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The Future of the Energy Supply Sector and the Role of Nuclear Power

What is the real price of energy?

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Abstract

The IPCC has composed three different future pathways that dictates the level of emission and air pollution based on actions done in the coming century. Two of the scenarios demand comprehensive emission reduction, especially in the energy supply sector. Global macroeconomic trends point to a great increase in energy demand during the century, which entails that energy production should be produced in large by renewable sources. While it is agreed upon by most nations that renewable energy is preferred, their share in the energy mix is marginal compared to fossil sources. The higher price per produced unit has been the main limiter for increased share of renewables. Widespread energy cost-calculation methods like Levelized Cost of Electricity do not generally account for externalities from fossil fuels. Research shows that externalities such as air pollution and intervention with nature generates substantial welfare cost and should therefore be included when calculating the real price of electricity production. This paper sheds light on different aspects of energy production costs and will in context with the current plans and trends of the leading energy stakeholders provide a new angle to the outlook of a cost-efficient future energy mix.

Contents

Tables and Figures

Abbreviations

Abbreviation	Definition
AEO	Anual Energy Outlook
BTU	British thermal units
CCS	Carbon Caputre and Storage
CO2	Carbon dioxide
CREA	Centre for Research on Energy and Clean Air
EIA	Energy Information Administration
EU ETS	EU Emission Trading System
GDP	Gross Domestic Product
GHG	Greenhouse Gas
Gtoe	Gigatonne of oil equivalent
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
LCOE	Levelized Cost of Energy
LTCA	Russian system for supporting the development of renewable Energy
MWh	Megawatt hours
NEA	Nuclear Energy Agency
NITI	National Institution for Transforming India
NO2	Nitrogen dioxide
NPV	Net Present Value
O&M	Operation and Maintenance
O3	Ozone
OECD	Organisation for Economic Co-operation and Development
ppm	part per million
RCP	Representative concentration Pathways

1. Introduction

1.1 Background and research question

In 1804, the world's population reached 1 billion. While it took 200 000 years for humanity to arrive at this point, it only took 200 more to hit 7 billion, and by 2050 the global population is projected to reach 10 billion (Roser, Ritchie, & Ortiz-Ospina, 2019). Combined with three industrial revolutions, the global need for electricity has skyrocketed. Since the first industrial revolution the world's energy mix has in large been dominated by fossil fuel sources, but in recent years as new information about the damages these energy sources cause, new alternative sources have emerged. New renewable alternatives have been developed and reached a 19% share of the final energy production in 2019 (DNV GL AS, 2019) to meet the increased need for cleaner energy. Energy production from renewable sources is not a new concept[1], but the emergence of new and more sophisticated technology is. While sources of energy such as wind, solar, biomass and hydro have been more or less acknowledged worldwide, the debate around nuclear power has been more polarized. With the increased share of intermittent energy power from wind and solar, there is a need for a stable baseload power source. For generations this stable power has stemmed from fossil sources, however, much points to the need for a clean alternative in which nuclear power could be a possible candidate.

The Intergovernmental Panel on Climate Change (IPCC) presented in their AR5 Synthesis report, three different representative concentration pathways (RCPs) for future greenhouse gas (GHG) emissions. The three RCPs represent scenarios of future GHG emission and atmospheric concentrations, air pollutant emissions and land use. The report includes one "business as usual" scenario (RCP8.5) with very high GHG emissions, one stringent mitigation pathway (RCP2.6) and an intermediate scenario (RCP4.5). The RCPs are used to showcase the global effect of reducing the concentration of GHG emission and forms a baseline to calculate the needed reduction in emission. In the pathways that dictates reduction in GHG emissions, the energy supply sector needs to greatly reduce their emissions: to reach

[1] Before the industrial revolution, the only source of energy was that of renewables such as hydro, biofuel etc.

the RCP2.6 target, the energy supply needs to stem from 80% low carbon sources by 2050, and 90% by 2100 (IPCC, 2015). The energy supply in each IPCC pathway would have different compositions, meaning that the price of energy would differ. One way to calculate this is using levelized cost of energy (LCOE). This measure takes into account all the lifetime costs of a power source, from investment to fuel and maintenance expenditures, and calculates a price per energy unit produced (USD/MWh). This makes it a good tool when comparing costs of different sources of energy generation (Narbel, Hansen, & Lien, 2014). By then using emission of CO2 equivalents from each energy source, we can compare the cost of mitigation.

We will in this paper conduct a scenario analysis of the energy supply sector based on the different IPCC RCPs. These scenarios will be compared with each other based on LCOE to further study mitigation costs, while also discussing other indirect costs such as air pollution, radioactive waste and intervention with nature. The following question will be answered in this paper:

> *Is a higher share of nuclear power production a cost-efficient and sustainable way to reduce CO2 emission and other externalities in the energy supply sector?*

The analysis will take into account the projected increase in population and changes in energy use. We will also touch on the subject of probability of the different scenarios based on countries dictated policies. The analysis will be mostly based on widely accessible sources of data and well-known metrics such as LCOE and CO2 equivalents.

The rest of our thesis is structured as follows. In Chapter 3 - Literature Review, the most relevant external literature of the study is explained and categorized. In Chapter 4 - Methodologies, we explain the data collection strategies, and the methods on how the analysis is being conducted. In Chapter 5 - Current Energy Production Mix and Trends, we provide a context of the energy mix and future outlooks in different parts of the world and summarize the findings. In Chapter 6 - Scenario Analysis, the future global energy needs are being outlined, followed by the main analysis. Finally, in Chapter 7 - Discussion and Conclusion the results are being discussed, before we propose a conclusion and review the analysis' limitations.

1.2 Relevance

In order to meet the goals, set by the Paris agreement, IPCC reports state that a sharp increase in nuclear energy production is needed. In the report *Global warming of 1.5°C*, all of the illustrative model pathways include an increase in the nuclear electricity production, ranging from 59% to 106% in 2030 compared to 2010. The report also suggests that the share of nuclear energy should increase progressively, meaning that a more energy intensive future demands a higher share of nuclear energy generation compared to fossil sources (IPCC, 2019). Even though all pathways suggest that renewables are increased further than nuclear towards 2030 and 2050, there is a need for a reliable baseload energy source, as renewables are challenged with intermittency. With capacity factors above 90%, nuclear is well fitted to serve as a reliable baseload energy source (EIA, 2020). It can be argued that the right energy mix for each pathway would be the one that provides the population with enough energy at the lowest possible expense. In this matter, all kinds of costs related with each power source must be addressed - also externalities, risks and intermittency challenges. The need for other metrics other than LCOE is also clearly stated by the IEA & NEA (2015) report *Projected Costs of Generating Electricity*: "[…] LCOE should be accompanied by other metrics when choosing among electricity generation technologies".

2. Literature Review

2.1 Estimating the Cost of Energy Production

There are several approaches when calculating the cost of energy production. Narbel et al. (2014) presents the three most common alternatives: Net Present Value (NPV), Real Options, and LCOE. All of these approaches take only into account the direct cost of energy, not the indirect costs. For example, a coal power plant has direct costs such as fuel and maintenance, while it also has indirect costs such as emitting CO2 into the atmosphere. While NPV and real options are great tools for investors to calculate whether a project is expected to be profitable or when it is most profitable to invest, LCOE is a better tool when comparing different sources of energy on a unit cost basis (usually USD/MWh or EUR/MWh). A multitude of researches and companies have calculated the cost of energy production, as well as future costs. The company Lazard[2] did an in-depth analysis of the Levelized cost of energy in the USA, with a focus on both price sensitivity of tax subsidies and carbon pricing (Lazard, 2018). A more holistic LCOE calculation has also been done by IEA & NEA (2015) in their *Projected Cost of Generating Electricity* report, where future energy technologies and energy needs have been taken into account. This report divides the world into segments and calculates LCOE based on local differences. The academic literature on LCOE calculation is in our opinion thoroughly sufficient.

Even though LCOE is the most common tool when comparing energy production costs, it has its limitations, as discussed by the international energy agency and the nuclear energy agency (IEA & NEA, 2015). One main criticism is that LCOE operates with generic risk, not market specific nor technology specific. This results in a gap between the LCOE and real financial costs for owners. Another criticism of this metric is, as briefly mentioned, the lack of indirect costs in the calculations. IEA and NEA therefore recommend that LCOE should be accompanied by other metrics. Both Narbel et al. (2014) and IEA & NEA (2015) tries to

[2] One of the leading asset management firms in USA.

calculate future energy production cost, but lacks is our opinion a greater analysis of how indirect costs affect the final cost of energy production.

2.2 Energy Production Externalitites

When calculating the cost of energy production, it is beneficial to take into account the indirect costs associated with generation. One of the main externalities is greenhouse gas emissions, especially CO2. Such emissions are not yet widely internalized by the power production companies and are therefore not usually part of the LCOE calculations. There are some systems in place to internalize emission cost, for instance the EU Emission Trading System (EU ETS); a system that sets a cap on total emission from different sectors and opens up for emission allowance trading[3] (European Commission, n.d.). This system has been widely criticised (Rensen, 2018) much due to the oversupply of allowances which has resulted in a low price on carbon. In later years as the system has developed, we have seen a sharp increase in allowance cost: in January 2018, the closing price of one allowance was 9.06 USD, while in January 2019 the price had risen to 22.30 USD (Market Insider, u.d.). Such a system shows that there is a potential when it comes to placing a price on GHG emission. What the correct cost of CO2 emission, and therefore the price, is a widely discussed topic. The EPA (2016) and the Obama administration (Shelanski, 2013) calculates the cost to be somewhere in the range of 36-69 USD/tCO2, while Ricke et al. (2018) finds that the social cost can be upwards to 417 USD/tCO2 due to already high levels of emission.

There are also other externalities connected to various energy production alternatives, some of them being sources of great social costs. Burning fossil fuels such as coal, oil and natural gas also release other types of air pollutants like fine particulate matter, Ozone (O3) and nitrogen dioxide (NO2), leading to welfare costs in all parts of the world. Centre for Research

[3] One allowance is equivalent to the emission of 1 tonne of CO2-equivalent.

on Energy and Clean Air (CREA), have quantified these costs in the form of work absence, years of life lost, and premature death, which results in a global daily cost of about 8 billion USD (Farrow, Miller, & Myllyvirta, 2020). This means an annual amount of almost 3 trillion USD, which is similar to what OECD (2016) suggests in their analysis. In 2060, these costs are projected to reach an annual amount of 18-25 trillion USD, depending on the linearity of costs increase. Much of this is due to the rising number of premature deaths in China and India, and as there is a considerable projected income increase in these countries, there are also higher values associated with each premature death. It should also be noted that increased demand for agricultural products and transport-emissions is a part of the projected increase in air pollutant-associated costs (OECD, 2016, p. 11). As the variance in this estimate is high, indicating that the prediction of this particular situation 80 years ahead is of high uncertainty, we have chosen to use the same range, 18-25, for the prediction of year 2100.

Nuclear power does also come with risks and externalities, for instance the treatment and storage of radioactive waste. (Lazard, 2018) does not take account for these costs in their LCOE analysis, nor does IEA & NEA (2015) due to measuring difficulties. There are however considerable costs connected to disposal and storage of spent nuclear fuel, ranging from 13 to 34 billion USD for 153,000 metric tons of waste. Disposal and storage cost also depend on the duration of storage, because it has to be repacked every 100 years due to safety. This means storing 153,000 metric tons of waste could surpass 200 billion USD. Decommissioning of the Hanford site in Washington, including stabilizing 56 million gallons of radioactive waste, is projected to end up with a total cost from 86 to more than 100 billion USD (GAO, 2009, pp. 22-39). In The World Nuclear Waste Report of 2019, studies of nuclear facilities in France and Germany shows that funding for covering waste-management costs was approximately equivalent to decommissioning costs funding (WNWR, 2019, pp. 102-108). In 2011, The World Nuclear Association estimated that disposal costs for UK facilities would cost operators less than 1 pound each MWh produced. This correlates with former Energy Minister of the UK, Andrea Leadsom, stating that the estimated cost of decommissioning and long-term waste management of the new Hinkley Point C power plant would come to 2.53 USD[4] per MWh

[4] 2 British pounds = 2.53 USD

(Cotton, 2017). For simplicity measures, we will use 2.5 USD/MWh as an assumption for decommissioning and waste management-costs of nuclear facilities in our analysis.

Risk of nuclear disasters must also be taken into consideration, even though safety regulations and requirements keep getting stricter due to past nuclear disasters, like Three Mile Island, 1979; Chernobyl, 1986; and Fukushima, 2011 (U.S.NRC, 2019). Besides direct health correlated side-effect, like increased risk of getting cancer[5], the clean-up costs of such disasters can get tremendously high. The former Soviet nuclear economist Yuri Koryakin estimated that "[…] by the year 2000, the Chernobyl accident may cost the country 283 to 358 billion USD in lost electricity production, contaminated farmland and other economic consequences […]. The total bill suggests that the Soviet Union may have been better off if it had never begun building nuclear reactors in the first place" (Evan & Manion, 2002). While the consequences of a major nuclear disaster could be devastating, studies show that the mortality rate per TWh produced nuclear energy is relatively low[6]. Kharecha & Hansen (2013) estimated that an average of 1.84 million air-pollution related deaths has been prevented from 1971 to 2009 by producing nuclear-, and not fossil-fuelled energy.

It should also be mentioned that different types of energy production sources also lead to externalities not being possible to measure directly in monetary values. For instance, building power production facilities and the surrounding infrastructure, would in many cases interfere with natural ecosystems, and at worst case impose threat on biodiversity. A common opinion is that wind turbines kill a lot of birds, an argument that has been put in front of quite a few wind-farm debates. However, some studies show that fossil-fuels are responsible for 17 times more fatalities in the US[7], while other studies calculated collisions with building glass to be

[5] In the most contaminated area after the Fukushima accident, the WHO estimated that there was a 70 percent higher risk of females exposed as infants developing thyroid cancer over their lifetime, increasing the natural rate from 0.75 to about 1.25 percent (Nebehay, 2013).

[6] Mean value of deaths/TWh: coal = 28.67, natural gas = 2.821, nuclear = 0.074 (Kharecha & Hansen, 2013).

