Biomass	50 EJ	1194.0
	Direct Solar Energy	1575 EJ	37611.0
	Total		45252.6

* Source: IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation

Technical potential is defined by Lopez et al. (2011) as representing the achievable energy generation of a particular technology given system performance, topographic limitations, environmental, and land-use constraints. The minimum estimated annual technical potential from different energy forms as categorised by the IPPC can be seen in Table 1. As seen, the annual technical potential exceeds the present primary energy usage according to the IPCC, even in the worst-case scenario, with direct solar energy carrying the lion's share of this potential. How much of this technical potential will be a viable economically is a difficult question to answer. In the next sections we are going to look at the main renewable technologies, along with their benefits, potential challenges and hazards.

Hydropower is defined as a "renewable energy source where the power is derived from the energy of water moving from higher to lower elevations" (IPPC, Technical Summary p. 80). Hydropower is one of the most widely used renewable energy, which feeds into the electrical system (International Energy Agency 2011). There are three main hydropower plant (HPP) project types, the run-of-river (RoR) type, the storage and pumped storage type plants (IPCC 2011). The lifetime of a hydropower plant is estimated presently at 40-80 years. The RoR plant types have a varying power generation ability, as they have usually no water storage available to regulate hydrological cycles, save for a few large scale plants operating in cascades (upstream plant with storage). Storage hydropower plants are built with water reservoirs, and are capable of functioning as baseload plants and energy storage, but can also effectively used as flood control and irrigation tool if required. Pumped water storage plants are capable to produce electrical

---

[6] The IPPC values are noted in EJ (1 MTOE= 0,04187 EJ), which converts to 23.88 MTOE.

energy on demand by reversing the flow of water, in a fast response time (IPCC 2011). Sediment transport and reservoir sedimentation are identified by the IPCC (2011) as potential problems, as they can with time deplete reservoir storage capacity, can increase downstream degradation and upstream flood risk. Using HPPs as peak-plants (supplying energy to meet peak demand) is however strongly discouraged, as it may produce very rapid fluctuations in the river flow. Besides the evident advantages of being carbon emission neutral, hydropower carries a number of local hazards, such as change to the ecosystem of the river, and the surrounding environment (IPCC 2011), relocation of large amounts people from the vicinity, as well as the potential of large-scale accidents. Despite of this, hydropower can be called a mature technology, which is capable of competing with other energy forms in open market conditions without subsidies.

Ocean energy technologies are presently in a development phase, and carry a potential to mitigate carbon reductions on the long term. There are presently six different ocean energy technologies, utilising wave energy (the kinetic energy of the wind above the ocean surface), tidal energy due to the gravitational forces of the Sun and the Moon, and tidal current energy utilising the coastal tidal changes of rivers. Furthermore ocean currents, the thermal energy of the oceans, or the difference in salinity gradients of the fresh and ocean waters could be technically utilised (IPCC 2011). These options are not equally distributed around the earth, with ocean thermal energy having the largest potential around the equatorial waters, and ocean wave power north of the 30° latitude. Of these options, only tidal range technologies are considered mature (IPCC 2011), which are mostly exploited through river-based hydroelectric dams, or tidal turbines. Gardiner, B. (2012) notes, that the first tidal stream project to deliver energy to the US grid went online in September 2012. Wave technologies currently under development include oscillating water columns, oscillating bodies, and overtopping devices. Many other forms of ocean energy concept, such as the thermal energy conversion is at the moment facing serious problems, and is not practically applicable at the time of this paper.

Geothermal energy has been used in the past centuries, although not as extensively as it is today. Geothermal energy utilises the warmth of the Earth's interior, trapped in rock and water. It can be used to generate electricity in a thermal power plant, or for district heating (International Energy Agency 2012). Geothermal energy is extracted through wells, or artificial fluid pathways. For heating applications it is recovered using heat pumps. Once a power plant is built, it is suitable for both base-load and peak power generation. Plant capacities usually range between 20 to 110 MW electrical (IPCC 2011), and include either binary cycle plants, where the geothermal fluid passes through a heat exchanger and heats a low-boiling point fluid in the secondary circuit, which in turn vaporises and drives the turbine. Or, a second type of plant design uses simply steam condensing turbines. Notably carbon dioxide emissions from geothermal resources do happen, and are the results of drilling and natural release of greenhouse gases from the earth. Micro-earthquakes or steam eruptions could also potentially occur (IPCC 2011). Geothermal energy has to cope with local environmental and land-use problems, which can be however addressed with careful planning.

Biomass or bioenergy includes among others fuelwood, charcoal, agricultural by-products, energy crops, animal by-products and are used even today by billions of people especially in developing countries (IPCC 2011). It is very difficult to estimate the actual share of bioenergy in total primary energy, and a number of reports do not consider it at all. The share of bioenergy in developed countries is significantly lower however, and is composed of high efficiency modern liquids and gases, such as biogas derived methane, ethanol, biodiesel. Potentially bioenergy could be used for district heating systems and road transportation (IPCC 2011). Most of these energy technologies survive on the market however only with heavy subsidies. Extensive use of bioenergy can lead next to the hazards to biodiversity, to modified land and water use, and to increasing food crop prices, that might take a worldwide impact, contributing in the worst case to famine and reduced food security. How much greenhouse gas reduction can be achieved with biomass is a controversial issue, as only certain technologies have the potential to reduce forcing levels, other must be coupled with carbon capture and storage technologies, that impact again on the overall costs.

Wind energy has a long standing tradition in most cultures, and has been used for electricity production since the 1970s. Grid connected wind turbines utilise the kinetic energy of the moving air (IPCC 2011). To increase the economic viability of wind turbines, turbine size has increased considerably and is further expected to expand in the future. Wind turbines can be located either onshore or offshore, whereas there is not much commercial experience with offshore wind parks. Technical challenges related to wind energy involve the lack of transmission infrastructure and storage of energy, challenges with the grid connection, as well as servicing and building problems with offshore wind energy. Since the 2011 German decision to phase out nuclear energy and support renewable energy forms, wind turbines have been erected in a large number in certain regions of Germany, leading to feed-in and transmission bottlenecks, that have to be coped with urgently. The IPCC (2011) report mentions, that public resistance to wind energy and issues with the (local) environmental impacts are likely to resist growth, well before any limit on the global technical potential could be reached.

Solar energy has a massive theoretical technical potential in meeting energy needs. However, the presently existing alternatives are very expensive and without the drastic reduction of costs, it is unlikely to reach a larger share in the global energy supply. The presently modelled deployment scenarios are still uncertain and do not consider all possible technologies (IPCC 2011). The main types of solar energy include solar thermal energy, photovoltaic systems, optical concentration of solar power, and solar fuel production (IPCC 2011). Of the four forms, the most controversial is the photovoltaic electricity generation, which —– very simply put —– uses a thin layer of semiconductor material, most of the time silicon. This material is consisting of two layers, introducing impurities into the silicon, and thus forms a junction at the interface. When solar photons strike the cell, electron hole pairs are generated, which are separated spatially by an internal electric field at the junction. This creates negative charges on one side and positive charges on the other side, resulting in voltage. (IPCC 2011, p.62). The photovoltaic (PV) industry uses a number of toxic and explosive gases as well as corrosive liquids in production (IPCC 2011), which also raises concerns about the proper disposal of the PV cells at the end of their lifetimes. Such concerns do not however impact upon other types of solar technologies, which offer a clean and greenhouse gas free energy. Concentrating solar power, transmits the sun's heat (beam) energy to a medium, which is used to (either with the support of a heat exchanger or without) drive a steam turbine. Presently, there are a number of different designs, for example the dish system and the Fresnel system in use (IPCC 2011). According to the Carbon Mitigation Initiative of the Princeton University, either increasing wind electricity capacity by ten times relative of today (+2 million large windmills), or installing 100 times the current solar electric capacity, or setting up 40.000 square km of solar panels to produce hydrogen as car fuel, or increasing ethanol production 12 times as of today, creating plantations equal to 1/6 of world cropland could each reduce carbon emissions by one wedge (Princeton University 2011).

2.4 Alternative energy forms

There are a number of alternative energy forms, the future deployment of which is largely uncertain and will be decided by future research results. Most notable is the alternative nuclear energy option in the form of fusion power. Despite of it great promise, deuterium-tritium fusion research up to now had failed to produce commercially usable results. Presently the International Thermonuclear Experimental Reactor (ITER) project, co-financed by a number of countries (ITER 2011), is planned, once it is built to move forward (magnetic) fusion research. Next to ITER there are a limited number of smaller research tokamaks or stellarators worldwide.

The largest fusion reactor known presently is the Sun, where thermonuclear fusion is happening in hot plasma. A hydrogen nucleus with an extra neutron is called deuterium (H2), and with two neutrons is called tritium (H3). In the core of the Sun, deuterium and tritium can fuse to form a Helium nucleus and a neutron, whereby releasing large amount of energy. To replicate this process is however very difficult, as the positively charged deuterium and tritium strongly repel each other, therefore such reaction is only possible in hot plasmas, where atoms are fully ionised. “The thermal energy of the nuclei in these plasmas is so high that positively charged nuclei can penetrate the Coulomb barrier and approach so closely that fusion can occur” (Phillips 1983, p.63). To recreate this process in laboratory circumstances, plasma has to be heated to very high temperatures, and confined long enough for fusion to occur (Lidsky 1983). Theoretically, there are two kinds of fusion options, the inertial confinement fusion and the magnetic confinement fusion. Gravely simplified, inertial confinement works by compressing a very small target, usually containing deuterium-tritium under extreme pressure and temperatures reaching 100 million Celsius, with the help of usually laser, before the plasma disperses (Commissariat à l'énergie atomique et aux énergies alternatives 2012). Inertial confinement fusion has military implications as well, as the conditions prevailing can be used to simulate thermonuclear weapons tests, or the ageing of thermonuclear weapons.

In practice however, the magnetic confinement fusion has looked more promising and two concepts evolved within, including the tokamak and the stellarator concept. Magnetic fusion requires creating and maintaining plasma at very high temperatures for sufficiently long time (about 10 seconds) for fusion to occur (Lidsky 1983). This is achieved in torus shaped containers, which are surrounded by a strong magnetic field, to keep the plasma from touching the walls of the container, as particles could escape or the plasma could develop turbulence while contaminated by heavier nuclei. Thus, a rectilinear (toroidal) magnetic field is deployed to act on the charged particles of the plasma (Commissariat à l'énergie atomique et aux énergies alternatives 2012), which moves along the field lines without touching the container. Helical magnetic lines are created by adding a perpendicular magnetic field to the toroidal fields. In a tokamak this is achieved by adding a strong axial current flowing through the plasma. In a stellarator, no current is flowing through the plasma, but the plasma is flowing in helical coils (Commissariat à l'énergie atomique et aux énergies alternatives 2012). Presently open technical challenges include the controlling of plasma turbulence and disruptions as well as the wall-plasma interaction.

Another noteworthy future technology would be the usage of hydrogen for transportation or electricity. Hydrogen is however very difficult to transport, as it is considerably less energy dense than other fuels even under 700 bar pressure (International Energy Agency 2012). An important variable in of future energy usage, energy efficiencies can be expected to continue in end-user as well as transformation technologies throughout the century. The choice of the resource will however determine where and which transformation technology will evolve most.

3 Data and Methodology

3.1 The Model

The aim of this paper is to project primary energy consumption, which we denote in million tons of oil equivalent, after the unit of measurement of British Petrol (British Petrol 2011b). We work with averaged coefficient estimates of 33 panel error correction models, gained using a panel sample of 64 countries. The primary energy consumption of our sample countries with 10552 MTOE constitutes approximately 94.5% of the worldwide total, as of 2009 (British Petrol 2011b). Each state in this sample was assigned into a set of nine panel error correction models, three basic composition models (E.YL, E.LK, E.LKA), and three attribute models (world, regional and wealth level).

The panel error correction equations estimated were:

1. The EC model of primary energy consumption on GDP and on population ($E.YL$)

$$\begin{aligned}\Delta logE_{i,t} = {} & \alpha(logE_{i,t-1} - \beta_0 - \beta_1 logY_{i,t-1} - \beta_2 logL_{i,t-1}) \\ & + \gamma_0 \Delta logE_{i,t-1} + \gamma_1 \Delta logY_{i,t-1} + \gamma_2 \Delta logL_{i,t-1} + \mu_i + \lambda_t + \epsilon_{i,t}\end{aligned} \tag{1}$$

2. The EC model of primary energy consumption on population and physical capital ($E.LK$)

$$\begin{aligned}\Delta logE_{i,t} = {} & \alpha(logE_{i,t-1} - \beta_0 - \beta_2 logL_{i,t-1} - \beta_3 logK_{i,t-1}) \\ & + \gamma_0 \Delta logE_{i,t-1} + \gamma_2 \Delta logL_{i,t-1} + \gamma_3 \Delta logK_{i,t-1} + \mu_i + \lambda_t + \epsilon_{i,t}\end{aligned} \tag{2}$$

3. The EC model of primary energy consumption on population, physical capital and technology ($E.LKA$)

$$\begin{aligned}\Delta logE_{i,t} = {} & \alpha(logE_{i,t-1} - \beta_0 - \beta_2 logL_{i,t-1} - \beta_3 logK_{i,t-1} - \beta_4 logA_{i,t-1}) \\ & + \gamma_0 \Delta logE_{i,t-1} + \gamma_2 \Delta logL_{i,t-1} + \gamma_3 \Delta logK_{i,t-1} + \gamma_4 \Delta logA_{i,t-1} + \mu_i + \lambda_t + \epsilon_{i,t}\end{aligned} \tag{3}$$

In our notation, E is the primary energy consumption, Y is real income, L is the total population, K is the physical capital calculated with the perpetual inventory method, and A is the total factor productivity computed as the Solow residual. A total of 33 models were estimated in Csereklyei and Humer (2012), where regional groups included Asia & Pacific (AS), Eastern Europe & Eurasia (EE), Middle East & Africa (ME), North America (NA), South America & Mexico (SA) and Western Europe (WE), while the gross domestic product per capita groups accounting for wealth effect consisted of low income (L) [$\leq 10K\$$], middle-low income (ML) [$10K\$ - 20K\$$], middle-high income (MH) [$20K\$ - 35K\$$] and high income (H) [$\geq 35K\$$] countries.

For the purpose of averaging, the cointegrating coefficients stemming from the six regional groups for each structural model (E.YL, E.LK, E.LKA) are aggregated into one regional model, weighted proportional to the number of observations in the regional groups. The coefficients from the income per capita level group are aggregated similarly, until we have only one real income per capita model for each of the three structural variants).

Since the model averaging in Csereklyei and Humer (2012) could be performed on only 45 countries due to the insufficient length of the Eastern European and partially of the Middle Eastern and Africa dataset, we re-estimate the averaged coefficients for the purpose of the projections. We use thus the results from all 64 countries and 6 regions, but weigh the parameter estimates of the 3×3 aggregate panel error correction models with the weights obtained on 45 models, as in Csereklyei and Humer (2012). This way we include the coefficients of the Eastern European region as well, enabling thus more accurate projections for the former Eastern Block countries.

The model weights calculated in Csereklyei and Humer (2012) based on both the out–of–sample forecasting errors and the in–sample–fit of the models are presented in Table 2.

Table 2: Model weights assigned to the averaged coefficients

	E.LKA$_W$	E.LK$_W$	E.YL$_W$	E.LKA$_R$	E.LK$_R$	E.YL$_R$	E.LKA$_G$	E.LK$_G$	E.YL$_G$
$w^{\xi}_{m,t+10}$	0.12	0.14	0.09	0.11	0.11	0.11	0.10	0.11	0.11
w^{SSE}_m	0.11	0.11	0.11	0.12	0.11	0.11	0.11	0.11	0.11

* Source: Own calculation, w^{SSE}_m: model weights assigned based on in-sample fit, $w^{\xi}_{m,t+10}$: model weights assigned based on the 10th step ahead forecast horizon, out–of–sample forecast errors

After the inclusion of the EE and ME regions into the averaging procedure, the averaged cointegration coefficients gained with the 64 countries are found in Table 3.

Next, we project the primary energy consumption, by utilising the long–run coefficient averages from above. To account for the uncertainty arising from varying macroeconomic developments, we use pro country four different macroeconomic scenarios (shared socioeconomic pathways), as

Table 3: Averaged Coefficient Estimates on the Determinants of Primary Energy Consumption

		α	β_1	β_2	β_3	β_4	β_0
$\mathcal{M}$	ξ	-0.06	0.09	1.51	0.12	-0.07	-13.52
	SSE	-0.06	0.10	1.54	0.10	-0.06	-13.64

[*] Source: Own Calculation, α: error correction coefficient, β_1: long–term coefficient on GDP, β_2: long–term coefficient on population, β_3: long–term coefficient on physical capital, β_4:long–term coefficient on total factor productivity.

defined in Kriegler et al. (2010). Thus, the number of models estimated pro country will be 4×2, sufficiently reflecting the inherent uncertainty in forecasting.

3.2 Data

We source the population (L), and the real income (Y) values for each of the four shared socioeconomic pathway (SPP) scenarios from the GDP projections of the IIASA (2012b), running from 2010 to 2100. The sample size for the projections is decreased to 56 countries however, due to the availability of real income and population forecasts [7].

The assumptions regarding population and economic development can be seen in the Annex. The four SSPs are defined as in Kriegler et al. (2010), and chosen to reflect scenarios with different worldwide challenges for adaptation and mitigation. Simply put, socioeconomic changes to mitigation include factors that tend to lead to high reference emissions in the absence of climate policies, and factors that would tend to reduce the inherent mitigate capacity of a society. On the other hand, socioeconomic challenges to adaptation are societal conditions that increase the risk associated with any given climate change scenario (Kriegler et al. 2010). High reference emissions can be caused according to Kriegler et al. (2010) by a number of factors, such as high population growth, rapid economic growth, energy intensive economic systems, or carbon intensive energy supplies.

In this study we work first with the SSP1 scenario, assuming reasonable mitigation and adaptation capability, with high rate of development and lessened inequalities. Rapid technological change and environmentally friendly energy resource use are assumed. Its opposite, the SSP3 scenario, on the other hand models a world with large challenges to both mitigation and adaptation. One manifestation would be very high population growth and large unmitigated emissions, coupled with slow technological change in the energy sector. In this world, investments

---

[7] We project thus primary energy consumption for Algeria, Argentina, Australia, Austria, Bangladesh, Belgium, Brazil, Bulgaria, Canada, Chile, China, Colombia, Czech Republic, Denmark, Ecuador, Egypt, Finland, France, Germany, Greece, Hong Kong, Hungary, India, Indonesia, Iran, Ireland, Italy, Japan, Kazakhstan, South Korea, Lithuania, Malaysia, Mexico, Netherlands, New Zealand, Norway, Pakistan, Peru, Philippines, Poland, Portugal, Romania, Russia, Saudi Arabia, Singapore, Slovak Republic, South Africa, Spain, Sweden, Switzerland, Thailand, Turkey, Turkmenistan, Ukraine, United Kingdom, United States.

in human capital are low and inequality is high, with institutional development leaving many people vulnerable to the aftermath of climate change. The SSP2 scenario is an intermediate case between the two extremes above (Kriegler et al. 2010). The last scenario we consider is the SSP5 scenario narrating a world with large challenges to mitigation but with adequate capabilities to adapt. An example would be high energy demand, which is met with fossil resources, thus creating high emissions. At the same time quick economic development strengthens institutions and investments in human capital are growing, which in turn reduces inequalities and population growth. This leads finally to reductions in energy consumption. (Kriegler et al. 2010). The assumed development of the sample population can be seen in Figure 1.

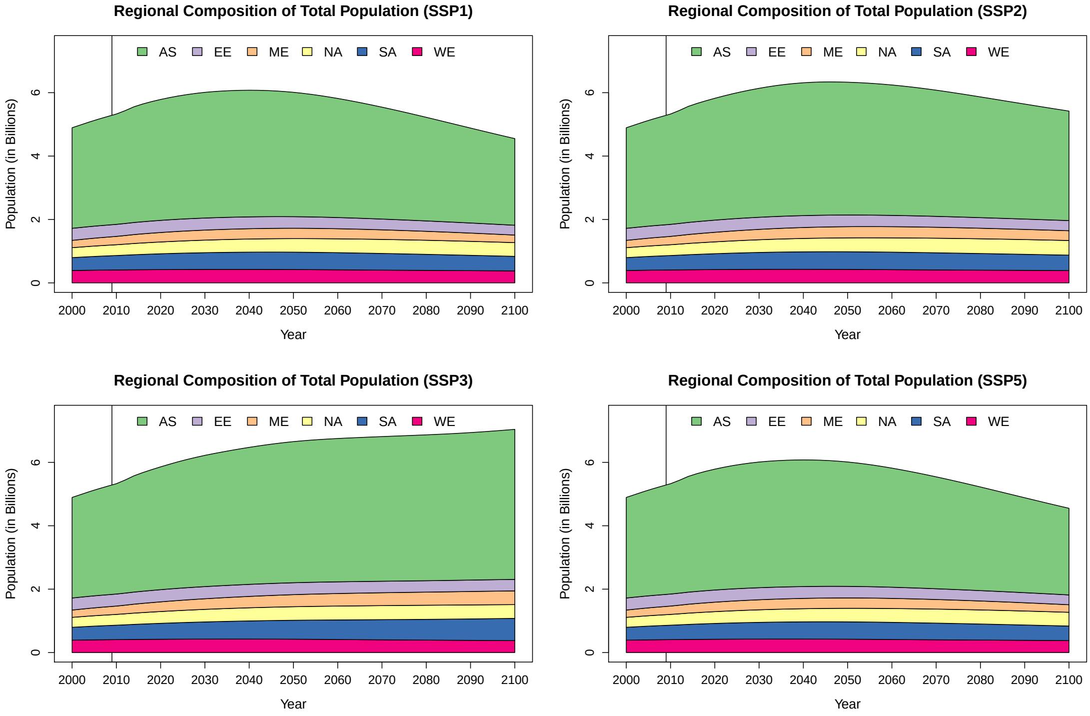

Figure 1: Projected Sample Population for 56 countries

Accordingly, the projected population is the highest in the SSP3 scenario, while the lowest in the SSP1 and SSP5 cases accordingly, with SSP2 presenting the middle way. As we can see, population is expected to peak around 2040–2060 for our sample, then slightly decreases in most scenarios. Similarly, as expected the growth rate of real income is modelled to be the highest for the SSP5 case, followed by SSP1 and SSP2, while the lowest in the SSP3 scenario. The real income scenarios were estimated with an econometric model implying that the growth rate of total output (Y) depends on the growth rate of each one of the factors of production (total factor productivity, physical capital, and of different subpopulations, divided into age and education level).[8] The GDP development of our sample countries can be seen in Figure 2.