[7] The study estimates that wind farms are responsible for 0.3 fatalities per gigawatt-hour (GWh) of electricity while fossil-fueled power stations are responsible for about 5.2 fatalities per GWh (Sovacool, 2009).

up to 3000 times more fatal than wind farms[8]. There is also debate regarding how the marine wildlife would respond to offshore wind instalments. Most researchers believe that the construction phase would impose the most negative impact on marine ecosystems. Potential impacts include disturbance effects from noise, electromagnetic fields and changed hydrodynamic conditions. There is not enough evidence of concluding long-time effects, but some researchers are afraid bird species are going to largely avoid wind farm areas, also after the construction phase. Others do however believe the local subsurface marine environment could benefit from wind farms, due to the prohibition of trawling, and that the foundations of the turbines could function as artificial reefs (Wilhelmsson, et al., 2010).

There is also loss of habitats and interference with ecosystems, as the infrastructure of solar power takes up significant amounts of land. Studies have documented direct mortality of birds from heliostat collisions and burning from solar rays directed to the central receiving point (McCrary, Schreiber, McKernan, Wagner, & Sciarotta, 1986). Hydropower and different types of biomass- and biofuels projects can also be a major driver of habitat change and fragmentation. Regarding hydro, a decline in water quality (upstream, downstream or within the reservoir) can lead to unwanted bacterial growth, eventually affecting biodiversity (Gasparatos, Doll, Esteban, Ahmed, & Olang, 2017). On the other hand, there are also studies showing that hydropower instalments have had a positive impact on biodiversity and animal habitats[9]. Biomass and biofuels production can also be linked to changes in land-use and biodiversity loss (Pedroli, et al., 2013). For instance, the expansion of sugar cane crops for ethanol production in Brazil has contributed to the destruction of riparian forests (Martinelli & Filoso, 2008). What can be drawn from this is that there is a lot to consider when choosing a source of power production, and some externalities might not be as clear or easy to quantify into monetary values.

[8] *Top Threats to Birds in the U.S.* Max range, collisions with building glass: 988,000,000. Max range, collisions with land-based wind turbines: 327,586 (U.S Fish & Wildlife Service, 2018).

[9] The population of a threatened brazilian giant otter species was boosted in lowland Amazonia, due to the creation of new open-water and shoreline lake habitats from hydropower installments (Palmeirim, Peres, & F.C.W., 2014).

2.3 Estimating Alternatives of Emission Mitigations

The first of three publications that together forms the sixth assessment report (AR6) provided by the IPCC, lays the grounds of our analysis. In the second chapter of this report, a summary for the different characteristics of four illustrative model pathways is showcased, and their likelihood of limiting temperatures below 2°C and 1.5°C towards 2100 compared to pre-industrial levels. In the first scenario, global energy demand is lowered due to social, business and technological innovations, while living standards increase, especially in the global South. In the second scenario the global community has a strong cooperative focus towards emission reduction and healthy consumption patterns. The third scenario illustrated a middle-of-the-road situation where historical patterns are set as base both societal and technological. The fourth and last scenario is a resource intensive scenario where increasing economic growth leads to a high global energy demand, and emission reduction mainly is achieved through technological development (IPCC, 2019).

The predictions of future energy use are based on assumptions about future socio-economic developments, including economic and population growth, equity, and sustainability. While it is mainly focused on future climate change, it is a good tool since IPCC divides sources of emission into different categories and discusses different mitigation alternatives. As our research question focuses on mitigation cost in the energy supply sector, this report will be a vital part of our paper. There is a lot of available research on global scale energy outlooks, but it lacks - in our opinion - an approach of regional penetration capabilities. This is something that we will consider in our analysis, as well as a discussion of different externalities and risks beyond just CO2 missions.

3. Methodologies

3.1 Data Collection

Data for this thesis is collected from different renowned sources, including but not limited to IPCC AR5 source data, World Data Centre for Climate (WDCC) and other secondary data sources. Our main source of data is the Global Power Plant Database from World Resource Institute (2019). This dataset contains around 85% of the world's power plants, derived from a multitude of sources. To cross-check and validate the measures regarding coal power plants from this dataset, the Global Coal Plant Tracker from Global Energy Monitor (2020) has been used. The Global Energy Monitor is an independent organization that is widely used by a wide range of both companies and national agencies, such as Bloomberg and IPCC. A summary of the collected data is showcased in Table 1 and Figure 1

Summary Table
Capacity for each power source

Power Source	Sum Capacity
Biomass	18,189
Coal	1,503,553
Cogeneration	459
Gas	718,831
Geothermal	7,311
Hydro	587,900
Nuclear	156,978
Oil	96,171
Other	2,294
Petcoke	68
Solar	34,081
Storage	454
Waste	11,126
Wind	127,302

Table 1: Summary table - Capacity for each power source

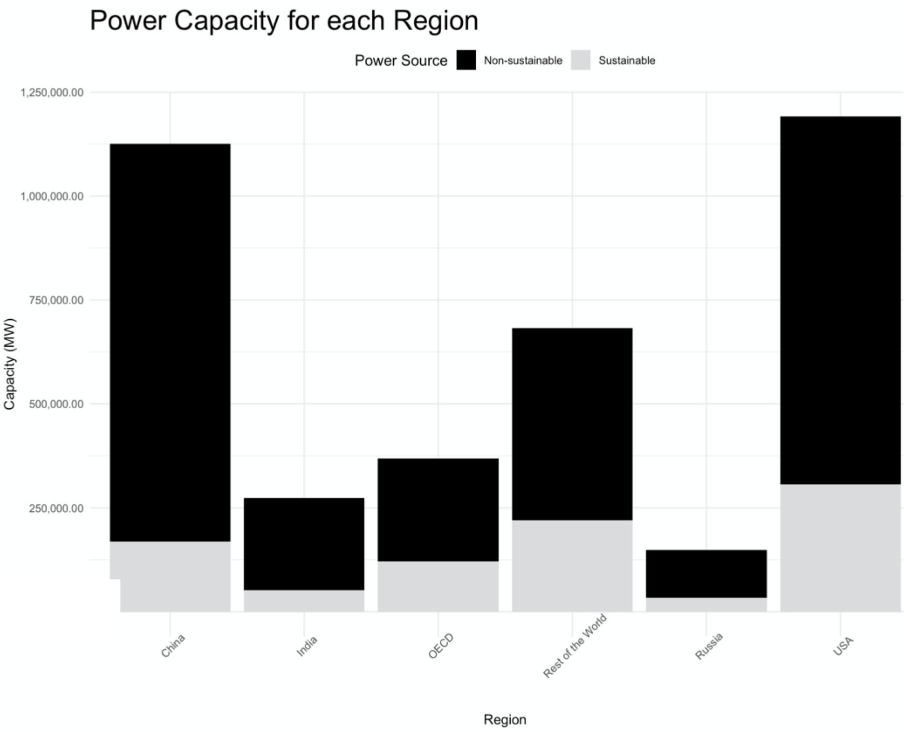


Figure 1: Sustainable and non-sustainable power capacity for each region

The above figures show that coal is the prevailing energy source, and that non-renewable energy sources account for the bulk of the generating capacity. This is especially clear in China, where non-renewable energy sources are fivefold that of renewables. This large difference between renewable and non-renewable has gradually developed over time at an escalating rate. Figure 2 shows how the share of the two energy categories has developed since 1990.

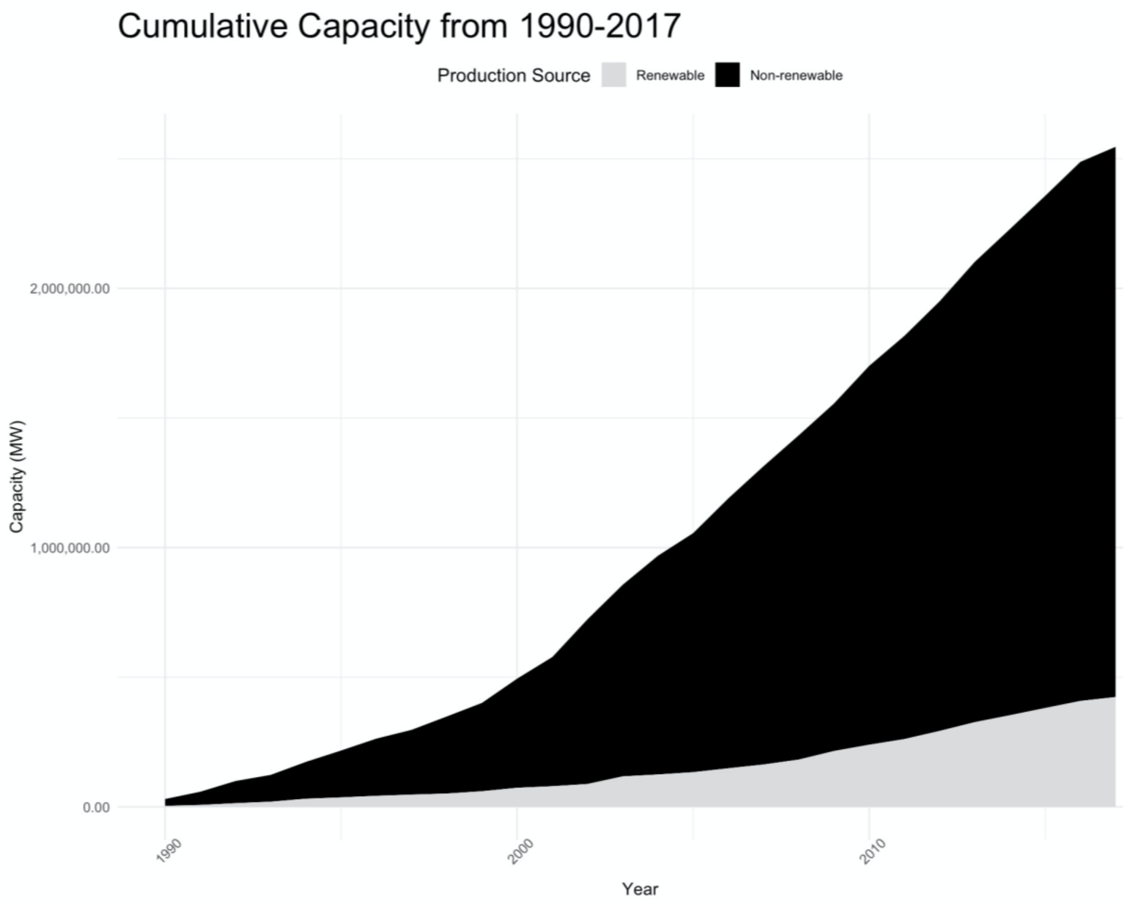


Figure 2: Cumulative capacity from 1990-2017

The distributors of the data are trying to maintain a high level of quality and accuracy, but there may be some disconnect between actual values and those posted on these databases. This is primarily due to the fact that these services rely on information collected from a multitude of sources, and information can therefore be lost or incorrect. This is in our opinion one of the biggest threats to reliability in this thesis. While some of the collected data is complete and from official sources[10], not all countries energy information is easily accessible on a generator-specific level. This mismatch is especially visible if we compare the collected data from Russia

[10] The EIA (2019) generator-specific information gives a comprehensive account of existing power plants in the US

with the aggregated data from the Energy Information Administration (EIA, 2017). EIA states that the 13% of energy in Russia stems from coal power plants, while the collected data

Table 2 shows this number to be 22.54%

Overview of capacity in Russia		
Power Source	Capacity (MW)	Share
Coal	33,440	22.54%
Gas	81,265	54.77%
Hydro	28,010	18.88%
Nuclear	5,480	3.69%
Oil	24	0.02%
Solar	160	0.11%
Wind	7	0.00%

Table 2: Overview of capacity in the Russian energy sector

While our dataset does not contain all the power plants in operation, we believe that it is sufficient as a basis for further calculations. To improve the analysis, a more complete dataset should be used.

Since our calculations are based on these data, a dataset that is not correct will affect the results. The validity of our thesis can also be partially vulnerable. This is due to, as mentioned above, the limitations that are imposed when using LCOE as a measure of future energy cost[11]. There are also some issues when selecting a LCOE-value for the different energy sources, much due to the fact that these greatly vary from region to region. To combat this issue, we will use a weighted average based on the share of total world energy capacity.

[11] The calculations do not take into account the difference in general market risk, and market-specific risk.

3.2 Data Manipulations and Usage

The data collected is generator specific information about capacity, date commissioned and country. The input concerning coal power plants were cross referenced with the Global Energy Monitors (2020) coal power plant tracker, while plants from the USA was matched with source data from EIA (2019). Some of the power plants had a designated decommission date, those that did not were given a lifetime as specified by IEA & NEA (2015) (Table 4). Those power plants that did not have a computed commission date or capacity, is excluded from the dataset. Part of the complete dataset can be found in the Appendix.

The different countries are grouped into the regions *OECD, USA, Russia, China, India* and *The rest of the world*. Energy sources are also group into *renewable* and *non-renewable,* based on their characteristics (Table 3). These grouping are used to create Figure 2 and to calculate the baseload in Figure 10 through Figure 14.

Power Plant Lifetime	
Power Source	Lifetime
Coal	40
Hydro	80
Wind	25
Solar	25
Gas	30
Nuclear	60
Biofuel	40
Oil	40
Geothermal	60

Table 4: Power plant lifetime

Energy source grouping	
Energy Source	Group
Coal	Non-renewable
Hydro	Renewable
Wind	Renewable
Solar	Renewable
Gas	Non-renewable
Nuclear	Non-renewable
Biofuel	Renewable
Oil	Non-renewable
Geothermal	Renewable

Table 3: Grouping of energy sources

When calculating the different scenarios in *Energy Composition in the Different RCPs*, the IPCCs (2015) *Climate change 2014 Synthesis Report* is used as reference for the concentration of fossil fuel in the energy mix in the RCP4.5 and RCP2.6 scenarios. In the RCP8.5 scenario we assume that the share of the energy sources is as they are today. We used a total energy need increase from 2017 to 2100 of 120% to calculate the yearly increase, which is the basis of the slope in the figures.

The LCOE-values of the energy sources in the different regions are based on numbers from IEA & NEA (2015) and Ram et al. (2018). To implement price of CO2-emission into the analysis, data from Volker Quaschning (2015) on emission per produced MWh electricity is being utilized. The final LCOE-value is a weighted average of both energy mix in each region and the regions share of total energy capacity.