---

[8] The model estimated is $g_Y = \lambda \log(\frac{Y}{L}) + \sum_{j=0}^{3} \varphi_j |\frac{L_{1j}+L_{2j}}{L}] + \sum_{j=0}^{3} \theta_j |\frac{L_{1j}+L_{2j}}{L}] \log(\frac{Y}{L}) + \alpha g_K + \sum_{j=1}^{2} \sum_{k=0}^{3} \beta_{jk} g_{L_{jk}}$, where g_X is the growth rate of variable X over the given period and all variables which are not growth rates

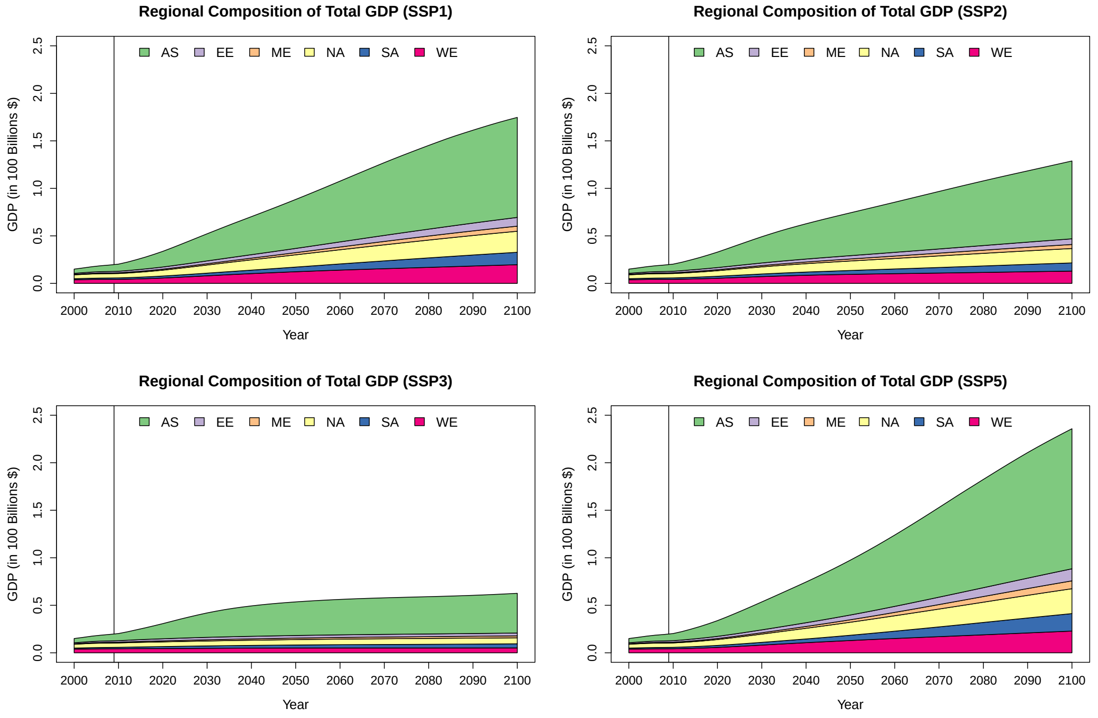

Figure 2: Projected Sample Gross Domestic Product for 56 countries

The series were interpolated as in Stineman (1980) between the five year non–overlapping intervals. The physical capital (K) series is calculated using the perpetual inventory method by Bernanke and Gurkaynak (2001). The starting capital stock was taken from our 2009 values, available in Csereklyei and Humer (2012). Afterwards, the series was constructed as:

$$K_{i,t} = K_{i,t-1}(1-\delta) + I_{i,t} \tag{4}$$

where I is the annual investment into physical capital, and δ is the depreciation rate, uniformly assumed to be 6%. Another necessary assumption involves the development in the investment share of income (k_i), which is used to calculate the annual investments (I), as a percentage of real income. Since k_i is a stationary, but very highly persistent variable, we have taken into account past trends in investment shares when projecting this series. For developed countries with an investment share around 20–25% we have reduced the expected values to 20% fast, while the k_i of presently developing countries was kept for a few decades high, following the pattern of earlier developments, then slowly reduced to the level of Western industrialised countries around the middle of the 21st century. As these countries will move towards more knowledge based GDP creation in the future, the investment share of GDP is likely to decrease. Based on the above we have constructed our dataset. The technology variable (A) was calculated as in Csereklyei and

---

are measured at the initial year of the considered 5 year period. Country–specific effects and period fixed effects (which we interpret as overall movements in the technology frontier that are independent of those caused by the variables of the model) are included (IIASA 2012c).

Humer (2012), as the Solow residual.

4 Results

In interpreting and analysing the results of this paper, we have to keep in mind first the inherent uncertainty regarding projections in general. Although we attempt to cover a wide range of scenarios based on differing assumptions, neither grave technological breakthroughs, wars, geopolitical conflicts, or other major events can be considered that might change the course and the pattern of the future drastically. The sample set of 56 countries does not cover the entire world. The primary energy consumption of our reduced sample set as of 2009 totalled approximately 10,225.20 MTOE, which constitutes based on the BP database about 89.9% of the worldwide usage. As other developing countries will grow both demographically and economically, the energy consumption in these regions is also likely to speed up. Therefore, we expect the total worldwide energy demand to be higher than our projections. Also, the pattern of energy consumption might also shift, as African, Middle East and South-Asian countries embark on a higher growth period.

4.1 Projecting long–term energy consumption

The energy projections in this section are gained by applying the long–term cointegrating relationships to the different shared socioeconomic pathway assumptions. The determinants of primary energy usage in our models are thus real income, population development, physical capital and technology. We work with the coefficients obtained through the averaging of our nine basic models.

The final parameter estimates on the drivers of energy consumption are thus determined by the specification of the model (E.YL, E.LK, E.LKA), the weights determined based on the performance of out–of–sample rolling forecasts, applied to the conditional on inclusion coefficients. The major driver of primary energy usage is thus in our specific case the population development, and a positive but lesser effect is carried by physical capital and real income increases. A crucial factor in decreasing primary energy consumption are technological improvements. As mentioned before, we model technology (A), as the Solow residual. This residual however may not only capture energy efficiency improvements, innovations, but also changes in the structure of economies and a move towards more service income in GDP generation. It is very difficult to decompose the components of total factor productivity, as all of the above factors work in the same direction. Present literature expects the presence of massive energy efficiencies (ExxonMobile 2012; International Energy Agency 2011) in the future.

How much total factor productivity will decrease primary energy consumption in our forecasts depends on the population and real income scenarios we draw upon for our projections. In all four scenarios, China, India and the United States are the highest energy consumers in the current century. The increases in total factor productivity however, in case of the United States are significantly lower than in case of India or China based on the IIASA dataset. While we recognise that this assumption limits the impact of TFP gravely in the US projections, we also note that contrary to these, both the United States Energy Information Administration (2012) and large energy companies such as ExxonMobile (2012) expect very low increase in US energy demand and even the lowering of energy demand up to 2035-40, which development is attributed mostly to improvements in energy efficiencies. The long–term energy projections for our sample countries can be seen in Figure 3.

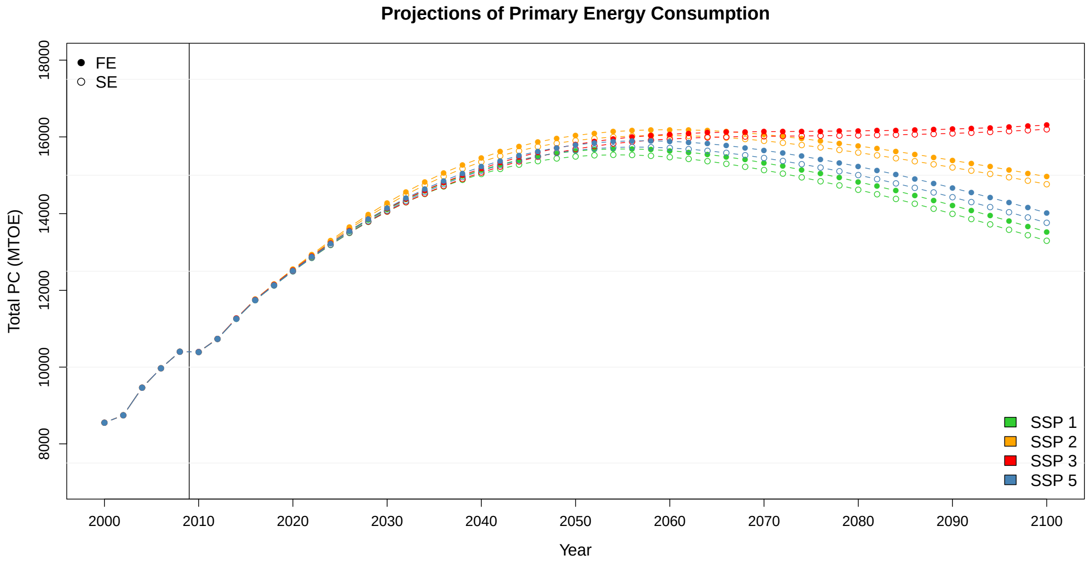

Figure 3: Projection of Primary Energy Consumption for 56 Sample Countries

The rapidly increasing energy demand up to the middle of the century is mostly driven by developing countries. All scenarios uniformly show a strong increase in energy consumption for presently low income countries such as China, India, Pakistan, Turkmenistan, Indonesia, Malaysia or Egypt and Algeria, while a stagnation or a gradual decrease for already developed, Eastern and Western European countries. The reasons behind the decreasing energy consumption in Europe are however twofold, partially decreasing population and partially total factor productivity increases. A country by country overview of the development of primary energy consumption as well as the relative change of the explanatory variables with respect to 2009 can be seen in the Annex. Our regional projections based on the four SSP scenarios are found in Table 4 and in Table 5. The SSP1 scenario, being the so called *best case* from a climate change point of view assumes reasonable mitigation and adaptation capabilities, with quick economic development and lowered inequalities. Also, the rate of total factor productivity increase is as expected high, dimming energy consumption for all regions.

When comparing SSP1 results to the other socioeconomic scenarios, we see that worldwide primary energy consumption is the lowest at all points in time. One interesting result is that while developing countries (mainly low income per capita countries) show lower primary energy use as in other cases, high income per capita countries, such as the Western European or the

Table 4: Projection of Energy Consumption (E_ξ) — MTOE

	2009	2015	2035	2050	2065	2070	2085	2100
SSP1								
AS	3960.70	4597.53	5982.56	6062.19	5566.33	5334.07	4611.87	3954.53
EE	1159.50	1217.17	1325.56	1316.41	1261.87	1241.16	1192.69	1157.93
ME	639.10	786.85	1088.12	1194.41	1184.31	1152.57	1009.64	842.29
NA	2501.20	2783.96	3728.69	4302.78	4719.07	4823.53	5006.59	4964.62
SA	548.30	619.87	826.26	919.37	954.03	954.33	924.44	865.05
WE	1446.40	1520.87	1747.17	1834.45	1827.66	1818.36	1790.28	1740.85
World	10255.20	11526.25	14698.35	15629.60	15513.28	15324.03	14535.51	13525.27
SSP2								
AS	3960.70	4603.69	6139.27	6353.84	6049.32	5881.85	5347.43	4887.99
EE	1159.50	1217.56	1324.79	1300.32	1236.06	1214.84	1169.59	1148.14
ME	639.10	791.00	1156.29	1326.38	1380.52	1370.61	1299.68	1207.37
NA	2501.20	2784.56	3745.44	4325.58	4752.84	4870.84	5101.85	5136.45
SA	548.30	620.39	836.67	920.10	943.03	940.94	913.03	867.13
WE	1446.40	1521.53	1742.45	1809.59	1792.87	1781.58	1752.39	1715.64
World	10255.20	11538.73	14944.91	16035.81	16154.64	16060.67	15583.96	14962.71
SSP3								
AS	3960.70	4609.87	6176.21	6538.08	6460.42	6397.04	6269.25	6342.58
EE	1159.50	1218.33	1323.24	1302.07	1244.16	1226.21	1202.47	1210.28
ME	639.10	794.79	1211.88	1456.65	1633.50	1674.99	1781.51	1893.72
NA	2501.20	2775.36	3507.77	3875.35	4113.95	4165.85	4220.41	4107.54
SA	548.30	621.22	856.42	988.52	1090.57	1122.54	1217.11	1339.37
WE	1446.40	1515.88	1637.18	1639.70	1574.39	1549.69	1483.25	1413.19
World	10255.20	11535.45	14712.70	15800.38	16117.00	16136.33	16174.00	16306.67
SSP5								
AS	3960.70	4597.41	6008.44	6137.91	5691.65	5473.08	4784.14	4141.72
EE	1159.50	1217.19	1330.98	1332.61	1290.69	1274.17	1237.60	1213.10
ME	639.10	786.85	1093.06	1211.45	1217.07	1189.90	1056.24	891.49
NA	2501.20	2783.99	3737.07	4331.17	4775.24	4889.88	5103.00	5085.56
SA	548.30	619.88	829.70	931.42	977.51	981.61	961.43	908.34
WE	1446.40	1520.89	1750.77	1845.47	1847.46	1841.11	1821.72	1779.77
World	10255.20	11526.20	14750.02	15790.03	15799.61	15649.75	14964.13	14019.99

[*] Source: Own Calculation, Primary Energy Projection for the different Shared Socioeconomic Pathways up to 2100, based on weights gained by the out–of–sample rolling forecast performance of the models.

North American region show higher energy consumption in this scenario as in the SSP3 version. The reason for this development is that while both real income growth and technology growth is higher in the first scenario, the positive impact of income growth for developed countries is not compensated by the total factor productivity increases.

Contrary to the first case, the SSP3 scenario, or the *worst case* picture models a world with large challenges to both mitigation and adaptation. This case assumes high population growth and large unmitigated emissions, as well as slow technological advancement in the energy sector. As expected, total primary energy use is the highest in our SSP3 scenario while SSP2 shows an intermediate energy demand between the two extremes.

The SSP5 scenario depicts a world with large challenges to mitigation but with adequate capabilities to adapt. High energy demand is coupled with quick economic development, but

Table 5: Projection of Energy Consumption (E_{SSE}) — MTOE

	2009	2015	2035	2050	2065	2070	2085	2100
SSP1								
AS	3960.70	4592.17	5915.39	5964.46	5457.15	5224.76	4503.11	3849.74
EE	1159.50	1215.83	1311.91	1298.10	1240.80	1219.14	1167.90	1130.85
ME	639.10	785.77	1085.86	1192.18	1178.99	1145.89	998.81	828.92
NA	2501.20	2785.93	3731.94	4295.18	4700.12	4800.92	4973.15	4920.49
SA	548.30	619.88	824.86	915.48	946.30	945.11	911.00	848.53
WE	1446.40	1520.26	1743.48	1823.88	1810.53	1799.43	1767.19	1714.67
World	10255.20	11519.83	14613.44	15489.28	15333.90	15135.24	14321.16	13293.19
SSP2								
AS	3960.70	4598.22	6071.65	6255.58	5941.43	5774.60	5240.88	4782.01
EE	1159.50	1216.21	1310.85	1282.59	1217.05	1195.44	1148.78	1125.74
ME	639.10	789.98	1154.90	1326.03	1378.18	1367.31	1293.12	1197.92
NA	2501.20	2786.12	3749.38	4323.22	4744.30	4860.45	5084.91	5111.54
SA	548.30	620.43	835.25	916.14	936.36	933.26	902.39	853.99
WE	1446.40	1520.75	1738.69	1800.23	1778.84	1766.37	1734.49	1695.57
World	10255.20	11531.71	14860.72	15903.79	15996.16	15897.43	15404.57	14766.77
SSP3								
AS	3960.70	4604.20	6107.77	6441.89	6359.63	6298.95	6179.32	6259.40
EE	1159.50	1217.00	1308.90	1284.57	1226.61	1208.81	1185.64	1193.93
ME	639.10	793.83	1211.15	1458.83	1637.61	1679.59	1787.27	1901.45
NA	2501.20	2775.51	3508.46	3876.88	4115.39	4167.00	4219.45	4102.43
SA	548.30	621.26	855.08	985.86	1087.11	1118.88	1213.30	1336.25
WE	1446.40	1514.25	1632.54	1633.85	1566.77	1541.58	1474.17	1403.33
World	10255.20	11526.06	14623.89	15681.87	15993.13	16014.82	16059.15	16196.78
SSP5								
AS	3960.70	4592.07	5941.64	6038.80	5577.94	5358.33	4666.63	4025.67
EE	1159.50	1215.85	1317.48	1314.14	1268.74	1250.96	1210.66	1182.89
ME	639.10	785.77	1091.03	1209.27	1211.08	1182.23	1043.52	875.59
NA	2501.20	2785.98	3740.64	4323.54	4755.19	4865.69	5066.30	5036.42
SA	548.30	619.89	828.43	927.48	969.15	971.52	946.34	889.48
WE	1446.40	1520.27	1747.22	1834.87	1829.87	1821.55	1797.42	1751.78
World	10255.20	11519.85	14666.44	15648.09	15611.97	15450.27	14730.87	13761.83

[*] Source: Own Calculation, Primary Energy Projection for the different Shared Socioeconomic Pathways up to 2100, based on weights gained by the in-sample fit of the models.

also with large investments in human capital, which as a consequence lessen inequalities and reduce population growth. This effect leads finally to reductions in energy consumption. As expected primary energy consumption is the lowest in the SSP5 scenario after the SSP1 scenario. Based on our simulations, except for the worst case scenario, energy consumption begins to decline for our sample around 2060. When asking the question whether countries in similar phases of economic development have similar energy use patterns, our answer would be, only if they experience similar population growth, and their in economic growth will be similarly physical capital driven. Leapfrogging to more efficient and modern technologies in developing countries appears unlikely, especially in regions with very low nominal price levels or where basic infrastructure is missing. Only after the heavy investments in physical capital are decreasing due to infrastructure saturation, inequalities are lessened and the income per capita is increasing, will energy consumption begin to decline due to the structure of the economy, and at the same time, more expensive and efficient technologies are likely to gain share. Simultaneously, this development also reduces energy consumption through slowing population levels, and slowing energy intensive capital increase. A decomposition of regional energy consumption growth can be seen in Figure 4.

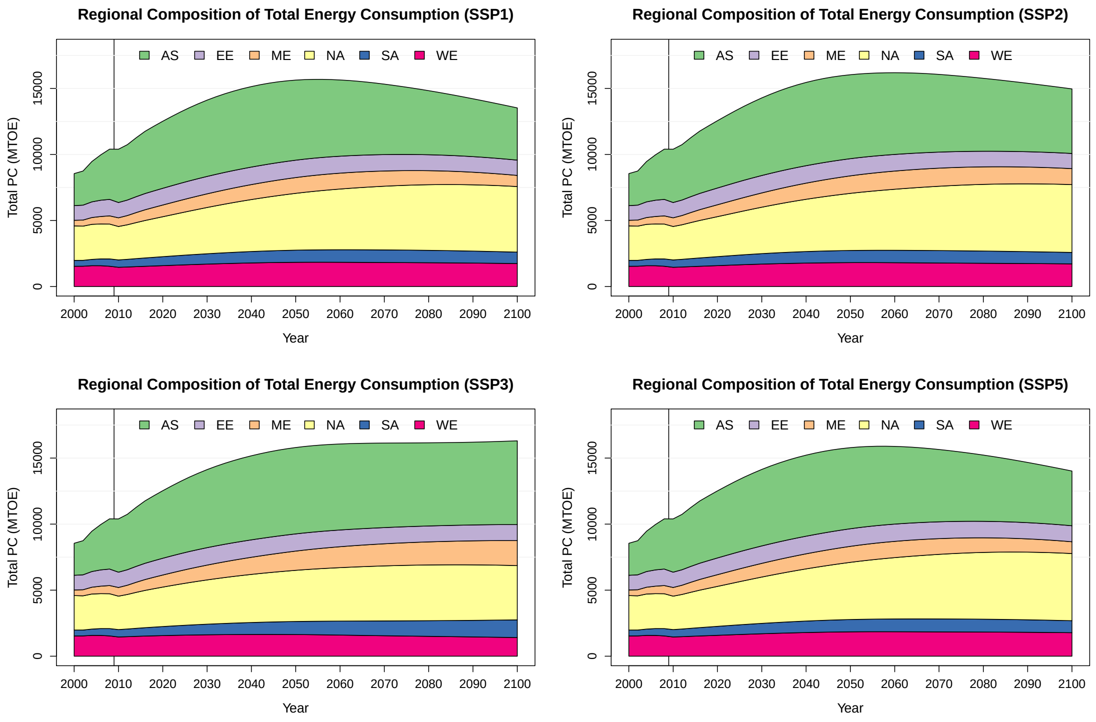

Figure 4: Projected regional Share of Energy Consumption for 56 Sample Countries

As mentioned earlier, we only model countries with uniformly available energy consumption data, and cover thus the states causing the majority of primary energy consumption as of 2009. This picture might be different by 2100 if large parts of Africa, and the Middle East pick up on economic and population development, and consequently on energy consumption. We would, in this case also except a similar development of consumption levels, with steep increases as population and economic speed up, a saturation decades later, followed by a slow decline.

Although it is not a universal phenomenon, yet often governments of developing countries subsidise energy in order not to harm economic development. Most of these subsidies (gas in Russia, oil in the Middle East, coal in China) are presently oriented at fossil fuels and are seen not only as a way of *subsidising* economic growth, but also a necessity to avoid social unrest. As most of the future energy consumption increase is expected from developing countries, this practice might have long-reaching consequences from a greenhouse gas emissions point of view. Some of these countries however, most notably China, have agreed to limit greenhouse gas emissions in the future. This is mostly possible through the very stable state budget and financing possibilities China possess at the moment.

Comparing our results (+ max 45.7% increase in primary energy consumption by 2035) with those of the IEA (using a bottom-up integrated modelling approach), our projections are very similar to the IEA current policies (+49,8%) and new policies (+40,9%) scenario as of 2035. We note here that the total energy consumption defined by the IEA as of 2009 was 12032 MTOE compared to the BP data of 11363 MTOE. Matching our results with the IIASA long–run projections, we are also well within the range of their possible scenarios. While the IIASA projections do not show a downward trend after 2060, this is likely attributable to the inclusion of presently developing countries in later years. One modelling discrepancy that we take note of is, as mentioned our North America model, where the expected gains in energy efficiency by the US EIA and Exxon are larger than those in our simulation.

4.2 The geopolitics of energy: an outlook

The share of the different energy forms is particularly difficult to predict for the future. Technological breakthroughs, sudden resource findings, or accidents can change the long-range future expectation within the span of few years, or few weeks. The geopolitics of energy, political and military considerations, as well as ownership laws influence the share of energy mix gravely in a world where one of the most important energy sources, natural gas, does not have a global market.

Recent publications, such as the International Energy Agency (2011) agree in the major role of natural gas for the future. Recent findings and development in unconventional gas technology have changed the energy landscape of the world. The United States is expecting to gain approximately 75% of its gas production from tight or shale gas by 2035 (United States Energy Information Administration 2012), a development no one has expected a few years ago. Shale gas in the United States is a very effective tool to greatly enhance energy security, and perhaps even to become an exporter of natural gas instead of importer. Next to the human knowledge and technological advancements one of the key enabling factor of shale gas development was the resource ownership rights in the US, which incentivises private investment, and gravely reduces resistance against the resource extraction. This, in turn significantly reduces gas prices, making heavily energy intensive industries gaining on competitive edge. From the present perspective –at least in North America, the future belongs to fossil fuels, most likely to unconventional gas and perhaps unconventional oil resources.