4. Current Energy Production Mix and Trends

4.1 China

China has had a tremendous economic growth for the past 40 years, lifting more than 750 million people out of extreme poverty (World Bank, 2017). Foreign trade, liberalisation and implementation of free-market reforms has resulted in China on average doubling their GDP every eight years since 1979 (Morrison, 2019). Consequently, the energy consumption has rapidly increased during this time, with a 234% increase in coal alone until 1995. Following the turn of the millennium, GDP-growth reached an all-time high, and coal production has since then increased 7.2% annually on average (Dong, Li, Sun, & Jiang, 2017). Coal is the dominant energy production source in China, which alone contributes to 45% of the global coal energy generation (Enerdata, 2019). The energy mix capacity as of 2017 in China is illustrated in Figure 3.

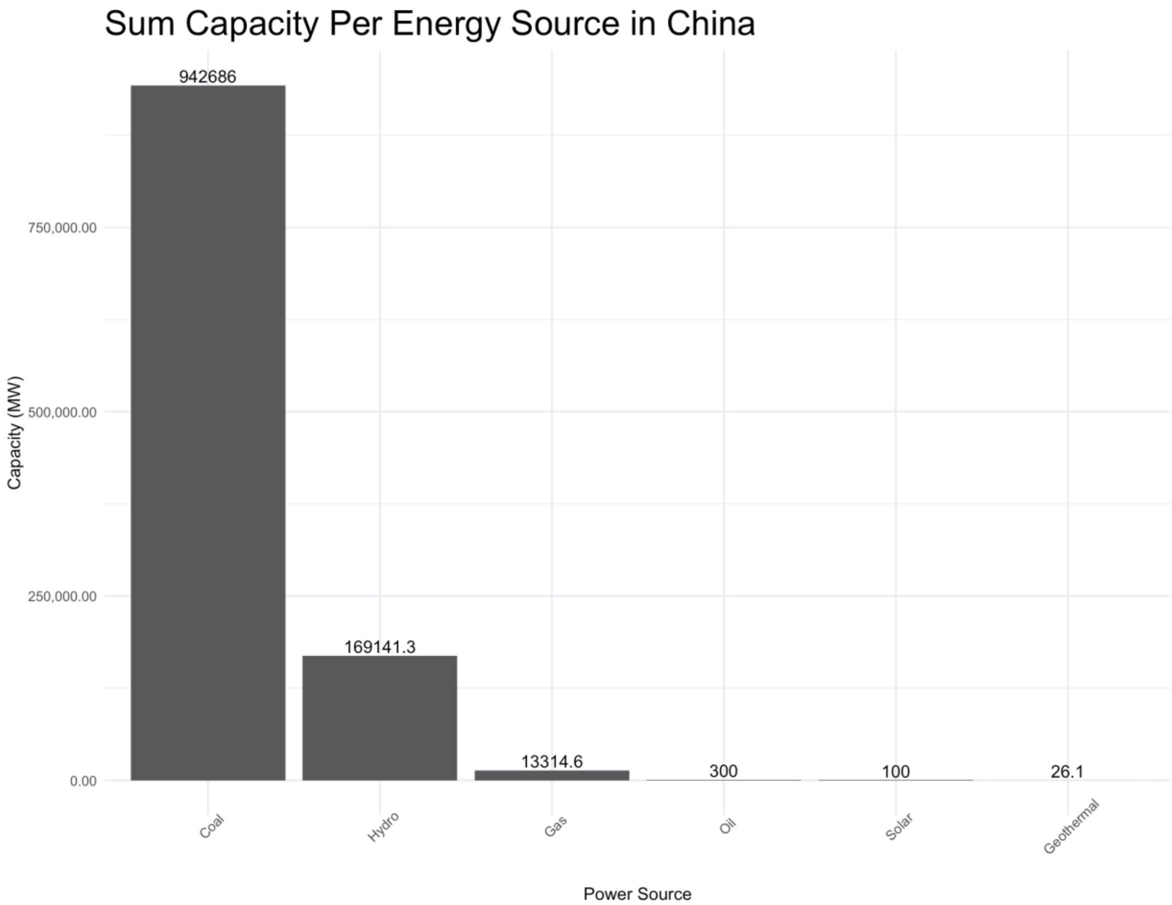


Figure 3: Sum capacity per energy source in 2017 in China

Coal supply in China is widely distributed and abundant compared to other fossil sources such as oil and natural gas, which in combination with a rapidly growing economy and energy demand makes it a preferred source of energy (Dong, Li, Sun, & Jiang, 2017). Since 2011, China has consumed more coal than the rest of the world combined, but the share of coal has declined (ChinaPower, 2020). Even though the total coal power capacity has slowly increased in the last years, the share is predicted to further fall from two-thirds today to less than 40% in 2040, as a result of the total energy demand slowing down (IEA, 2017). China is also the biggest oil importer in the world, and the oil dependency rate hit a record high 68% in 2016. Natural gas accounts for slightly above 5% of the total energy consumption, but imports jumped 33% in 2017 (Planete Energies, 2018).

The overall strategic policy of the energy sector in China is to “gradually lower the proportion of coal consumption and raise the proportion of natural gas consumption and substantially increase the consumption proportions of renewable energy such as wind power, solar energy, geothermal energy and nuclear power.” (IAEA, 2018a). The Chinese government's energy agency claimed in early 2017 that they will spend $360 billion through 2020 on renewable power sources like solar and wind (Forsythe, 2017). In 2017, global investment in renewable power was $279.8 billion, in which China accounted for $126.6 billion. The US, which was second, invested only $40.5 billion in comparison (Louw, et al., 2018, p. 11). This renewable boost in China has however seemed to be set on hold due to factors like the US-China trade war, which has phased out renewable subsidies (Standaert, 2019).

China is also a large producer of nuclear power and ranks third in the world both in installed capacity and electricity generated after the US and France. Historically, the public opinion in China on nuclear power has been through a rough path due to major disasters, the latest being Fukushima in 2011. A comprehensive 2005-2020 development plan was postponed after the accident, which dramatically altered the situation and demanded improvement actions of existing plants, as well as regulatory revisions for planned facilities. Now, China is gradually ramping up construction again and has 15 units under construction as of July 2018.

4.2 United States

In 2016, natural gas surpassed coal as the fuel most used to generate electricity in the United States, and it remains as the leading source of electricity generation through 2050, according to the AEO2019 (Annual Energy Outlook) reference case. Natural gas accounted for 34% of total electricity generation in 2018 and is projected to increase to about 40% throughout 2050. The US is nearly self-sufficient with energy consumed from natural gas, and in 2018 the production was 30.6 trillion cubic feet, the highest annual amount ever recorded (EIA, 2019). In fact, the US is also a major oil and gas exporter, accounting for over 16% of global oil supply and 20% of gas supply in 2019, even though they hold consequently less than 4% and 6% of the global oil and gas reserves. The growth rates in oil and gas output exceeded any other country's annual increase the last 50-year period (BP, 2019). Before the domination of natural gas, coal was as mentioned the source generating the most electricity. The average US coal plant is now 40 years old, and more than 500 power units have been shut down or announced retired in the past decade. The turn-around for coal is due to a price decline in natural gas production, and that renewables have made it hard for coal plants to make money in electricity markets (Rhodes, 2020).

Renewable energy is the fastest growing source of energy in the US and has doubled since the last decade in terms of installed capacity. In April 2019, renewables outpaced coal for the first time ever providing 23% of US power production, compared to coal's share of 20%. The fastest growing renewable sources are wind and solar, and in 2019 annual wind generation exceeded hydroelectric generation for the first time and became the top renewable source in the US. As of the end of 2019, 77% of installed wind capacity was installed in the past decade (EIA, 2020). Solar power, which is projected to stay the fastest growing electricity generation source, was 80 times greater in the end of 2019 than in the end of 2009 (BCSE, 2020).

Nuclear power plays a major role in the energy market in the US, accounting for about 19% of the energy generated in the US. As of 2018, The United States is the world's biggest nuclear power generator and has 50% more installed capacity than the second largest producer, France. Currently the US has 97 operating nuclear reactors, with a capacity of almost 100 GW (IAEA, 2019a). Commercial nuclear reactors were built at large scale after the Atomic Energy Act of 1954, and installed capacity grew tremendously during the 70s. Most US nuclear facilities were built between 1970 and 1990 (EIA, 2017). The Three Mile Island accident in 1979, led to a declining and slow period for a few years, before capacity started to rise again. The last 20 years installed capacity has been stalling, much due to new safety requirements driving the cost per kWh upwards. In 2018, installed capacity was at the same level as of 2003 (EIA, 2020). For this reason, analysts believe that the share of nuclear power in the US is likely to decline in the following years. There have already been examples of reactors which recently have been shut down before reaching the end of their operation licence, due to economic challenges. New builds have been limited, and only two projects have moved forward in the last decade.

The latest EIA Annual Energy Outlook reports has been somewhat disagreeing on what power source will be dominant in the US through 2050. While the report of last year projected natural gas to remain the largest source with 39% against 31% renewables (EIA, 2019), the 2020 report forecasts renewables to account for 38% of the 2050 energy mix against 36% natural gas. This is again only projections, but it also illustrates the pace of renewables economic competitiveness. Nuclear power is projected to decrease from 19% today to 12% in 2050.

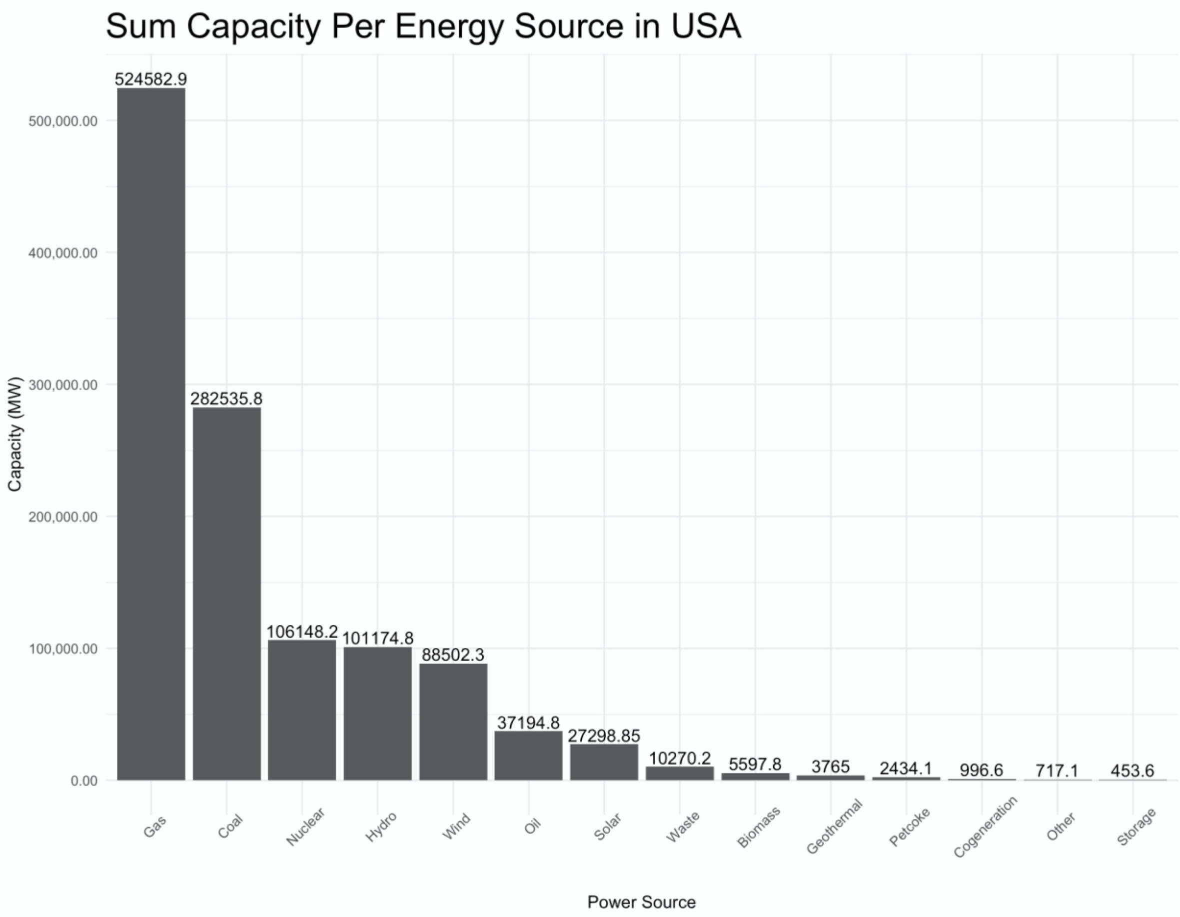


Figure 4: Sum capacity per energy source in 2017 in USA

4.3 Russia

Russia's rich hydrocarbon resources are of great importance in terms of energy consumption, but also GDP. Income from oil and natural gas accounts for more than one third of the federal budget revenues (EIA, 2017). As of 2018, Russia is the second largest natural gas, and the third largest oil producer in the world, accounting for 17% and 12% of the global output, respectively (BP, 2019). The country is also the global leader of crude oil production, in which the major part is being exported. Out of the 556 million tons of crude oil that was produced in Russia in 2018, 409.3 million was exported. The last 20 years, crude oil consumption has been substituted by increased consumption of natural gas, which has increased the export share of crude oil. In 1990, the export share was 47.7% compared to 73.6% in 2018 (Zubarevich, et al., 2020). Russia is also estimated to have the second largest coal deposits in the world (Banktrack, 2013), which accounts for 13% of annual electricity consumption (EIA, 2017). The coal industry faced some challenges in the period following the dissolution of the USSR, but production has increased overall since the late 1990's. In 2016, Russia was the third largest coal exporter in the world (EIA, 2017). Consumption has followed the same pattern as the downscale in the 90's and has remained at this level (Worldometers, 2016).

From Figure 5 it is clear that renewables have not yet set their presence in Russia's energy mix, expect for hydro which is a significant power generator. In terms of hydropower resources, Russia ranks second in the world, which implicates an even bigger potential in this area. The international hydropower association claims that only 20% of the Russian hydro resources are utilized (IHA, 2017). Followed by hydro is bioenergy, with 1.35 GW of total installed capacity. The lack of renewables in the energy mix is mainly explained by governmental decision making, in which a general scepticism towards renewable power sources has been present (Mitrova & Melnikov, 2019). This again could be explained by the last decades' stagnant economy which have led to low investment availability for new technology deployment, which obviously limits investment capacity.

IRENA's made reference case projects the renewable energy share to be 4.5% in 2030, including hydropower (Gielen & Saygin, 2017). Compared to the rest of the world, Russia does not seem to have a strong commitment towards new renewables such as wind and solar, and the government's capacity agreement support scheme of wind and solar instalments (LTCA), only lasts until 2024 as of today. Nuclear power has a strong position in Russia with 18% of the total electricity supply (IAEA, 2019b). The Obninsk reactor was the first ever nuclear reactor to produce electricity back in 1954. Towards the mid 80s, there were 25 reactors operating in Russia, before the Chernobyl accident also led to a slowdown. Between the accident and the mid 90s only one reactor was commissioned in Russia. Today, the government has big plans for the nuclear industry, and the latest Federal Target Programme suggests a 25–30% nuclear share in energy supply by 2030, 45–50% by 2050 and 70–80% by the end of the century (IAEA, 2019b). Russia is also a global leader in fast reactors and sees this as a solution to be the first to close the fuel cycle in nuclear power production (World Nuclear Association, 2020).

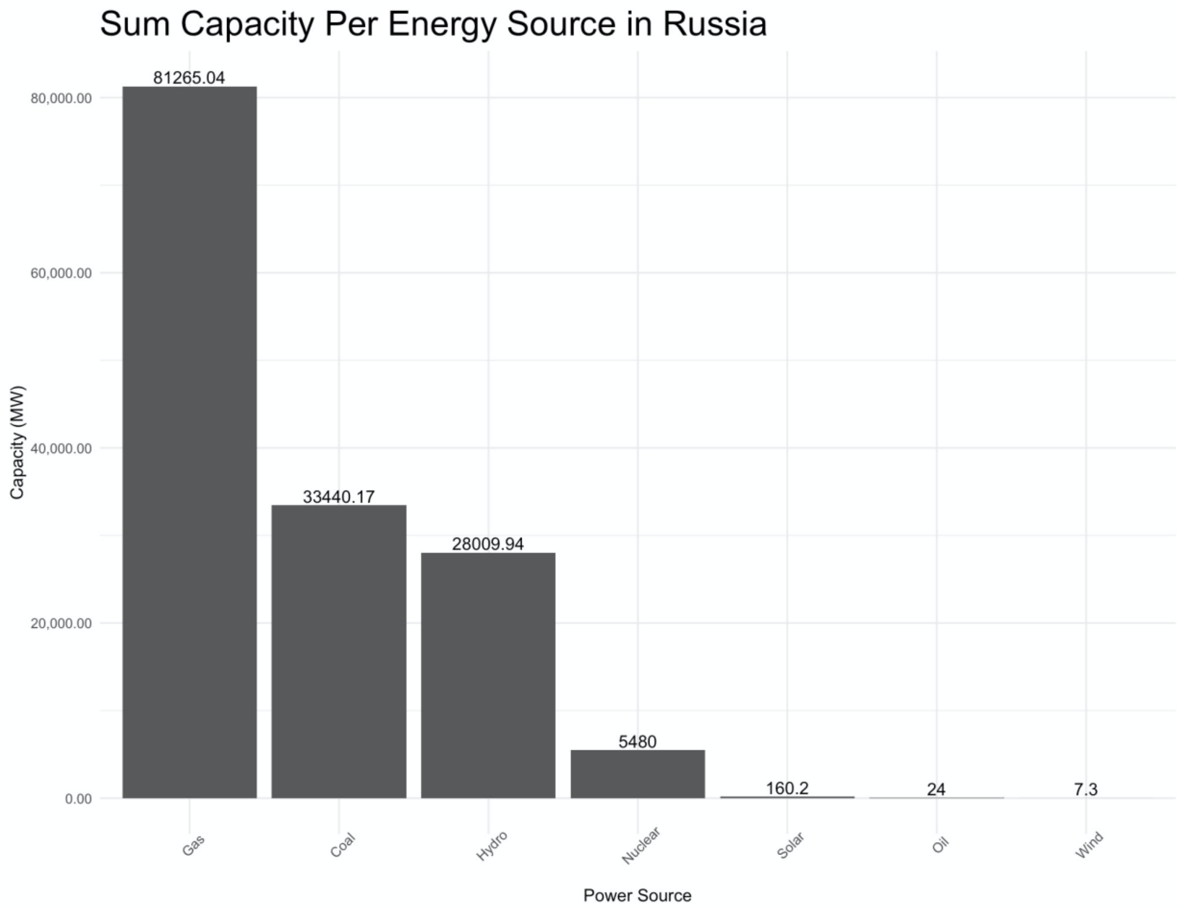


Figure 5: Sum capacity per energy source in 2017 in Russia

4.4 India

Similar to China, India has also faced great challenges in terms of population growth combined with giving people access to electricity. Between 2000 and 2019, around 750 million people gained access to electricity in India, which reflects strong and effective policy implementation. With an increase of 55% in energy supply in the last decade (highest of all G20 countries), coal has been the favourable choice due to its cost and India's strong coal history and great reserves (IEA, 2020). The quality of coal is however low in India compared to other countries, with a gross calorific value of about 4500 Kcal/kg[12] (Siddayao, 1985, p. 126). However, the preferred source of energy in India is sector dependent. Coal is dominant in the industry sector (36%), Oil in the transport sector (95%) and bioenergy and waste in the residential sector (68%). Domestic energy production has alone not been able to keep up with demand, resulting in significant imports of oil, and an increasing trend of natural gas import.

India's plans to boost renewable electricity are ambitious and targets a share of 44% non-fossil-based installed capacity by 2027. Today, the share of renewables in electricity generation is about 16%; a higher share than most G20 countries, but mostly due to traditional use of biomass (IEA, 2020). The government of India has also set a target of installing 175 GW of renewable energy capacity by 2022, where 100 GW is to be installed from solar, 60 GW from wind, 10 GW from bio-power, and 5 GW from small hydropower (NITI, 2015). Renewable energy in India has had a tremendous growth in recent years, and 6083.48 MW of renewable capacity has been added only since November 2019 (Joshi, 2019). India has also large hydropower resources, and EAI ranks India 5th in a global scenario with a total potential of 250 000 MW (EIA, 2019). In comparison, current installed capacity is about 45 400 MW, which points to a utilization of only 18% (CEA, 2020).

Regarding nuclear energy, there are 21 reactors operating in India, accounting for 2.5% of the total energy generation mix (IEA, 2020). 1969 was the first time a reactor was put on the grid in India, and there are currently 7 reactors under construction. India relies on import of raw materials for nuclear production, as there are no domestic uranium reserves. Need for fuel import and known issues regarding nuclear waste, has resulted in India putting effort into developing a thorium fuel cycle as part of an ambitious three-stage policy program (IAEA, 2016). The Fukushima disaster made a clear impact on the public opinion also in India, leading to several mass protests against multiple projects. This has delayed the development process of these to a certain extent (Srivastava, 2011).

[12] A calorific value that is almost 30% lower compared to e.g. Australia.

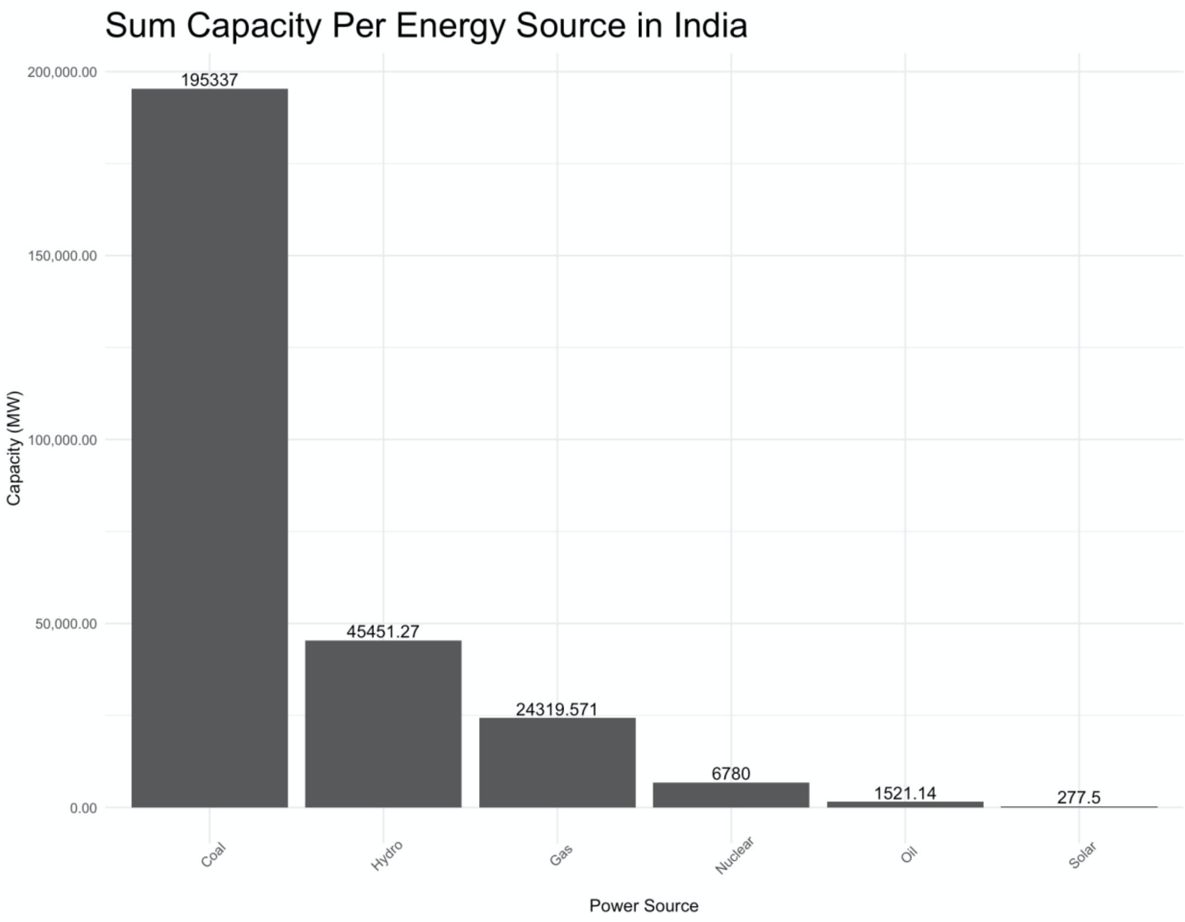


Figure 6: Sum capacity per energy source in 2017 in India

4.5 OECD

The OECD (Organisation for Economic Co-operation and Development) is a group of 34 countries including most of the large European countries, Canada, Japan, Korea, Israel, Australia, New Zealand, United States, Mexico, Chile, and Argentina. In this paper, the United States is excluded from the OECD and is treated as its own region due to their large share of world energy capacity. The EU region has a long history of industrialisation, and many countries are relying on an increased share of non-fossil energy. A lot of the energy consumed in the EU is also important. In 2017, only 45% of consumed energy was produced domestically. The total energy mix in the EU in 2017 was: Oil (36%), Natural gas (23%), coal (15%), renewables (14%) and nuclear (12%) (Eurostat, 2019). This, however, varies considerably between member states. Canada on the other hand is the world's second largest hydropower producer, and 67% of Canada's electricity comes from renewable sources. Canada is also the second largest power exporter behind Germany, with a 10% export share of total electricity production. Nuclear is also substantial in Canada, and makes up 15% of total electricity generation, 6th on a global basis in terms of generated electricity (Government of Canada, n.d.).

In eastern-Asia, the situation is rather different, and renewable energy has yet to make its impact on the energy mix. Both Japan and South-Korea rely on fossil sources, where coal, oil, and natural gas all provide considerable amounts of energy. The greatest renewable source in the countries is biofuels, which makes up about 3% of the total energy production mix both for South-Korea and Japan as of 2018 (IEA, 2018b; IEA, 2018a). Nuclear power was a rather large part of the energy mix (15% in 2010) in Japan until the Fukushima accident, which led to all reactors being shut down. In 2015, the first two reactors were reinstated, and today, Japan is scaling up nuclear power again. In South-Korea, nuclear power has a strong position with approximately 12% of the energy mix in 2018. However, South-Korea has a large dependence on energy imports (IEA, 2018b).

In Australia, coal, oil and natural gas supplies accounted for 93% of energy production in 2019 (IEA, 2018). Australia is also the world's largest coal exporter, and accounts for approximately 38% of total world coal exports (Workman, 2020). In 2015, 68% of the total energy production in Australia was shipped overseas. As there is no focus on producing nuclear energy, Australia benefits from exporting great amounts from the world's largest uranium reservoir, storing with (about 29% of the world total) (EIA, 2017). New Zealand has relatively more renewables in the energy mix, in which geothermal energy and hydro makes up the greatest part. In 2018, renewables accounted for 40% of the total energy production mix.

In Mexico and Argentina, natural gas and oil are the main energy supply sources, accounting for about 90% of the production mix. Chile, however, has a renewable share of 28% in the energy mix, mainly biofuels and hydro (EIA, 2019). Nuclear power is small and constant in these countries, and little points towards that an upscaling is about to happen any time soon. In all Latin America and the Caribbean, there are seven power reactors in operation, contributing to just 2% of the total energy production (IAEA, 2018b, pp. 41-46).