At the same time, on the other side of the globe, Russia, which harboured earlier plans to build natural gas pipelines not only to China but perhaps to the Kamchatka Sea to supply LNG to North America, had to rethink those plans as a result of the very fast shale development in the United States. Gas consumer prices are presently one of the lowest in the world in Russia, mainly due to the local subsidies. At the same time, as Russia coupled its long–term gas supply contracts to the price of oil, the revenues from hydrocarbon exports have been continuously rising from approximately 2% in 1995 to about 50% during the last 15 years (Cohen 2012), making the country immensely depend on its resource exports. This might turn out to be a suboptimal way of budget financing, especially since European Union antitrust laws are giving problems to the Russian state owned gas companies, which try to diversify towards China and the rest of Asia (Cohen 2012). How the Russian energy future looks is questionable. Russia has definitely abundant hydrocarbon resources (even without the North Pole extractions), and is further enhancing also nuclear technologies. The International Energy Agency (2011) mentions that Russia would certainly need more energy efficiency at home, a process that is not at all encouraged by low gas prices. A vital issue, Russia will have to consider when preparing future budgets, is a China or a Europe developing own shale gas operations.

Are China, or Europe then likely to start shale gas extraction in the foreseeable future? In our opinion China has all possibilities to do so. It has a strong central government, the necessary means to build infrastructure, coordinate the operations and most importantly a pressing need for energy. Also, concerning other energy forms, China has taken a very pragmatic and standardised approach. It is presently building a large number of modern nuclear power plants, with even more in their pipeline to come. Nuclear energy is clean, concentrated and provides energy security for a long term. The problem of waste can be dealt with on the long–term, by the existing technologies. The answer to the question why China and other Asian states are building in the first place nuclear power plants, and why they can build them so fast and cheap, is economies of scale, standardisation, stable political environment regarding nuclear energy, and a national energy strategy, that is being followed with large financing coming from the state itself.

As the United States Energy Information Administration (2012) puts it, after Fukushima the prospects of nuclear power are lowered in Europe and Japan, but not in other parts of the world. We can expect China, India, and perhaps South Korea going ahead with their constructions, as nuclear energy is among the cleanest in cheapest in Asia. The United States has also passed laws to support the building of nuclear power plants in the past years. It is not Fukushima, or public resistance that is giving the American private nuclear industry an evidently hard time, but the large investment requirements and the financial crisis of 2008-2009 that left a stagnating economy behind, with a little will from the markets to invest into giant projects. If the Chinese and Indian nuclear model provenly functions for the next decades, and the economic situation improves, then nuclear constructions have a chance of picking up elsewhere. Without a rise in the share of nuclear energy, energy security would be even harder to reach for any state (International Energy Agency 2012), not speaking of the goals to lower greenhouse gas emissions.

Europe is a special marketplace with constantly growing energy insecurity and dependence on imports. There have been in the past widespread sentiments against a range of energy technologies such as nuclear, shale gas, or even wind energy across Europe. Coping with public pressure is one main determinants of energy policy in many European states, a factor, other governments are not necessarily facing. At the moment the future of European energy hopefully lies in renewables, with heavy laws and state subsidies supporting these. Unfortunately, most renewable technologies in Europe would not be able to survive on the market without these subsidies, even though the price of the competing natural gas is 5-8 times higher than in Russia or in North America (Lewis, Economides, and Ajao 2012). The best case scenario could be, to reach economies of scale for certain renewable technologies, so that the price of energy could to a great extent reduce. Whether this is achievable or not, remains open. It also remains open, whether and how long a European Union with financing problems, growing unemployment and slow economic growth can subsidise renewable energy.

While the European Union plans a renewable energy future, Brooks (2012) argues that fossil fuel technology has advanced faster than renewables technology in the past years in the United States. The withdrawal of subsidies would mean the end of many renewable energy sources. The landscape of the United States is also different from the European in the price aspect, as fossil energies are significantly cheaper there, than in Europe. Despite of this, some increase in renewable energy generation are expected in the North American continent. Presently the United States Energy Information Administration (2012) expects the increase of non–hydro renewables in electricity generation (about 40% of energy consumption) from 3 to 15% by 2035, conditional that subsidies rise almost 5 times to 180 billion USD.

Conventional and unconventional oil sources will likely continue to be the major source of energy for the transportation sector in the coming years. However due to the increasing difficulty in oil production, cheap oil seems to be of the phenomenon of the past, save for the Middle East, where oil is subsidised by governments or ruler families in the context of a *social contract* with the population. As mentioned earlier, it is very difficult to predict what new technologies may arise or if a breakthrough might change the energy landscape of the future. It also remains to be seen, if presently expected high degree energy efficiencies could be reached, massively dimming energy consumption in the future in developed countries.

Due to significantly increasing energy consumption of the next decades, the world will face increased greenhouse gas emissions as well as the accompanying climate change. Therefore the usage of cleaner, cheap and concentrated energy sources such as natural gas, nuclear technologies and renewables would be crucial, to–at least–limit the extent of the impending greenhouse gas emissions.

5 Conclusion

Projecting long–term energy consumption is a vital task, that is surrounded with much uncertainty. Meeting energy demand is not only crucial to enable economic development of a country, but is a factor of national security, and is highly influenced by the geopolitical situation. In this paper we use the long–term cointegrating coefficients between primary energy consumption, real income, capital, population and technology, obtained by averaged panel error correction parameters, to project the the long–term primary energy consumption of 56 countries up to 2100. In forecasting long–term primary energy consumption, we work with four different Shared Socioeconomic Pathway Scenarios (SSPs) developed for the IPCC framework, assuming different challenges to adaptation and mitigation. We find that in all scenarios, China, the United States and India will be the largest energy consumers, while highly growing countries will also significantly contribute to energy use.

We observe for our dataset for most scenarios a sharp increase in global energy consumption, followed by a levelling–out and a decrease towards the second half of the century. The reasons behind this pattern are not only slower population growth, but also infrastructure saturation, and increased total factor productivity. This means, as countries move towards more knowledge based societies, and higher energy efficiency, their primary energy usage is likely to decrease as a result. We note that while our projections take into account a wide range of macroeconomic possibilities, major changes in technology, wars or geopolitical conflicts that may change the course of the future cannot be anticipated.

We also find, that key factor of reducing energy consumption in a country with a full infrastructure lies in energy efficiencies. Despite of the technological progress however, global primary energy consumption is expected to increase significantly in the coming decades, thus increasing the pressure on policy makers to cope with the questions of energy security and greenhouse gas mitigation at the same time.

References

Australian Government Bureau of Resources and Energy Economics (2011): *Australian Energy Projections to 2034–35.* ISBN 978-1-921812-78-1. www.bree.gov.au.

Bernanke, B.S. and R.S. **Gurkaynak** (2001): “Is Growth Exogenous? Taking Mankiw, Romer, and Weil Seriously”. In: *NBER Macroeconomics Annual* 16, pp. 11–57.

Böck, H. and M. **Villa** (2011): *Nuclear Engineering I–II.* Technische Universität–Wien, Atominstitut.

British Petrol (2011a): *Energy Outlook 2030.* Tech. rep. British Petrol. URL: `www.bp.com`.

— (2011b): *Statistical Review of World Energy.* Tech. rep. British Petrol. URL: `www.bp.com`.

Brooks, D. (2012): “A Sad Green Story”. In: *The New York Times.* URL: `http://www.nytimes.com/2012/10/19/opinion/brooks-a-sad-green-story.html?_r=0`.

Burke, P. J. (2011): “The National–Level Energy Ladder and its Carbon Implications”. In: *CCEP working paper 1116, Australian National University.*

Cohen, A. (2012): “The Rise of Shale Gas and LNG and its Impact on Europe and Russia”. In: *31st North American Energy Economics Conference, Austin, USA, November 4-7, 2012.*

Commissariat à l’énergie atomique et aux énergies alternatives (2012): *La fusion magnétique.* Tech. rep. URL: `http://www-fusion-magnetique.cea.fr/`.

Csereklyei, Z. and S. **Humer** (2012): “Modelling Primary Energy Consumption under Model Uncertainty”. In: *WU Working Papers in Economics Nr. 147.*

Davidson, R. and J.G. **MacKinnon** (2009): *Econometric Theory and Methods.* ISBN 978-0-19-539105-3. Oxford University Press.

Deffeyes, K.S. and I.D. **MacGregor** (1980): “World Uranium Ressources”. In: *Scientific American* 242, pp. 66–76.

European Commission (2008): *Market Observatory for Energy, Europe’s Energy Position.* Tech. rep. ISBN: 978-92-79-10036-9. European Commission.

— (2011a): *Assessment of the Required Share for a Stable EU Electricity Supply until 2050.* Tech. rep. EUR 24996. European Commission.

— (2011b): *Investment needs for future adaptation measures in EU nuclear power plants and other electricity generation technologies due to effects of climate change.* Tech. rep. EUR 24769. European Commission.

Eurostat, ed. (2009): *Panorama of Energy.* ISBN 978-92-79-11151-8. Eurostat.

ExxonMobile (2012): *2012 The Outlook for Energy: A View to 2040-US Edition.* Tech. rep. ExxonMobile. URL: `exxonmobil.com/energyoutlook`.

Fuhrmann, M. (2012): “Splitting Atoms: Why do countries build nuclear power plants?” In: *International Interactions* 38.1, pp. 1–28.

Gardiner, B. (2012): *Marine Energy Projects Pick Up Momentum.* Tech. rep. URL: `http://www.nytimes.com/2012/10/02/business/energy-environment/marine-energy-projects-pick-up-momentum.html?smid=pl-share`.

Goodfellow, M.J., H.R. **Williams**, and A. **Azapagic** (2011): “Nuclear renaissance, public perception and design criteria: An exploratory review”. In: *Energy Policy* 39, pp. 6199–6210.

Hansen, J., M. **Sato**, and R. **Ruedy** (2012): “Perception of Climate Change”. In: *PNAS.* DOI: `www.pnas.org/cgi/doi/10.1073/pnas.1205276109`.

IIASA (2011): “Education — a key determinant of population growth and human–well being”. In: Press Release. URL: `www.iiasa.ac.at`.

— (2012a): *Global Energy Assessment Scenario Database.* Tech. rep. Version 2.0.2. URL: `http://www.iiasa.ac.at/web-apps/ene/geadb/dsd?Action=htmlpage&page=about`.

— (2012b): *Shared Socioeconomic Pathways Database.* Tech. rep.

— (2012c): *Supplementary note for the SSP data sets.* Tech. rep.

International Atomic Energy Agency (2005): *Thorium fuel cycle — Potential benefits and challenges, IAEA TECDOC 1450.* ISBN 92-0-103405-9. IAEA.

— (2011): *Nuclear Technology Review 2011.* IAEA. URL: `www.iaea.org/Publications/Reports/ntr2011.pdf`.

International Energy Agency (2008): *Worldwide Trends in Energy Use and Efficiency.* International Energy Agency.

— (2011): *World Energy Outlook 2011.* ISBN: 978 92 64 08624 1. International Energy Agency.

International Energy Agency (2012): *Energy Technology Perspectives 2012*. ISBN: 978-92-64-17488-7. International Energy Agency. URL: `www.iea.org/etp`.

International Monetary Fund (2011): *World Economic Outlook 2011*. Tech. rep. ISBN 978-1-61635-059-8.

IPCC (2011): *Special Report on Renewable Energy Sources and Climate Change Mitigation*. Tech. rep. IPCC Working Group III, ISBN 978-1-107-02340-6.

ITER (2011): *International Thermonuclear Experimental Reactor Project*. Tech. rep. URL: `www.iter.org`.

Jakob, M., M. **Haller**, and R. **Marschinski** (2012): "Will history repeat itself? Economic convergence in energy use patterns". In: *Energy Economics* 32, pp. 95–104.

Jakob, M., G. **Luderer**, et al. (2012): "Time to act now? Assessing the costs of delaying climate measures and benefits of early action". In: *Climatic Change* 114, 10.1007/s10584-011-0128-3, pp. 79–99.

Kleinberg, R. (2012): *Unconventional Gas and Oil : Environmental and Regulatory Issues*. Tech. rep. 31st USAEE/IAEE North American Conference; Unconventional Gas & Oil Workshop.