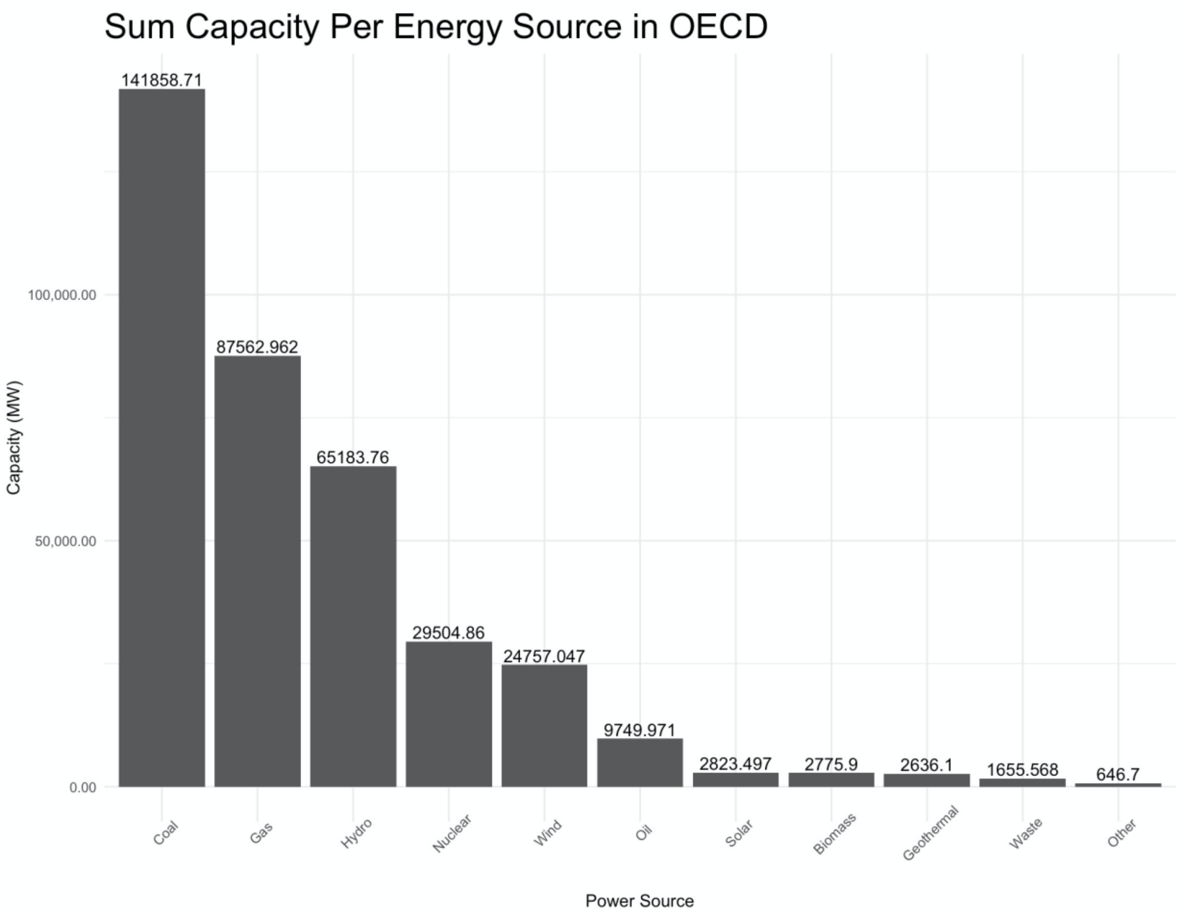
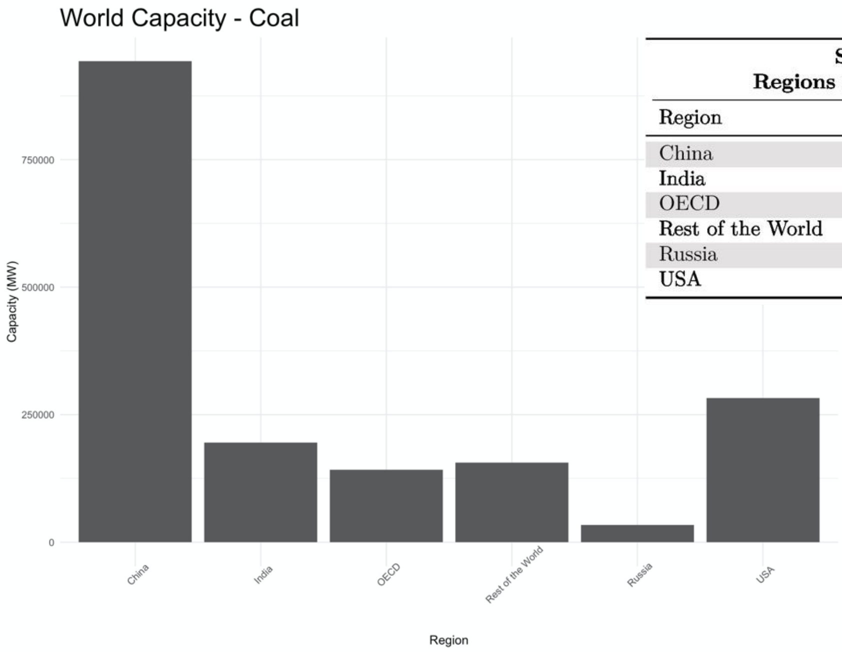


Figure 7: Sum capacity per energy source in 2017 in OECD

4.6 Summary

Over the course of many years, China has increased their energy capacity to be among the biggest energy producers in the world with a share of total capacity of almost 30%. With China and the US combined, they account for over 60% of the worlds' total energy capacity. It is also clear that coal is the prevailing energy source in all regions, totalling more than gas and hydro combined (Figure 9). China is by far the largest producer of energy from coal, with more capacity than all other regions combined (Figure 8). However, China is also the leading investor in renewables, keeping technologies to develop and prices to drop. India, which is on a track to overtake China as the most populous country within a decade, does fortunately have ambitious plans of renewable expansion. Overall, the shape of a future energy outlook is being formed by a race between a growing middle-class in the most populous parts of the world, and cost-competitive renewable energy supply.



Region	Capacity	Share of total Capacity
China	1,125,568	29.69%
India	273,686	7.22%
OECD	369,155	9.74%
Rest of the World	682,406	18.00%
Russia	148,387	3.91%
USA	1,191,672	31.44%

Table 5: Summary table - Regions share of total capacity

Figure 8: Coal capacity per region

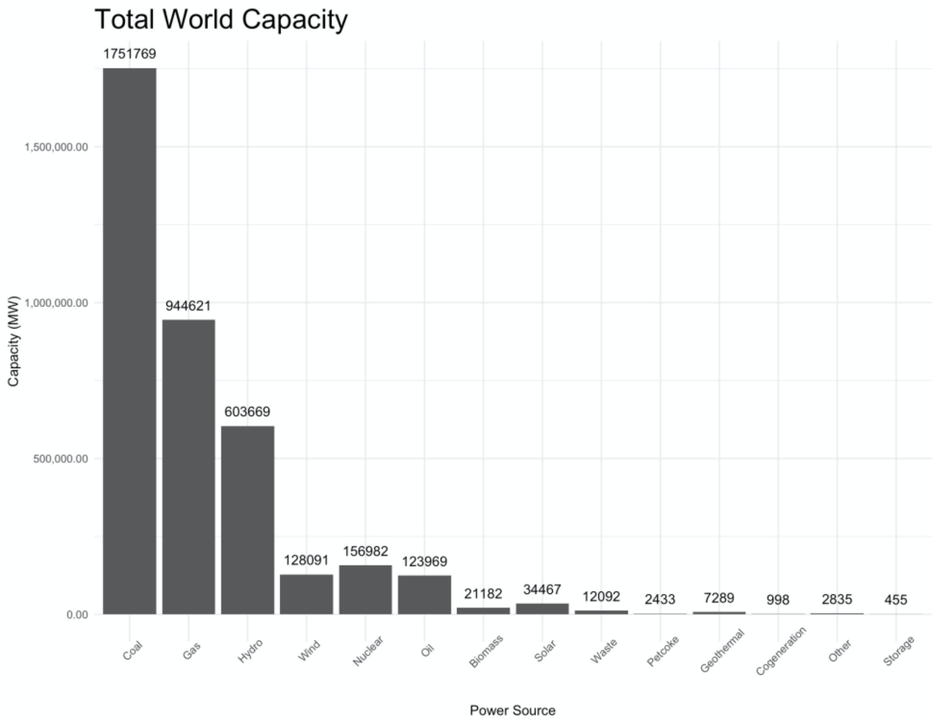


Figure 9: Total world capacity for each power source

5. Scenario Analysis

5.1 Future Energy Mix and Energy Need

From the previous sections it is clear that the plans for future energy supply differs vastly between countries. One thing that is clear to most climate scientists is that the emission goals set by the UN and IPCC will most likely not be met based on the current track. In the 2019 *World Energy Outlook* published by IEA, two possible scenarios are presented. One scenario is called the “Current Policies Scenarios”, which tells that the current track is going to lead to a 1% energy demand rise each year until 2040. Photovoltaics (PVs) are going to supply half of this increase, while natural gas will account for a third. Oil demand will flat out during the 2030s and coal use will fall more steeply. Rise in emissions will slow, but not peak until 2040, and current sustainability goals will not be met (IEA, 2019b). The other scenario is called the “Sustainable Development Scenario” and includes rapid and widespread changes in all parts of the energy system. This scenario holds on to the goals set by the Paris agreement, fully aligned to keep temperature rise below 2° C, but preferably below 1.5° C. This change is made possible thanks to multiple technologies and fuels providing cost-effective and efficient energy services.

EIA also states that energy security will be a critical factor in the future, and that oil will have the paramount position in this. About 20% of the increase in global energy demand of 2018 was due to hotter summers, which pushed demand for cooling. These tendencies are likely to continue, and oil will play a key role in this due to its import and production flexibility. The US will be a global leader, accounting for 85% of the oil production increase, and 30% of the natural gas increase according to the Stated Policies Scenario. Whichever of the two scenarios that becomes most true to reality, the world would still be relying on oil supply from the Middle East. There is no sign that the demand for liquid fossil fuels would slow down anytime soon in the large growing economies of e.g. China and India, which would keep the position of the Middle East as a global supplier strong for a long time (IEA, 2019b).

Several studies also point to the fact that the developing world is going to account for the largest increase in energy demand in the coming decades. The economic development of Africa will have a great impact on the global energy demand, and in the Stated Policies Scenario, it is measured that Africa will have a greater oil consumption increase than China towards 2040. The question is whether the speed of solar PVs is keeping up with the energy demand in Africa, which has the world's greatest potential of exploiting this resource. Today, Africa alone has about 5 GW of installed solar capacity, which is less than 1% of the world's total (IEA, 2019a). Wolfram et al (2012), suggest that from 2007 to 2035, energy consumption in OECD countries will grow 14%, while in non-OECD countries it will grow 84%. The reason for this is essentially the increase in income of the poor and near-poor population which gives access to energy demanding goods like vehicles and refrigerators, both in terms of manufacturing and usage[13]. This typically results in an S-shaped pattern in energy-usage as income increases among the very poor within a country. There is little increase among the people that already own refrigerators, vehicles and air-conditioners, but a large increase among the people that don’t (Wolfram, Shelef, & Gertler, 2012, p. 134). As for electricity consumption per capita, there is great variety between countries in terms of their energy mix and grade of economic development. For illustration, per capita consumption in 2016 was 21 711 kWh in Norway, while in Turkey it was 2 881 kWh. Looking at the growth rate, we find that Norway's per capita electricity consumption has decreased at an average annual rate of 0.9% between 2005 and 2016, while for Turkey it grew with an annual 6.3% rate. The growth of consumption in Turkey, is due to their rapid transition to a modernised economy. Similar cases are likely to occur also in other less developed countries.

Regarding energy outlooks for the next 50-100 years, several uncertainties make projections highly variable. Learning rates and costs of different technologies, population change, and impacts of climate change are only some of them. A study conducted by Schrattenholzer (1997), suggested that global primary energy use in 2100 would vary from 40 to 20 Gtoes[14], depending on the pace of technology development. In a future high consumption scenario, this

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[13] Also referred to as energy growth along the extensive margin.

[14] 40 Gtoes = 465 billion MWh

translates to an increase in energy supply of 186% as energy production was slightly above 14 Gtoes in 2017 (IEA, 2019a). In a medium consumption scenario (30 Gtoes in 2100), it would translate to a 114% increase from 2017. This corresponds with the results energy professor and geologist Dr. Euan Mearns (2018) found in his study on the subject. He discovered that a medium population forecast would demand 29.5 Gtoes in 2100, which translates to a 124% increase from 2015 levels. EIA does not have further projections than 2050 but projects a nearly 50% increase in global energy usage by then. To meet this consumption demand, energy supply needs to increase with 79%. The major consumption increase will happen in regions driven by strong economic growth, like Asia, which will need to increase energy supply accordingly, much like the case with Turkey. In our analysis, we will base our calculations on a 120% increase in global energy usage.

Dividing energy demand into sources, IEA projects that the fast-growing economies in Asia, such as China and India will account for over half of the global increase in electricity generation from renewables. There will be a three-way race among coal, natural gas and renewables to provide power and heat to these areas. Demand for natural gas has been growing fast in the industry and residential sector, but the price-sensitivity of these markets makes it hard to estimate natural gas' future competitiveness. In the Stated Policies Scenario, oil demand will flatten out in the 2030s, much due to the transport sector switching from fossil fuels to electricity. However, the speed at which battery costs decline is a critical factor for this power market, as well as solar PVs (IEA, 2019b). For Europe, cost reductions and learning rates are making the offshore wind sector potentially attract a trillion-dollar investment towards 2040. Technically, offshore wind could meet today's energy demand many times over and has a constrained potential to meet 78% of the projected energy demand in Europe in 2030 (EEA, 2009, p. 34).

Even though scientists and analysts are certain that the need for energy in the future will increase, it is hard to predict a specific shape of the future energy mix. The main drivers or decision makers of the future energy mix can be divided into three categories: the government and public sector, industry and technology and consumer behaviour. Governments have power in terms of banning, subsidizing, and indirect steering of the energy markets through programs like carbon emission trading. Changes in technology and industries influence prices of energy, which again affects governmental decisions and consumer behaviour. Choices made by the consumer also inflict the energy mix. Will people get used to taking half an hour instead of five minutes to fuel their car? Will future generations be willing to invest hard in solar panel roofs, which would affect the market and consequently the subsidizing of solar PVs? These three drivers are dynamic and therefore hard or impossible to predict, which complicates the vision of a clear future energy mix (Laclau & Brogan, 2018).

5.2 Future Energy Technologies

To predict energy needs and development of energy sources in the next 50 to 100 years, the fact that future technologies will make its presence is inevitable. It might also be a crucial factor in providing future generations a clean and sustainable energy mix, taking into account that today's important renewable technologies like wind and solar, had their economic and technological breakthrough only about 40 years ago.

Regarding nuclear power, there is a lot of research going on how to utilize the technology more efficiently. As known, one of the main issues with nuclear power production is waste management, and how to store it properly. To be able to solve this issue, researchers have been experimenting with the idea of using different fuels in the cycle, to reduce the amount of nuclear waste. Today, the common procedure in nuclear fission reactors is - oversimplified - by hitting the isotope Uranium-238 with neutrons, causing it to split and release kinetic energy which is transformed into heat. The split of Uranium-238, releases new neutrons reacting with new Uranium-238 elements in a chain reaction, but also fission fragments considered as waste. This waste is essentially radioactive isotopes like Strontium-90, and Cesium-137 which have half-lives of about 30 years (Narbel, Hansen, & Lien, 2014). Replacing Uranium-238 with an element that leads to a smaller amount of waste in the other end, would not only mean a solution to the waste problem, but also automatically increased efficiency and sustainability in the power production, as more of the "waste" now is used in increased chain-reaction[15].

One of the fuels heavily discussed is thorium, already mentioned being ambitiously on the agenda in the Indian government. Thorium is much more abundant than uranium on Earth, it is more efficient (Touran, 2009) and it creates less waste and weaponizable isotopes[16]. However, making thorium-based reactors cost-effective is as of now difficult due to for instance the need for highly enriched uranium-235 to start the reactors. The industry also relies on governmental financial support to fully develop technologically working solutions, which struggles due to the stigma of the public opinion (Surampalli, 2019).

Another exciting technology that probably lies further down the timeline compared to using different fuels in the cycle, is creating energy using nuclear fusion. Fusion means combining light elements into larger compounds which also release energy, which can be translated into the opposite of nuclear fission. This is what happens on the sun, when two hydrogen atoms fusion into helium. Theoretically, a fusion reactor could solve all mankind's energy supply problems, as the fuel - hydrogen - is an almost infinite resource (Narbel, Hansen, & Lien, 2014). The challenge is to create a facility with sun-like conditions. Currently, there is an experimental fusion reactor being built in France[17] designed to produce 10 times more energy than it needs to operate. Initial experiments are scheduled to begin in 2025 (ITER, 2020).

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[15] According to Einstein's mass-energy formula ($E = mc^2$), the reduced amount of mass has to be transformed into energy in a bound system (Narbel, Hansen, & Lien, 2014).

[16] A fuel cycle using thorium and uranium-233 combinations produce little or no plutonium which is used to make nuclear weapons.

[17] The International Thermonuclear Experimental Reactor (ITER).

5.3 Analysis

5.3.1 Cost of Energy

The levelized cost of energy has for long been the preferred way of calculating cost of energy production and is widely used by international agencies and companies. In-depth analysis of the cost of the different generating technologies has been done by a multitude of entities, such as IEA & NEA (2015), Narbel et al. (2014), and Lazard (2018). Even though the calculations are always based on the general LCOE formula, their assumptions vary greatly as well as their underlying data. Lazard bases their calculations on their own estimates in the USA with an 8% interest rate, while IEA & NEA uses a 5-10% interest rate with reported data from both OECD nations and China. The assumptions also differ in their capacity factors, with IEA & NEA using an 85% capacity factor for coal, gas and nuclear, while Lazard uses a capacity factor between 85-93%. While it is hard to conclude which of the different calculations that are more correct, we have chosen to base our analysis on the findings from IEA & NEA. This is mostly due to the fact that the researchers divide their calculations on different countries and is therefore better at highlighting the differences in the various regions.

The IEA & NEA (2015) report calculates cost on a country level, while our analysis is region based. The cost of the different generating technologies in the OECD region is based on a weighted average LCOE of the different countries[18]. Some of the power sources are based on various generating technologies with great differences in LCOE, therefore is a weighted average used on these occasions. The IEA & NEA report does not calculate the LCOE in Russia and India and therefore the report by Ram et al. (2018) form the basis of the LCOE-values for these regions. The energy sources solar thermal and hydro are not calculated in this report and detailed calculations for these two regions are scarce, therefore the global weighted average will be used, as dictated in the IRENA Renewable Power Generation Cost in 2018 report (IRENA, 2019).

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[18] The weighted average is based on the countries share of total capacity in the given energy source.

LCOE-value in the different regions for particular energy sources					
Energy Source	USA	China	OECD	India	Russia
Gas	54.86	81.77	116.25	73.75	78.1
Coal	68.59	48.74	64.60	38.58	52.95
Nuclear	77.71	47.61	80.89	71.48	72.8
Solar PV	95.49	72.64	145.74	62.41	175.93
Solar Thermal	104.21	-	190.00	185	185
Wind Onshore	54.47	64.1	92.80	64.67	62.64
Wind Offshore	137.37	-	178.98	206.51	140.28
Biomass	119.64	-	73.98	-	-
Hydro	110.82	22	91.19	50	50
Geothermal	84.87	-	55.34	-	-

Table 6: : LCOE-value of the different energy sources

In Table 6 a summary of the LCOE-values of the different regions are presented. It shows that the LCOE value varies greatly between each region. By calculating the weighted average cost of the energy sources based on the region's total energy capacity share, we get the LCOE-values as presented in Table 7. These LCOE-values do not take into account the price for CO2 emission. As discussed previously, this cost can be set to 30 USD/tCO2. Based on data from Volker Quaschning (2015) emission per produced MWh electricity from coal and gas is 0.34 tCO2/MWh and 0.20 tCO2/MWh respectively. By inserting the cost of CO2 into the LCOE calculation, we see that the cost for Gas and Coal increase quite significantly. These LCOE-values will form the foundation of our scenario analysis.

Weighted average LCOE in all regions		
Energy Source	LCOE	LCOE with price of CO2
Gas	74.75	87.35
Coal	57.48	63.48
Nuclear	66.45	66.45
Solar PV	94.34	94.34
Solar Thermal	137.48	137.48
Wind Onshore	63.86	63.86
Wind Offshore	155.16	155.16
Biomass	108.68	108.68
Hydro	67.97	67.97
Geothermal	77.78	77.78

Table 7: Weighted average LCOE

5.3.2 Energy Composition in the Different RCPs

RCP8.5 – Business as Usual

As previously mentioned, the representative concentration pathways represent different global emission pathways and how the energy supply sector should be shaped accordingly. The RCP8.5 is a high concentration pathway that is in line with the current energy mix and is therefore dubbed the "business as usual" scenario. In this scenario we assume that the share of the energy sources is as they are today, but that the need for energy increases as discussed above (120% total increase). Figure 10 showcases how the development of the energy mix towards the year 2100 based on today's mix. The baseload is the power generators already built and the remaining lifetime of these. Table 8 shows the composition of the different energy production sources, as well as emission CO2 emission.

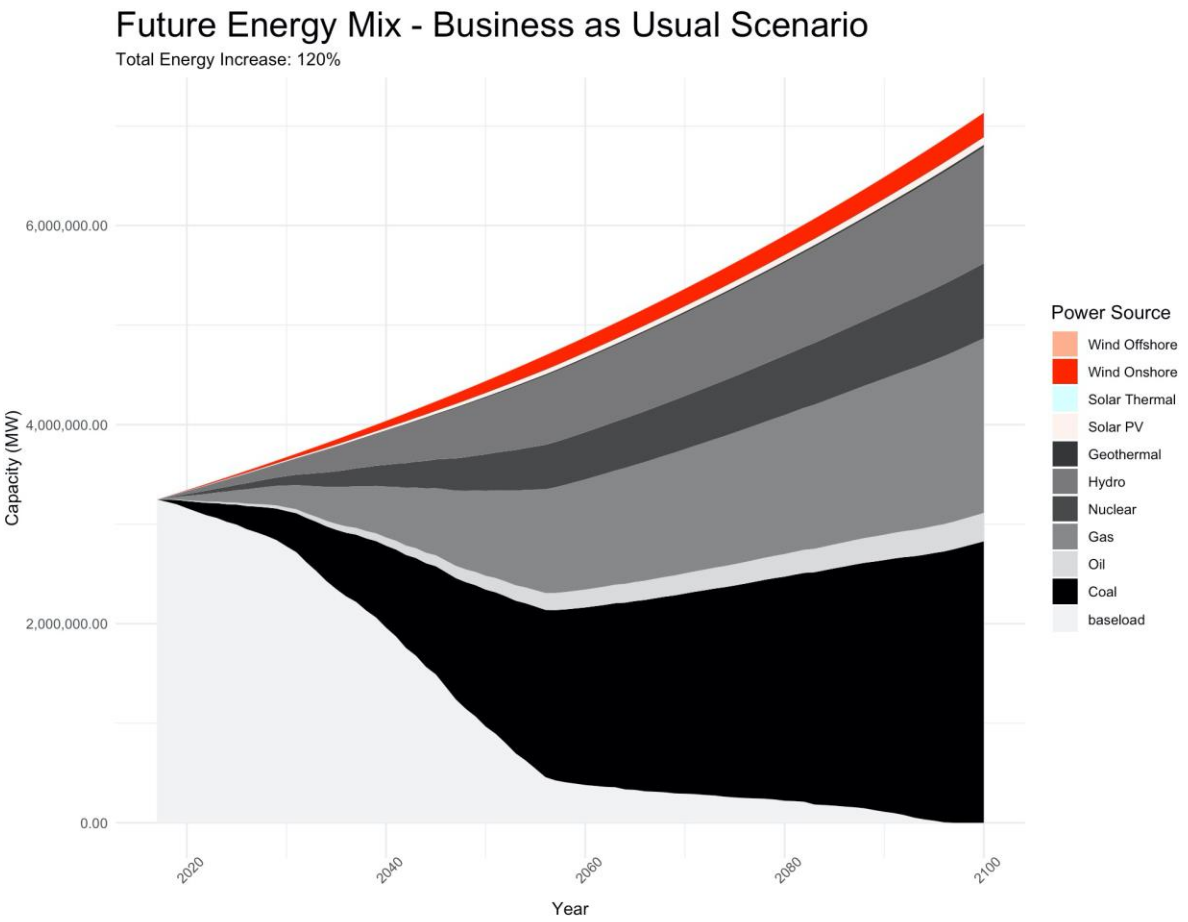

Figure 10: RCP8.5 - Business as usual scenario

RCP8.5 - Business as Usual					
Energy Source	LCOE	LCOE with price of CO2	Capacity (MW)	MtCO2	Share of total production
Wind Onshore	63.86	63.86	245,031	0.00	3.44%
Solar Thermal	137.48	137.48	2,143	0.00	0.03%
Solar PV	94.34	94.34	72,866	0.00	1.02%
Geothermal	77.78	77.78	23,574	0.00	0.33%
Hydro	67.97	67.97	1,168,006	0.00	16.38%
Nuclear	66.45	66.45	752,239	0.00	10.55%
Gas	74.75	87.35	1,754,510	2093.04	24.60%
Oil	74.75	87.35	285,036	273.85	4.00%
Coal	57.48	63.48	2,828,218	13669.94	39.66%

Table 8: RCP8.5 energy mix overview

In the business as usual scenario, the weighted average LCOE is 65.77 without CO2-costs, and 71.75 with CO2-costs (Table 13). Using medium population/consumption estimates conducted by Schrattenholzer (1997) and Mearns (2018), the energy needed in 2100 could reach 30 Gtoes, which translates to about 350 billion MWh. Based on the average LCOE-value in RCP8.5, the total energy production costs would in 2100 be 65.77 x 350 x 109 = 23.0195 trillion USD. Including CO2-costs, it would correspond to 25.1125 trillion USD. By also taking account of the welfare costs of air pollution, the adjusted total energy costs get much higher. Using the estimates quantified by CREA and OECD which predicted welfare costs to reach 18-25 trillion USD in 2060, we are looking at a total energy production cost of at least 43.1 trillion USD annually in 2100. Still, the costs of decommissioning or managing waste from 752 GW of nuclear instalments is not being accounted for. Using a cost of 2.5 USD/MWh derived from Cotton (2017), and a nuclear share of 10.55%, this translates to 10.55% x 350 billion MWh x 2.5 USD/MWh = 92.3125 billion USD. From this, it is clear that the decommissioning and waste management costs correspond to about 0.2% of the total, when taking account of welfare costs. This leaves us with a total of 43.2 trillion USD minimum in 2100 for the business as usual (RCP8.5) scenario. It should be noted that this is a conservative measure, weighing welfare costs of air pollution at an absolute minimum (OECD, 2016). As air pollutants also stem from sources such as agriculture development, we believe using the lower cost-estimate for a fossil-intensive energy mix, and higher for less fossil-intensive energy mix removes risk of bias in the comparison.

RCP4.5 – Renewable Scenario

In the RCP4.5 scenario (Figure 11), the situation becomes quite different. The weighed LCOE-values is higher than the RCP8.5 scenario both with or without CO2-emissions included, with 88.58 and 89.66 USD/MWh (Table 13). This means a total cost of energy production in 2100 of 31.38 trillion USD including CO2 costs. Compared to the initial costs of the RCP8.5 scenario including CO2 costs, this results in an almost 25% increase in energy expenditure for the RCP4.5 scenario. However, this pathway would lead to a significant reduction in fossil fuel related air pollutants, as the share of fossil fuels have been reduced from 68.26% to 14.4%. In CO2 emissions, this is a reduction from 16 036 to 3 474 Mt (Table 9) or a 78.34% decrease. Assuming that air pollution levels follow the same pattern, the welfare costs will range from 3.9 to 5.4 trillion in 2100. This adds up to 36.8 trillion USD, using 5.4 trillion as base. Regarding costs of decommissioning and waste management of nuclear facilities, it is calculated to approximately 146.125 billion USD in 2100. In total, the energy production costs of the RCP4.5 scenario translates to about 37.95 trillion USD.