Kriegler, E. et al. (2010): "Socio economic Scenario Development for Climate Change Analysis". In: *CIRED Working Paper* 2010-23.

Lewis, P.E., M. **Economides**, and O. **Ajao** (2012): "Market for transport fuels in the US will remain subject to diversification". In: *Oil and Gas Journal* 110.10, pp. 30–36.

Lidsky, L.M. (1983): "The Trouble With Fusion". In: *MIT Technology Review, October 1983*, pp. 1–12.

Lopez, A. et al. (2011): "U.S. Renewable Energy Technical Potentials: A GIS Based Analysis". In: Technical Report NREL/TP-6A20-51946, Prepared under Task Nos. SA10.1012 and SA10.20A4. URL: `www.nrel.gov`.

Massachusetts Institute of Technology (2003): *The Future of the Nuclear Power*. ISBN: 0-615-12420-8. Massachusetts Institute of Technology.

— (2007): *The Future of Coal*. ISBN 978-0-615-14092-6. Massachusetts Institute of Technology (MIT).

— (2010): *The Future of Natural Gas*. ISBN 978-0-9828008-0-5. Massachusetts Institute of Technology.

— (2011): *The Future of the Nuclear Fuel Cycle*. ISBN:978-0-9828008-4-3. Massachusetts Institute of Technology (MIT).

Patzek, T. (2012): *Multi-scale physics of hydrofracturing and flow in mudstones*. Tech. rep. 31st USAEE/IAEE North American Conference; Unconventional Gas & Oil Workshop.

Phillips, J. A. (1983): "Magnetic Fusion". In: *Los Alamos Science* Winter/Spring, pp. 63–67.

Potter, E. (2012): *Geology Basics of the Shale Gas and Shale Oil Revolution.* Tech. rep. 31st USAEE/IAEE North American Conference; Unconventional Gas & Oil Workshop.

Princeton University (2011): *Carbon Mitigation Initiative.* Tech. rep. URL: `http://cmi.princeton.edu/wedges/intro.php`.

Rubinstein, J.L., W.L. **Ellsworth**, and A. **McGarr** (2012): *Signficant (induced?) earthquakes in the Central and Eastern US since 2008.* Tech. rep. URL: `http://earthquake.usgs.gov/hazards/about/workshops/CEUS-WORKSHP/2.22.2012/Rubinstein2012InducedEqs.pdf`.

Schaeffer, M., W. **Hare**, S. **Rahmstorf**, and M **Vermeer**: “Long–term sea–level rise implied by 1,5 oC and 2 oC warming levels”. In: *Nature Climate Change.* PUBLISHED ONLINE: 24 JUNE 2012. DOI: `DOI:10.1038/NCLIMATE1584`.

Slovic, P. (1987): “Perception of Risk”. In: *Science* 236 (4799), pp. 280–285.

Stern, N. (2007): *The economics of climate change.* ISBN 9780521700801. Cambridge University Press.

Stineman, R. W. (1980): “A Consistently Well Behaved Method of Interpolation”. In: *Creative Computing* 6, pp. 54–57.

Umweltbundesamt Österreich (2011): *Energiewirtschaftliche Inputdaten und Szenarien als Grundlage für die Klimastrategie 2020 und den Monitoring Mechanism 2011.* Tech. rep. ISBN 978-3-99004-135-2.

United Kingdom Department of Energy and Climate Change (2012): *Energy and Emissions Projections.* Tech. rep. URL: `http://www.decc.gov.uk/en/content/cms/about/ec_social_res/analytic_projs/en_emis_projs/en_emis_projs.aspx`.

United States Energy Information Administration (2012): *Annual Energy Outlook 2012 with Projections to 2035.* Tech. rep. DOE/EIA-0383(2012).

Villa, M. (2008): *Reaktorphysik, AIAU 98402.* Technische Universität–Wien, Atominstitut.

Weitzman, M.L (2009): “On Modeling and Interpreting the Economics of Catastrophic Climate Change”. In: *The Review of Economics and Statistics* 91.1, pp. 1–19. DOI: `doi:10.1162/rest.91.1.1`.

Zobak, M.D. and S.M. **Gorelick** (2010): “Earthquake triggering and large-scale geologic storage of carbon dioxide”. In: *PNAS.* DOI: `www.pnas.org/cgi/doi/10.1073/pnas.1202473109`.

6 Annex

Table 6: Real Income (Y) Projections — Relation to 2009

	2009	2015	2035	2050	2065	2070	2085	2100
SSP1								
AS	1.00	1.61	4.84	7.24	9.88	10.76	13.12	14.79
EE	1.00	1.26	2.14	2.87	3.76	4.07	4.96	5.91
ME	1.00	1.25	2.03	3.01	4.32	4.79	6.09	7.16
NA	1.00	1.15	2.12	2.82	3.47	3.68	4.28	4.83
SA	1.00	1.22	2.20	3.38	5.07	5.68	7.45	9.02
WE	1.00	1.13	2.15	2.88	3.46	3.63	4.12	4.61
World	1.00	1.33	3.11	4.48	5.95	6.44	7.79	8.86
SSP2								
AS	1.00	1.60	4.59	6.33	7.95	8.50	10.05	11.50
EE	1.00	1.25	1.91	2.26	2.67	2.82	3.29	3.83
ME	1.00	1.25	2.00	2.80	3.62	3.90	4.75	5.69
NA	1.00	1.12	1.79	2.18	2.53	2.65	3.00	3.30
SA	1.00	1.23	2.11	2.81	3.71	4.04	5.02	5.93
WE	1.00	1.11	1.86	2.23	2.48	2.55	2.79	3.03
World	1.00	1.31	2.85	3.76	4.61	4.90	5.73	6.53
SSP3								
AS	1.00	1.58	4.11	4.96	5.32	5.39	5.56	5.86
EE	1.00	1.25	1.71	1.77	1.79	1.80	1.83	1.90
ME	1.00	1.25	1.79	2.10	2.38	2.45	2.59	2.76
NA	1.00	1.05	1.15	1.23	1.29	1.31	1.35	1.37
SA	1.00	1.22	1.87	2.18	2.45	2.52	2.72	2.97
WE	1.00	1.04	1.13	1.19	1.20	1.19	1.20	1.21
World	1.00	1.27	2.34	2.71	2.89	2.93	3.02	3.17
SSP5								
AS	1.00	1.61	5.08	8.12	11.88	13.26	17.33	20.72
EE	1.00	1.26	2.25	3.22	4.53	5.01	6.51	8.18
ME	1.00	1.25	2.16	3.48	5.51	6.31	8.75	11.03
NA	1.00	1.15	2.18	2.99	3.82	4.10	4.93	5.71
SA	1.00	1.23	2.32	3.81	6.17	7.08	9.93	12.70
WE	1.00	1.13	2.21	3.04	3.76	3.99	4.67	5.36
World	1.00	1.33	3.25	4.95	7.01	7.76	9.98	11.96

Table 7: Population (L) Projections — Relation to 2009

	2009	2015	2035	2050	2065	2070	2085	2100
SSP1								
AS	1.00	1.07	1.16	1.14	1.06	1.02	0.91	0.79
EE	1.00	1.00	0.99	0.96	0.91	0.89	0.85	0.82
ME	1.00	1.09	1.24	1.26	1.20	1.16	1.04	0.92
NA	1.00	1.06	1.20	1.26	1.30	1.31	1.31	1.28
SA	1.00	1.06	1.19	1.21	1.18	1.17	1.10	1.02
WE	1.00	1.02	1.05	1.04	1.00	0.99	0.96	0.93
World	1.00	1.06	1.15	1.14	1.08	1.05	0.96	0.86
SSP2								
AS	1.00	1.07	1.20	1.21	1.17	1.15	1.08	1.00
EE	1.00	1.01	1.00	0.97	0.92	0.91	0.87	0.84
ME	1.00	1.10	1.30	1.36	1.35	1.33	1.26	1.18
NA	1.00	1.06	1.22	1.30	1.35	1.36	1.38	1.37
SA	1.00	1.06	1.21	1.23	1.21	1.20	1.14	1.08
WE	1.00	1.02	1.05	1.04	1.01	1.00	0.98	0.95
World	1.00	1.06	1.18	1.20	1.17	1.15	1.09	1.03
SSP3								
AS	1.00	1.07	1.23	1.29	1.32	1.32	1.34	1.37
EE	1.00	1.01	1.01	0.99	0.96	0.96	0.95	0.95
ME	1.00	1.10	1.34	1.46	1.54	1.56	1.61	1.67
NA	1.00	1.06	1.20	1.27	1.30	1.31	1.31	1.29
SA	1.00	1.07	1.24	1.33	1.39	1.41	1.48	1.56
WE	1.00	1.02	1.05	1.04	1.00	0.99	0.96	0.93
World	1.00	1.07	1.20	1.26	1.28	1.29	1.31	1.33
SSP5								
AS	1.00	1.07	1.16	1.14	1.06	1.02	0.91	0.79
EE	1.00	1.00	0.99	0.96	0.91	0.89	0.85	0.82
ME	1.00	1.09	1.24	1.26	1.20	1.16	1.04	0.92
NA	1.00	1.06	1.20	1.26	1.30	1.31	1.31	1.28
SA	1.00	1.06	1.19	1.21	1.18	1.17	1.10	1.02
WE	1.00	1.02	1.05	1.04	1.00	0.99	0.96	0.93
World	1.00	1.06	1.15	1.14	1.08	1.05	0.96	0.86

Table 8: Physical Capital (K) Projections— Relation to 2009

	2009	2015	2035	2050	2065	2070	2085	2100
SSP1								
AS	1.00	1.43	4.79	7.62	10.03	10.59	12.48	14.19
EE	1.00	1.28	2.54	3.44	4.41	4.78	5.96	7.24
ME	1.00	1.33	2.19	2.97	4.08	4.51	5.85	7.12
NA	1.00	1.13	1.93	2.77	3.63	3.91	4.74	5.52
SA	1.00	1.22	2.22	3.36	5.07	5.76	8.03	10.32
WE	1.00	1.12	1.86	2.64	3.39	3.62	4.27	4.88
World	1.00	1.27	3.13	4.78	6.31	6.72	8.07	9.34
SSP2								
AS	1.00	1.43	4.67	7.05	8.62	8.89	9.91	11.06
EE	1.00	1.28	2.40	2.96	3.41	3.58	4.16	4.84
ME	1.00	1.33	2.17	2.85	3.65	3.92	4.75	5.66
NA	1.00	1.12	1.75	2.29	2.79	2.96	3.43	3.87
SA	1.00	1.22	2.19	3.05	4.07	4.45	5.70	7.00
WE	1.00	1.12	1.72	2.21	2.60	2.71	3.02	3.32
World	1.00	1.27	3.00	4.30	5.24	5.46	6.18	6.96
SSP3								
AS	1.00	1.43	4.40	6.07	6.57	6.49	6.29	6.23
EE	1.00	1.28	2.30	2.57	2.62	2.62	2.64	2.69
ME	1.00	1.33	2.08	2.42	2.70	2.78	2.94	3.08
NA	1.00	1.11	1.35	1.49	1.59	1.62	1.70	1.75
SA	1.00	1.22	2.07	2.61	3.04	3.17	3.49	3.82
WE	1.00	1.10	1.29	1.37	1.41	1.41	1.43	1.44
World	1.00	1.26	2.70	3.48	3.75	3.74	3.70	3.72
SSP5								
AS	1.00	1.43	4.91	8.20	11.46	12.34	15.57	18.86
EE	1.00	1.28	2.60	3.69	5.03	5.57	7.42	9.56
ME	1.00	1.33	2.25	3.24	4.84	5.53	7.83	10.32
NA	1.00	1.13	1.96	2.88	3.89	4.24	5.30	6.36
SA	1.00	1.22	2.28	3.63	5.87	6.83	10.18	13.90
WE	1.00	1.12	1.89	2.73	3.60	3.88	4.71	5.54
World	1.00	1.27	3.20	5.10	7.10	7.71	9.84	12.03