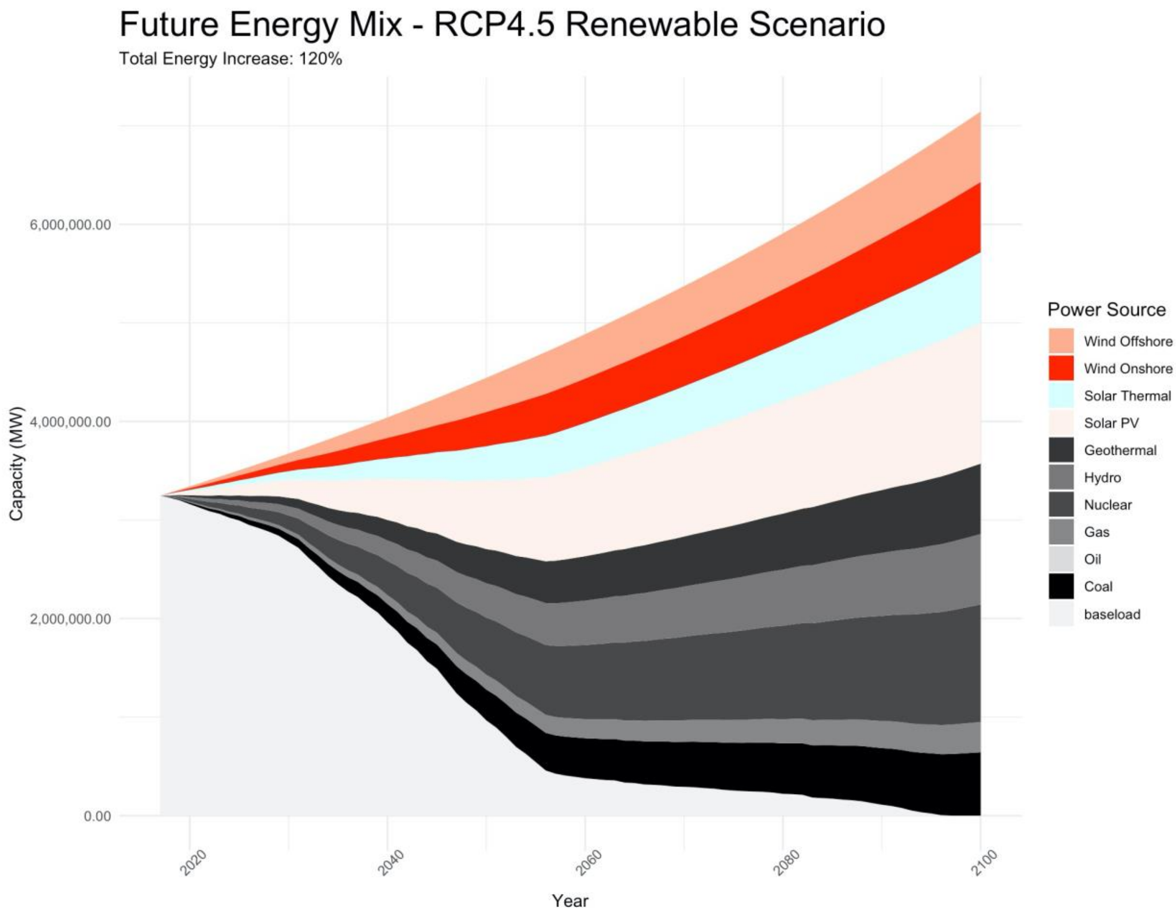

Figure 11: RCP4.5 - Renewable scenario

RCP4.5 - Renewable scenario					
Energy Source	LCOE	LCOE with price of CO2	Capacity (MW)	MtCO2	Share of total production
Wind Offshore	155.16	155.16	714,377	0.00	10.00%
Wind Onshore	63.86	63.86	714,377	0.00	10.00%
Solar Thermal	137.48	137.48	714,377	0.00	10.00%
Solar PV	94.34	94.34	1,428,754	0.00	20.00%
Geothermal	77.78	77.78	714,377	0.00	10.00%
Hydro	67.97	67.97	714,377	0.00	10.00%
Nuclear	66.45	66.45	1,193,009	0.00	16.70%
Gas	74.75	87.35	307,182	366.45	4.30%
Coal	57.48	63.48	642,939	3107.59	9.00%

Table 9: RCP4.5 renewable scenario - Energy mix overview

RCP4.5 – Nuclear Scenario

The scenario with a relatively larger share of nuclear power (40%) does have a lower weighted average LCOE-cost with or without CO2 included, compared to the renewable-intensive pathway (Table 13). Inherently, the total energy cost is calculated to be 27.77 trillion USD in 2100 including CO2-costs. The fact that only the share of nuclear is higher in spite of other renewables, means that the level of air pollutants remains the same as in the previous scenario. This leads to a total cost of 33.17 trillion USD with a total welfare cost of 5.4 trillion USD. Also taking account of decommissioning and waste management costs, which is relatively larger in this scenario, the total costs of the high-nuclear RCP 4.5 scenario in 2100 is 33.52 trillion USD.

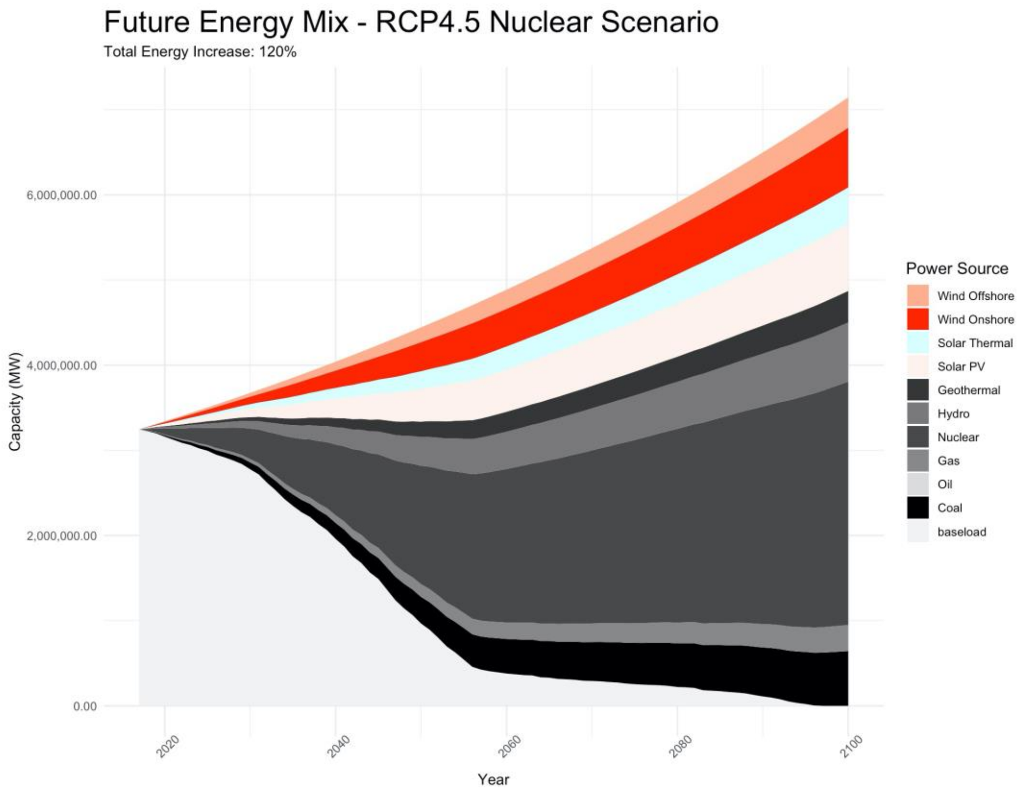

Figure 12: RCP4.5 Nuclear scenario

RCP4.5 - Nuclear scenario					
Energy Source	LCOE	LCOE with price of CO2	Capacity (MW)	MtCO2	Share of total production
Wind Offshore	155.16	155.16	357,188	0.00	5.00%
Wind Onshore	**63.86**	**63.86**	**700,089**	**0.00**	**9.80%**
Solar Thermal	137.48	137.48	428,626	0.00	6.00%
Solar PV	**94.34**	**94.34**	**785,815**	**0.00**	**11.00%**
Geothermal	77.78	77.78	371,476	0.00	5.20%
Hydro	**67.97**	**67.97**	**692,946**	**0.00**	**9.70%**
Nuclear	66.45	66.45	2,857,507	0.00	40.00%
Gas	**74.75**	**87.35**	**307,182**	**366.45**	**4.30%**
Coal	57.48	63.48	642,939	3107.59	9.00%

Table 10: RCP4.5 nuclear scenario - Energy mix overview

RCP2.6 – Renewable Scenario

In the RCP2.6 scenario consisting of 90% renewables, the weighted average LCOE costs are respectively 91.44 and 92.70 USD/MWh (Table 13) with and without CO2 costs. This is due to relatively more expensive sources such as solar PVs and offshore wind replacing coal. Initial total costs of energy production are equal to approximately 32.245 trillion USD, including CO2 costs. CO2 emissions are down from 16 036 to 852.22 Mt, equivalent to a 94.69% reduction in air pollutants. This means additional welfare costs of between 0.95 and 1.33 trillion USD. Nuclear decommissioning and waste treatment costs are estimated at 138.25 billion USD. In total, a RCP2.6 renewable scenario in 2100 would ultimately have annual energy costs of 33.713 trillion USD.

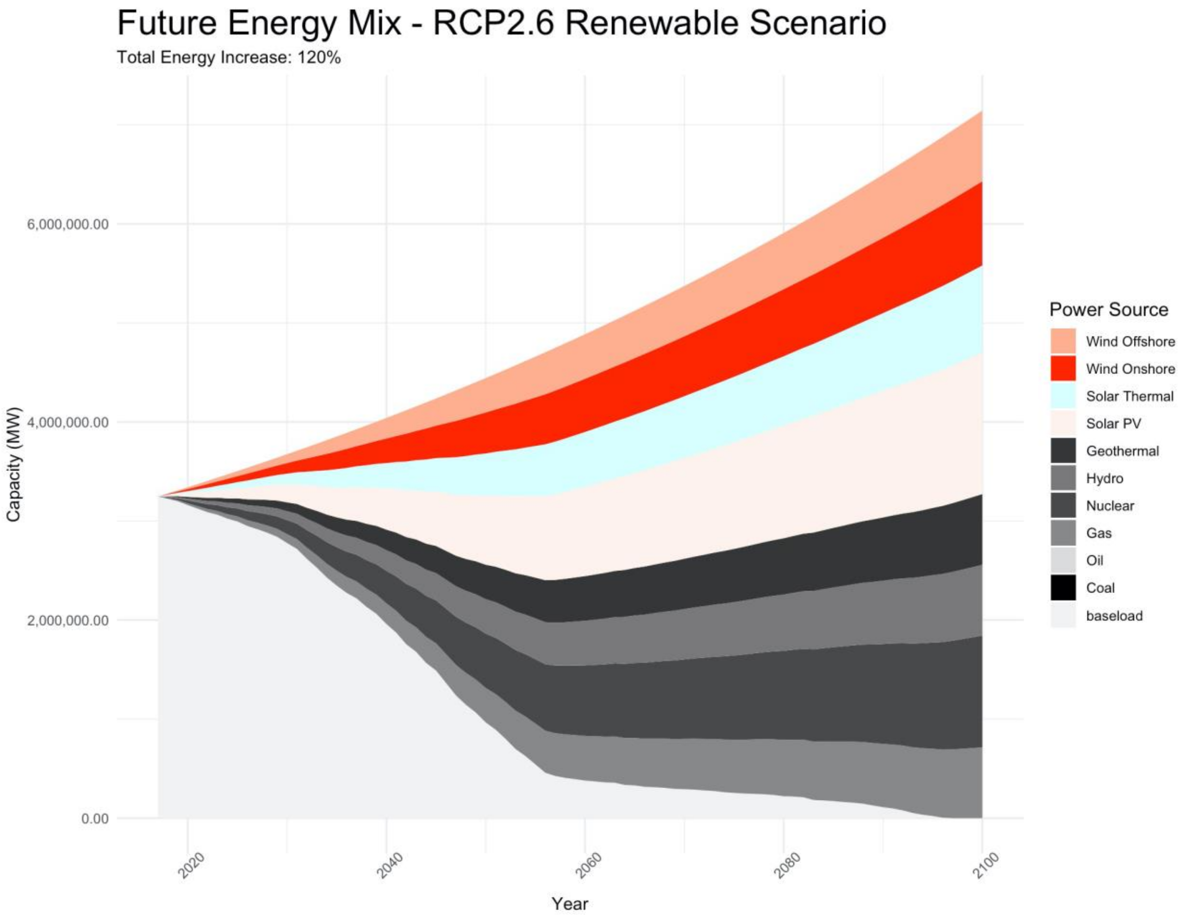

Figure 13: RCP2.6 - Renewable scenario

RCP2.6 - Renewable scenario					
Energy Source	LCOE	LCOE with price of CO2	Capacity (MW)	MtCO2	Share of total production
Wind Offshore	155.16	155.16	714,377	0.00	10.00%
Wind Onshore	63.86	63.86	850,108	0.00	11.90%
Solar Thermal	137.48	137.48	878,684	0.00	12.30%
Solar PV	94.34	94.34	1,428,754	0.00	20.00%
Geothermal	77.78	77.78	714,377	0.00	10.00%
Hydro	67.97	67.97	714,377	0.00	10.00%
Nuclear	66.45	66.45	1,128,715	0.00	15.80%
Gas	74.75	87.35	714,377	852.22	10.00%

Table 11: RCP2.6 renewable scenario - Energy mix overview

RCP2.6 – Nuclear Scenario

The RCP2.6 nuclear scenario suggests a 43.3% share of nuclear in the energy mix, making it the largest share of all the scenarios. The weighted LCOE with CO2 costs is 80.79 USD/MWh, making the initial costs of energy 28.277 trillion USD. The costs of air pollution will be the same as for the renewables RCP2.6 scenario, a maximum of 1.33 trillion USD. Decommissioning and waste treatment costs of nuclear facilities will in this case be 378.9 billion USD, the largest share of all scenarios. Adding these together, the energy costs of the RCP2.6 nuclear scenario will be an annual 29.99 trillion USD in 2100, totalling as the lowest of all the compared scenarios.