Table 9: TFP (A) Projections — Relation to 2009

	2009	2015	2035	2050	2065	2070	2085	2100
SSP1								
AS	1.00	1.15	1.73	2.16	2.64	2.80	3.30	3.82
EE	1.00	1.18	1.67	2.08	2.60	2.77	3.21	3.68
ME	1.00	1.06	1.32	1.77	2.38	2.61	3.30	3.99
NA	1.00	1.08	1.65	1.88	2.08	2.14	2.34	2.57
SA	1.00	1.13	1.61	2.14	2.85	3.10	3.83	4.54
WE	1.00	1.08	1.64	1.98	2.28	2.36	2.62	2.88
World	1.00	1.11	1.65	2.03	2.45	2.58	2.98	3.38
SSP2								
AS	1.00	1.13	1.52	1.77	2.05	2.15	2.44	2.73
EE	1.00	1.17	1.52	1.71	1.97	2.06	2.34	2.63
ME	1.00	1.06	1.26	1.57	1.90	2.02	2.41	2.86
NA	1.00	1.06	1.39	1.51	1.60	1.64	1.75	1.87
SA	1.00	1.13	1.53	1.82	2.22	2.36	2.81	3.25
WE	1.00	1.06	1.43	1.60	1.74	1.79	1.93	2.08
World	1.00	1.10	1.46	1.66	1.88	1.96	2.19	2.43
SSP3								
AS	1.00	1.09	1.23	1.29	1.36	1.38	1.43	1.48
EE	1.00	1.17	1.38	1.38	1.41	1.42	1.46	1.50
ME	1.00	1.05	1.12	1.18	1.25	1.26	1.29	1.32
NA	1.00	0.99	1.00	1.01	1.02	1.03	1.05	1.07
SA	1.00	1.13	1.36	1.41	1.46	1.47	1.49	1.53
WE	1.00	1.00	1.00	1.03	1.06	1.07	1.10	1.13
World	1.00	1.06	1.15	1.19	1.22	1.24	1.27	1.31
SSP5								
AS	1.00	1.15	1.79	2.33	2.97	3.21	3.97	4.78
EE	1.00	1.18	1.74	2.29	3.01	3.26	3.95	4.69
ME	1.00	1.06	1.39	1.99	2.87	3.21	4.31	5.44
NA	1.00	1.08	1.69	1.98	2.24	2.33	2.61	2.92
SA	1.00	1.13	1.69	2.37	3.36	3.72	4.85	5.98
WE	1.00	1.08	1.68	2.08	2.45	2.56	2.90	3.25
World	1.00	1.11	1.70	2.18	2.74	2.93	3.52	4.13

Table 10: Countries (SSP1): E.ma.fe— Units

	2009	2015	2035	2050	2065	2070	2085	2100
DZA	39.70	48.29	67.21	76.38	77.62	76.64	72.69	67.62
ARG	73.30	80.58	106.15	121.93	131.73	133.41	134.04	130.31
AUS	119.20	149.46	231.41	274.67	296.85	300.48	304.31	296.37
AUT	32.00	33.81	36.45	37.27	37.31	37.37	37.62	37.40
BGD	22.90	26.15	40.43	47.08	49.19	48.81	45.58	41.48
BEL	69.40	75.12	87.13	93.24	96.02	96.78	98.29	97.25
BRA	225.70	245.94	312.59	335.05	338.72	335.67	316.36	290.90
BGR	17.40	18.16	15.49	13.10	10.88	10.27	9.06	8.49
CAN	319.20	360.76	508.11	599.46	666.22	682.51	714.65	716.67
CHL	28.10	33.17	43.82	48.23	49.19	48.98	47.16	44.59
CHN	2177.00	2558.64	3199.25	3055.83	2618.76	2456.49	2006.38	1651.40
COL	29.00	36.96	54.24	62.80	67.60	68.53	68.93	66.47
CZE	39.60	43.05	47.22	48.14	48.25	47.92	47.85	48.14
DNK	16.10	16.99	18.76	18.75	18.35	18.21	17.62	16.74
ECU	12.40	14.16	19.67	21.37	21.28	20.93	18.88	15.84
EGY	76.30	98.03	153.32	176.58	180.60	177.56	158.12	129.37
FIN	25.00	26.62	29.45	29.72	29.60	29.51	28.89	27.82
FRA	241.90	248.12	302.06	333.11	346.55	348.92	351.43	342.77
DEU	289.80	289.55	286.56	276.74	265.16	263.17	260.95	260.48
GRC	32.70	36.72	42.17	45.48	45.95	45.77	45.50	44.54
HKG	23.90	26.85	39.17	46.93	53.07	54.84	60.69	66.88
HUN	22.40	22.43	22.84	23.15	23.31	23.23	23.17	23.15
IND	468.90	600.22	1023.23	1147.13	1104.48	1058.51	876.35	673.89
IDN	128.20	146.14	198.61	223.86	236.53	237.61	236.28	229.90
IRN	204.80	227.87	283.07	295.29	274.62	262.39	223.26	197.06
IRL	13.90	15.50	21.60	25.63	27.91	28.31	29.29	29.52
ITA	163.40	170.86	183.44	186.15	179.64	177.10	174.66	174.73
JPN	463.90	460.49	439.09	402.92	359.78	345.67	315.40	300.42
KAZ	64.40	77.85	102.44	106.96	100.93	97.91	86.26	72.22
KOR	237.50	250.04	278.17	263.66	231.31	220.26	193.78	177.53
LTU	8.20	7.45	7.10	6.80	6.52	6.40	6.17	6.14
MYS	55.70	67.32	99.14	114.60	119.28	118.38	108.76	92.12
MEX	163.20	189.47	262.98	300.99	317.01	319.01	314.65	296.96
NLD	93.30	97.38	109.57	110.25	107.31	106.63	104.24	99.64
NZL	17.60	20.73	28.25	31.51	32.51	32.64	32.44	31.10
NOR	42.50	49.00	61.57	67.36	71.42	72.45	74.45	73.58
PAK	65.80	74.47	123.29	152.50	162.25	160.77	146.21	123.59
PER	16.60	19.58	26.81	29.00	28.50	27.80	24.42	19.99
PHL	24.20	26.83	44.11	54.14	57.68	57.20	51.89	43.59
POL	92.30	95.34	100.72	96.97	92.02	89.35	83.05	80.46
PRT	22.30	22.74	22.23	20.98	18.56	17.65	15.53	14.14
ROU	34.60	33.91	33.14	30.93	27.63	26.53	24.21	22.85
RUS	635.30	663.50	685.98	659.54	620.57	610.01	593.18	589.30
SAU	191.50	271.37	427.93	490.29	502.59	490.75	427.13	341.46
SGP	60.80	80.25	111.71	118.08	116.31	114.92	109.40	105.67
SVK	16.80	17.56	18.41	17.90	17.15	16.74	15.85	15.49
ZAF	126.80	141.29	156.59	155.87	148.88	145.22	128.44	106.78
ESP	132.60	144.56	173.00	185.97	176.10	170.45	157.75	148.29
SWE	43.20	48.19	61.40	67.47	70.08	70.39	70.18	67.78
CHE	29.40	31.15	34.45	33.71	31.92	31.34	29.98	28.93
THA	95.10	109.94	126.70	129.29	128.35	127.49	124.39	120.60
TUR	93.00	100.26	135.60	150.56	155.46	155.50	151.51	143.32
TKM	23.00	26.46	45.62	56.09	59.94	60.19	58.72	55.27
UKR	112.50	111.19	111.00	106.27	99.21	97.12	93.66	93.09
GBR	198.90	214.57	277.35	302.62	305.79	304.31	293.91	277.22
USA	2182.00	2423.20	3220.57	3703.33	4052.84	4141.02	4291.94	4247.94
World	10255.20	11526.25	14698.35	15629.60	15513.28	15324.03	14535.51	13525.27

Table 11: Countries (SSP2): E.ma.fe— Units

	2009	2015	2035	2050	2065	2070	2085	2100
DZA	39.70	48.30	67.84	77.24	78.46	77.48	73.44	68.94
ARG	73.30	80.72	109.60	123.05	130.96	131.92	131.03	127.21
AUS	119.20	149.17	232.39	272.53	294.64	298.07	302.27	298.29
AUT	32.00	33.75	35.79	35.52	34.63	34.45	33.94	33.60
BGD	22.90	26.15	40.28	46.16	47.72	47.27	44.27	40.43
BEL	69.40	75.17	86.96	92.00	94.42	95.02	96.69	96.43
BRA	225.70	245.98	312.52	329.46	325.36	320.49	299.26	276.16
BGR	17.40	18.17	15.42	12.88	10.55	9.94	8.80	8.35
CAN	319.20	359.56	494.76	576.10	638.34	654.37	686.91	694.86
CHL	28.10	33.17	43.44	46.49	46.37	45.96	43.86	41.47
CHN	2177.00	2559.67	3233.29	3123.99	2755.50	2616.70	2234.36	1957.22
COL	29.00	36.99	56.12	63.84	67.77	68.35	68.36	66.56
CZE	39.60	43.01	46.49	46.55	45.51	44.80	43.91	43.75
DNK	16.10	17.02	18.97	18.78	18.33	18.17	17.59	16.92
ECU	12.40	14.29	21.33	24.69	26.55	26.87	27.04	26.37
EGY	76.30	98.84	171.82	213.03	236.26	239.85	238.45	229.23
FIN	25.00	26.66	29.62	29.70	29.72	29.65	29.28	28.60
FRA	241.90	248.55	305.78	334.37	348.21	351.13	354.95	350.85
DEU	289.80	289.32	279.73	263.91	247.79	244.52	239.66	238.46
GRC	32.70	36.66	41.14	43.51	43.16	42.81	42.23	41.25
HKG	23.90	26.58	37.57	43.68	48.77	50.42	55.40	61.68
HUN	22.40	22.42	22.57	22.33	22.00	21.79	21.49	21.51
IND	468.90	605.78	1141.89	1367.07	1428.54	1414.11	1321.92	1201.54
IDN	128.20	146.20	197.79	217.09	223.27	222.76	216.54	206.16
IRN	204.80	228.07	285.13	296.81	272.75	259.81	220.94	197.22
IRL	13.90	15.50	21.55	25.60	27.76	28.18	29.35	29.75
ITA	163.40	170.83	180.76	180.11	169.56	165.85	160.60	158.97
JPN	463.90	459.91	427.80	385.39	341.82	328.15	299.62	286.86
KAZ	64.40	78.56	116.55	132.00	137.08	138.35	138.41	135.37
KOR	237.50	249.75	272.21	253.27	220.95	210.33	185.28	170.98
LTU	8.20	7.46	7.05	6.60	6.19	6.05	5.77	5.74
MYS	55.70	67.80	110.70	135.12	149.24	152.26	153.42	149.32
MEX	163.20	189.49	264.27	298.32	309.41	310.50	306.99	294.18
NLD	93.30	97.49	110.50	110.58	107.67	107.19	105.19	102.21
NZL	17.60	20.77	29.32	32.34	33.67	33.79	33.65	32.80
NOR	42.50	49.00	61.96	66.82	70.60	71.46	73.15	72.86
PAK	65.80	75.12	133.11	173.10	197.99	202.35	206.02	198.92
PER	16.60	19.75	29.39	34.25	36.61	36.84	36.50	35.19
PHL	24.20	27.06	49.58	67.82	78.67	80.84	82.48	79.61
POL	92.30	95.33	100.02	94.64	88.78	85.96	79.55	77.69
PRT	22.30	22.73	21.91	20.23	17.57	16.69	14.58	13.31
ROU	34.60	33.92	33.23	30.74	27.28	26.14	23.83	22.81
RUS	635.30	663.12	672.65	629.24	578.47	565.52	543.82	540.10
SAU	191.50	273.30	454.71	550.19	594.98	593.75	566.94	516.88
SGP	60.80	80.02	108.57	112.34	109.62	108.01	102.10	98.98
SVK	16.80	17.55	18.21	17.33	16.30	15.82	14.80	14.52
ZAF	126.80	142.50	176.78	189.11	198.07	199.71	199.90	195.10
ESP	132.60	144.32	171.82	184.56	174.59	169.19	157.59	150.08
SWE	43.20	48.22	62.06	67.52	70.16	70.35	70.24	68.55
CHE	29.40	31.13	34.21	33.29	31.38	30.80	29.52	28.78
THA	95.10	109.73	124.76	123.94	118.92	116.79	110.09	105.20
TUR	93.00	100.32	137.05	151.80	155.34	154.95	150.82	144.22
TKM	23.00	26.47	44.95	53.30	54.86	54.45	51.84	48.34
UKR	112.50	111.22	110.60	102.92	93.70	91.07	86.54	85.73
GBR	198.90	215.18	279.70	303.11	307.32	306.11	297.82	285.00
USA	2182.00	2424.99	3250.69	3749.48	4114.51	4216.47	4414.93	4441.59
World	10255.20	11538.73	14944.91	16035.81	16154.64	16060.67	15583.96	14962.71

Table 12: Countries (SSP3): E.ma.fe— Units

	2009	2015	2035	2050	2065	2070	2085	2100
DZA	39.70	48.31	67.81	77.18	79.55	79.14	77.63	75.85
ARG	73.30	80.69	108.06	125.58	139.22	143.00	153.74	166.28
AUS	119.20	148.89	217.34	249.56	265.10	267.44	269.57	263.97
AUT	32.00	33.77	35.53	35.15	33.96	33.61	32.74	31.88
BGD	22.90	26.18	40.09	44.98	45.23	44.47	40.88	36.95
BEL	69.40	74.71	78.84	78.66	76.71	76.05	73.63	69.50
BRA	225.70	246.27	321.16	354.99	378.33	384.95	405.01	437.71
BGR	17.40	18.16	15.27	12.46	9.87	9.16	7.75	6.92
CAN	319.20	359.59	475.71	537.73	578.60	586.60	595.51	577.92
CHL	28.10	33.19	43.86	47.50	47.91	47.65	46.43	45.47
CHN	2177.00	2559.77	3234.39	3145.72	2799.73	2678.27	2383.40	2240.35
COL	29.00	37.01	55.66	66.01	73.77	75.98	81.97	88.08
CZE	39.60	43.03	46.30	45.62	43.64	42.59	40.45	39.00
DNK	16.10	16.97	18.25	17.58	16.44	16.06	14.86	13.58
ECU	12.40	14.43	23.64	30.92	39.10	42.25	52.94	66.67
EGY	76.30	99.58	177.66	231.16	276.33	288.89	320.25	346.74
FIN	25.00	26.56	28.04	27.24	26.32	26.00	24.86	23.55
FRA	241.90	247.14	279.00	292.79	295.64	295.50	292.53	282.16
DEU	289.80	289.21	276.37	254.66	230.33	224.01	209.32	197.89
GRC	32.70	36.57	39.10	40.03	38.85	38.25	36.85	35.18
HKG	23.90	26.77	37.32	43.47	48.41	49.86	54.91	60.31
HUN	22.40	22.43	22.51	22.07	21.29	20.89	19.99	19.31
IND	468.90	611.17	1197.91	1554.01	1809.36	1875.05	2064.67	2295.05
IDN	128.20	146.21	196.35	211.22	210.73	207.77	194.52	177.14
IRN	204.80	228.02	286.09	297.87	277.83	267.17	235.58	218.88
IRL	13.90	15.45	20.31	23.12	24.42	24.57	24.82	24.53
ITA	163.40	170.25	171.28	165.01	151.80	147.37	139.09	134.12
JPN	463.90	459.40	418.16	370.38	322.54	307.71	275.51	258.35
KAZ	64.40	79.02	117.86	140.66	157.56	163.55	184.14	204.03
KOR	237.50	249.72	270.42	248.45	211.95	200.17	172.26	155.20
LTU	8.20	7.46	7.02	6.54	6.11	5.94	5.63	5.58
MYS	55.70	68.27	113.46	143.92	168.83	174.93	189.33	198.75
MEX	163.20	189.75	272.20	323.04	362.73	376.02	413.45	457.86
NLD	93.30	96.98	102.09	98.26	93.27	92.13	89.11	85.43
NZL	17.60	20.71	27.66	30.25	30.72	30.72	30.30	29.16
NOR	42.50	48.92	59.52	63.03	64.73	65.00	64.98	62.80
PAK	65.80	75.73	142.03	193.45	235.83	247.62	280.08	310.64
PER	16.60	19.89	31.84	40.48	49.52	52.68	63.58	77.30
PHL	24.20	27.25	51.23	71.18	89.66	94.99	109.40	122.59
POL	92.30	95.34	99.51	93.75	87.54	84.75	78.61	76.51
PRT	22.30	22.68	21.08	19.00	16.08	15.11	12.86	11.52
ROU	34.60	33.92	33.17	30.62	27.02	25.89	23.67	22.54
RUS	635.30	663.36	669.71	619.45	556.94	539.05	502.75	481.96
SAU	191.50	275.06	488.72	615.84	708.18	724.95	753.89	762.25
SGP	60.80	79.81	103.57	104.84	100.56	98.68	92.47	88.29
SVK	16.80	17.55	18.08	16.99	15.57	14.96	13.57	12.80
ZAF	126.80	143.81	191.60	234.60	291.61	314.84	394.17	490.00
ESP	132.60	144.17	166.16	175.18	165.22	160.52	151.39	147.73
SWE	43.20	47.99	56.74	59.36	59.51	59.16	57.35	54.18
CHE	29.40	31.07	33.22	31.73	29.82	29.28	28.31	28.19
THA	95.10	109.99	126.27	126.66	121.77	119.37	111.96	105.84
TUR	93.00	100.37	138.85	158.51	171.95	176.22	190.79	211.93
TKM	23.00	26.46	44.43	52.02	52.42	51.58	47.45	42.33
UKR	112.50	111.24	110.53	103.38	94.24	91.63	87.67	87.38
GBR	198.90	213.43	251.64	258.89	251.28	247.09	230.54	210.95
USA	2182.00	2415.77	3032.06	3337.62	3535.35	3579.25	3624.90	3529.62
World	10255.20	11535.45	14712.70	15800.38	16117.00	16136.33	16174.00	16306.67

Table 13: Countries (SSP5): E.ma.fe— Units

	2009	2015	2035	2050	2065	2070	2085	2100
DZA	39.70	48.29	67.58	77.68	80.23	79.71	76.95	72.65
ARG	73.30	80.58	106.55	123.36	134.59	136.77	138.75	136.04
AUS	119.20	149.46	231.92	276.34	300.06	304.22	309.60	302.92
AUT	32.00	33.81	36.54	37.56	37.87	38.02	38.54	38.58
BGD	22.90	26.15	40.80	48.27	51.24	51.11	48.92	45.84
BEL	69.40	75.12	87.26	93.65	96.77	97.64	99.52	98.79
BRA	225.70	245.94	313.85	339.37	347.01	345.23	328.97	305.42
BGR	17.40	18.16	15.56	13.30	11.20	10.61	9.49	9.01
CAN	319.20	360.76	509.36	603.70	674.66	692.49	729.26	735.19
CHL	28.10	33.17	44.03	48.94	50.54	50.55	49.28	47.11
CHN	2177.00	2558.56	3213.37	3094.35	2678.64	2521.22	2081.42	1729.14
COL	29.00	36.96	54.52	63.85	69.75	71.07	72.54	70.83
CZE	39.60	43.05	47.40	48.71	49.33	49.16	49.64	50.42
DNK	16.10	16.99	18.82	18.93	18.66	18.57	18.12	17.35
ECU	12.40	14.16	19.78	21.70	21.93	21.68	19.85	16.86
EGY	76.30	98.03	154.31	179.89	187.32	185.35	168.08	139.64
FIN	25.00	26.62	29.52	29.94	30.00	29.97	29.53	28.60
FRA	241.90	248.12	302.63	334.89	349.82	352.71	356.73	349.32
DEU	289.80	289.55	287.34	279.11	269.41	268.08	267.86	269.25
GRC	32.70	36.72	42.26	45.74	46.41	46.31	46.23	45.45
HKG	23.90	26.85	39.26	47.25	53.73	55.63	61.94	68.64
HUN	22.40	22.43	22.93	23.41	23.80	23.79	23.97	24.16
IND	468.90	600.16	1028.16	1162.36	1130.38	1087.03	909.28	705.73
IDN	128.20	146.14	199.80	227.91	244.34	247.10	250.91	248.37
IRN	204.80	227.87	284.36	299.71	282.42	271.13	233.76	208.77
IRL	13.90	15.50	21.65	25.82	28.27	28.73	29.89	30.29
ITA	163.40	170.86	183.78	187.15	181.38	179.09	177.40	178.22
JPN	463.90	460.49	440.21	406.00	364.75	351.22	322.65	309.27
KAZ	64.40	77.85	102.88	108.27	103.20	100.47	89.44	75.60
KOR	237.50	250.05	279.15	266.57	236.05	225.49	200.33	185.19
LTU	8.20	7.45	7.13	6.89	6.67	6.57	6.40	6.43
MYS	55.70	67.33	99.62	116.37	122.67	122.29	113.79	97.48
MEX	163.20	189.47	264.01	304.70	324.26	327.46	326.30	310.72
NLD	93.30	97.38	109.76	110.81	108.29	107.74	105.76	101.49
NZL	17.60	20.73	28.34	31.78	33.03	33.25	33.28	32.11
NOR	42.50	49.00	61.72	67.89	72.49	73.71	76.29	75.89
PAK	65.80	74.47	124.19	155.67	167.78	167.17	155.37	133.97
PER	16.60	19.58	26.95	29.50	29.44	28.86	25.75	21.36
PHL	24.20	26.83	44.48	55.36	59.78	59.65	55.50	47.77
POL	92.30	95.34	101.10	98.08	93.98	91.56	85.93	83.98
PRT	22.30	22.74	22.28	21.11	18.77	17.88	15.81	14.47
ROU	34.60	33.91	33.27	31.31	28.26	27.23	25.12	23.94
RUS	635.30	663.52	688.75	667.53	634.50	625.97	615.27	617.19
SAU	191.50	271.38	429.50	496.04	514.06	503.75	443.10	357.50
SGP	60.80	80.25	111.93	118.72	117.44	116.21	111.12	107.79
SVK	16.80	17.56	18.48	18.11	17.54	17.19	16.44	16.23
ZAF	126.80	141.29	157.30	158.13	153.04	149.96	134.35	112.94
ESP	132.60	144.56	173.37	187.14	178.12	172.71	160.68	151.78
SWE	43.20	48.19	61.52	67.83	70.74	71.15	71.24	69.08
CHE	29.40	31.15	34.52	33.93	32.31	31.79	30.59	29.68
THA	95.10	109.95	127.23	130.96	131.77	131.50	130.04	127.52
TUR	93.00	100.26	136.16	152.53	159.36	160.06	157.79	150.75
TKM	23.00	26.46	45.86	56.84	61.33	61.81	60.93	57.90
UKR	112.50	111.19	111.49	107.64	101.51	99.73	97.18	97.52
GBR	198.90	214.58	277.80	303.96	308.14	307.00	297.51	281.54
USA	2182.00	2423.23	3227.72	3727.47	4100.58	4197.39	4373.74	4350.37
World	10255.20	11526.20	14750.02	15790.03	15799.61	15649.75	14964.13	14019.99