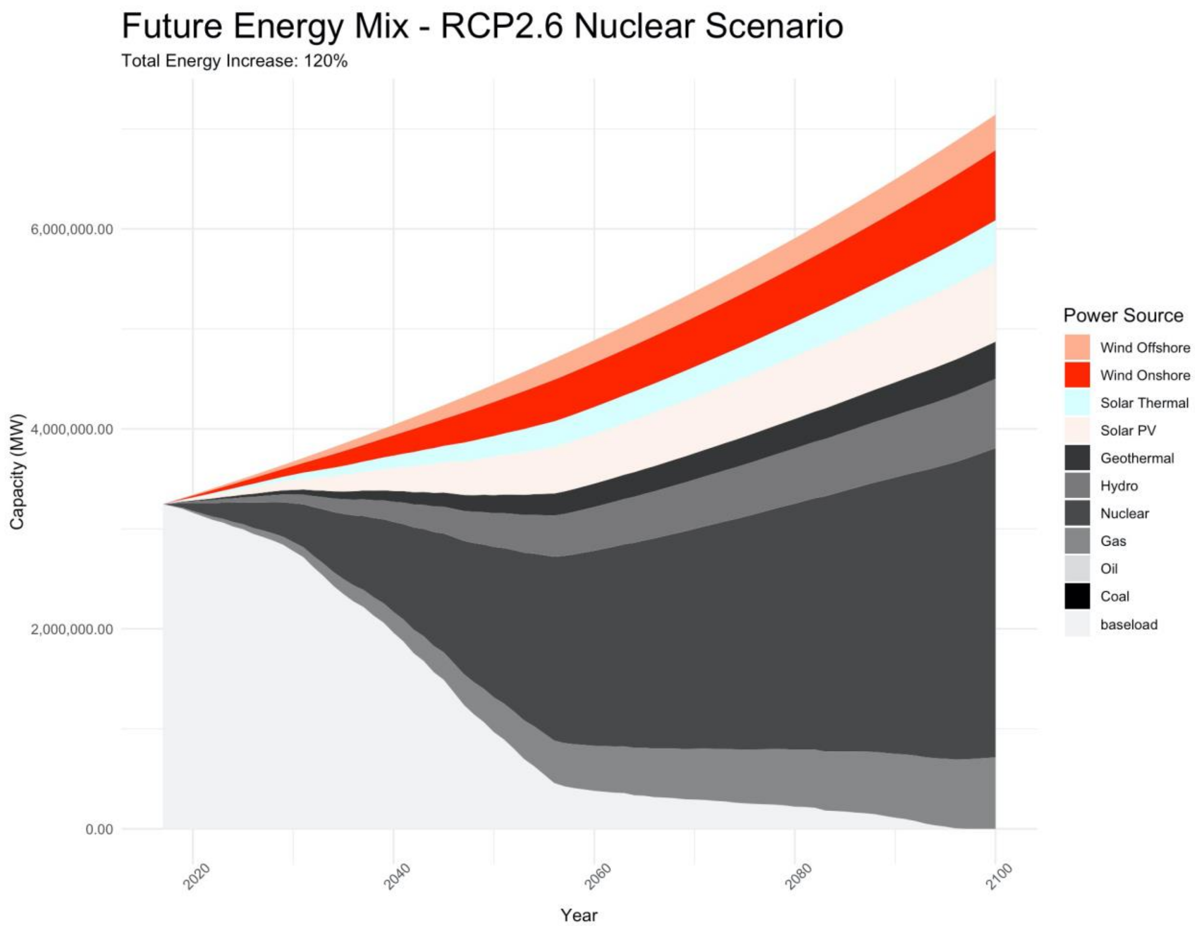

Figure 14: RCP2.6 - Nuclear scenario

RCP2.6 - Nuclear scenario					
Energy Source	LCOE	LCOE with price of CO2	Capacity (MW)	MtCO2	Share of total production
Wind Offshore	155.16	155.16	357,188	0.00	5.00%
Wind Onshore	63.86	63.86	700,089	0.00	9.80%
Solar Thermal	137.48	137.48	428,626	0.00	6.00%
Solar PV	94.34	94.34	785,815	0.00	11.00%
Geothermal	77.78	77.78	371,476	0.00	5.20%
Hydro	67.97	67.97	692,946	0.00	9.70%
Nuclear	66.45	66.45	3,093,252	0.00	43.30%
Gas	74.75	87.35	714,377	852.22	10.00%

Table 12: RCP2.6 nuclear scenario - Energy mix overview

LCOE Value and Total cost of Energy				
Pathways	LCOE	LCOE with Price on CO2	Total cost of Energy with price on CO2	Total cost of Energy with Price on CO2 and Emission
RCP8.5	65.77	71.75	25.1125 Trillion USD	43.2 Trillion USD
RCP4.5 - Renewable	88.58	89.66	31.38 Trillion USD	37.95 Trillion USD
RCP4.5 - Nuclear	78.25	79.33	27.77 Trillion USD	33.52 Trillion USD
RCP2.6 - Renewable	91.44	92.70	32.234 Trillion USD	33.713 Trillion USD
RCP2.6 - Nuclear	79.53	80.79	28.227 Trillion USD	29.99 Trillion USD

Table 13: Total price of energy and LCOE value of each RCP scenario

6. Discussion and Conclusion

6.1 Discussion

A discovery that is quite noticeable and crucial for the results of the analysis, is the weight that air pollution puts on the different scenarios in terms of costs. It is very clear that a limitation of this types of externalities will be essential in a minimization of the global energy related costs of 2100. We have also chosen a CO_2- cost of 30 USD/tCO_2 in this analysis, which definitely is in the lower end according to researchers such as Ricke et al (2018), which suggests a price tenfold higher. Using a higher estimate for CO_2 would have made the results a whole lot clearer in favour of the less carbon-intensive pathways, already coming out as relatively inexpensive due to lower levels of air pollution. The business-as-usual, RCP8.5 pathway, comes out at the costliest by far, with more than 30% associated costs compared to the nuclear intensive RCP2.6 pathway (Table 13). As the RCP8.5 also involve increased total costs compared to the other pathways suggesting relatively more renewables, the overall indication is that there lays an advantage in renewable investments. This is because the increased LCOE of renewable-concentrated pathways gets compensated by relatively lower welfare costs. Since renewable technologies compared to fossil-fuels in general is less mature, there is also reason to believe that the LCOE for renewables will decrease significantly towards 2100 as new technologies emerge. Evidently, in a global cost-minimizing perspective, much points to that governments should invest in renewable technologies and nuclear. This is however challenging due to the fact that the "polluter pays principle" still yields to the "tragedy of the commons" in the current global community. As long as the social costs from CO_2-emissions and other externalities is not accounted for in the global market, essential market-mechanisms will not adjust the production mix accordingly. Consequently, the cheapest forms of energy production still reign in each regional market, even though the total global costs suggest otherwise. A well-functioning and global cap-and-trade system[19] could potentially solve these problems, which as of now face challenges with quota-pricing and missing mechanisms to ensure individual commitment.

[19] Such as the EU ETS (The European Union Emission Trading Scheme) and the Kyoto Protocol.

6.2 Conclusion

After comparing the different RCPs, it is clear that taking account of other direct-and indirect social costs of energy production distorts the picture of a traditionally preferred energy mix, containing significant amounts of fossil-fuels. Studies conducted by CREA and OECD predict that welfare costs of air pollution could get as high as 18-25 trillion USD in 2060, alone surpassing the actual costs of energy production in fossil-fuel heavy scenarios. A cost-optimization of the future global energy mix consequently suggests a great reduction of fossil-fuels to minimize indirect costs of energy production. To ensure energy-security, a sufficient baseload energy source is necessary, as renewables are affected by intermittency. In this case, a high share of nuclear energy production turns out to be the cheapest alternative. Our analysis suggests that the most cost-efficient energy production scheme is following a high-nuclear RCP2.6 pattern. The total costs of this scenario in the year 2100 is estimated to be just under 30 trillion USD. There should be mentioned that there are certain risks with relying on a high share of nuclear energy, potentially leading to high economic consequences. 33 years on, Ukraine last year spent 5-7% of their national budget on recovery activities related to the Chernobyl disaster in 1986. The overall economic loss for Belarus alone is estimated at almost 300 billion USD adjusted for inflation (UN News, 2019). Despite this, studies on mortality per produced TWh shows that nuclear comes out as some of the best (Kharecha & Hansen, 2013). Changes in land use and interference with biodiversity is also something that needs to be thoroughly considered when building new energy production infrastructure. This is regardless of the energy source cleanliness, and long-term consequences must be evaluated carefully even though they inherently appear non-monetary.

What ultimately turns out to be the global energy outlook is a result of decision-making in independent states and regions, which all have different takes on what the optimal energy mix should look like. The current state indicates that the minimisation of future global energy production costs depends on whether the ambitious plans for ramping up renewable and nuclear energy gets carried out in fast growing economies like China and India.

6.3 Limitations

This scenario analysis is trying to calculate the future cost of energy production in 2100 based on the different pathways presented by the IPCC. As with all predictions, one of the biggest limitations is the difficulty to predict future development in technology and prices. Our analysis is based upon price levels and technologies that are available as of today, but history has shown that technology advances are rapid in the energy supply sector and that new energy sources greatly affect this sector. This development is clearly visible with the advances achieved in solar and wind power production, as well as the emergence of carbon capture and storage[20]. To further strengthen this research, we recommend trying to implement the learning curves of the different energy sources to get a better prediction of future prices, as well as a more in depth look at the effect new technologies have on the final price of electricity.

Another weakness with this analysis is that it does not take into account where the increase in energy production takes place, i.e. how the particular regions have limitations when it comes to the possibilities for increasing the amount of energy produced. Where the increase of the different energy sources is placed, will have a considerable impact on the final energy price since some regions have higher capacity factors in their respected energy sources than others. While we try to limit this issue by using weighted averages on both the individual LCOE-value of the various energy sources and the final LCOE-value, a closer in depth look at the different regions would be beneficial in further research.

[20] CCS has in large reduced the negative externalities of fossil fuel in the energy supply sector.

References

Banktrack. (2013). *Russia Putin's New Coal Age*. Retrieved from https://www.banktrack.org/download/russia_hotspot_pdf/russia_hotspot.pdf

BCSE. (2020, February 13). *Energy Efficiency, Natural Gas and Renewable Energy Drove Decade of U.S. Energy Transformation* . Retrieved from https://www.bcse.org/bcse-and-bloombergnef-release-2020-sustainable-energy-in-america-factbook/

BP. (2019). *BP Statistical Review – 2019: Russia's energy market in 2018*. Retrieved from https://www.bp.com/content/dam/bp/business-sites/en/global/corporate/pdfs/energy-economics/statistical-review/bp-stats-review-2019-russia-insights.pdf

BP. (2019). *BP Statistical Review – 2019: The US energy market in 2018*. Retrieved from https://www.bp.com/content/dam/bp/business-sites/en/global/corporate/pdfs/energy-economics/statistical-review/bp-stats-review-2019-us-insights.pdf

CEA. (2020, January 31). *All India Installed Capacity (in MW) of Power Stations*. Retrieved from http://www.cea.nic.in/reports/monthly/installedcapacity/2020/installed_capacity-01.pdf

ChinaPower. (2020). *How is China's energy footprint changing?* Retrieved from https://chinapower.csis.org/energy-footprint/

Cotton, M. (2017). *Nuclear Waste Politics - An Incrementalist Perspective* . London: Routledge.

DNV GL AS. (2019). *Energy Transition Outlook 2019 - A global and regional forecast to 2050.* Høvik: DNV GL AS.

Dong, K., Li, H., Sun, R., & Jiang, H. (2017, February). *A review of China's energy consumption structure and outlook based on a long-range energy alternatives modeling tool*. Retrieved from https://www.researchgate.net/publication/311711700

EEA. (2009). *Europe's onshore and offshore wind energy potential.* Luxembourg: EEA.

EIA. (2017, March 7). *Country Analysis Brief: Australia*. Retrieved from https://www.eia.gov/international/content/analysis/countries_long/Australia/australia.pdf

EIA. (2017, April 27). *Most U.S. nuclear power plants were built between 1970 and 1990*. Retrieved from https://www.eia.gov/todayinenergy/detail.php?id=30972

EIA. (2017). *Russia - 2017 primary energy data in quadrillion Btu*. Retrieved from https://www.eia.gov/international/overview/country/RUS

EIA. (2019, January 24). *EIA's Annual Energy Outlook 2019 projects growing oil, natural gas, renewables production*. Retrieved from https://www.eia.gov/todayinenergy/detail.php?id=38112

EIA. (2019, October 18). *Electric Power Annual*. Retrieved from https://www.eia.gov/electricity/annual/

EIA. (2019, February 6). *Future U.S. electricity generation mix will depend largely on natural gas prices*. Retrieved from https://www.eia.gov/todayinenergy/detail.php?id=38252

EIA. (2020, April 15). *Nuclear explained - U.S. nuclear industry* . Retrieved from https://www.eia.gov/energyexplained/nuclear/us-nuclear-industry.php

EIA. (2020, May 26). *Table 6.07.B. Capacity Factors for Utility Scale Generators Primarily Using Non-Fossil Fuels*. Retrieved from https://www.eia.gov/electricity/monthly/epm_table_grapher.php?t=epmt_6_07_b

EIA. (2020). *Wind has surpassed hydro as most-used renewable electricity generation source in the U.S.* Retrieved from https://www.eia.gov/todayinenergy/detail.php?id=42955

Enerdata. (2019). *Coal and lignite production*. Retrieved from https://yearbook.enerdata.net/coal-lignite/coal-production-data.html

EPA. (2016, December). *Social Cost of Carbon*. Retrieved from https://www.epa.gov/sites/production/files/2016-12/documents/social_cost_of_carbon_fact_sheet.pdf

European Commission. (n.d.). *EU Emissions Trading System (EU ETS)*. Retrieved from https://ec.europa.eu/clima/policies/ets_en

Eurostat. (2019). *Where does our energy come from?* Retrieved from https://ec.europa.eu/eurostat/cache/infographs/energy/bloc-2a.html

Evan, M. W., & Manion, M. (2002). In *Minding the Machines: Preventing Technological Disasters* (p. 180). Prentice Hall: PTR.

Farrow, A., Miller, K. A., & Myllyvirta, L. (2020, February). *Toxic air: The price of fossil fuels*. Retrieved from https://storage.googleapis.com/planet4-southeastasia-stateless/2020/02/21b480fa-toxic-air-report-110220.pdf

Forsythe, M. (2017, January 5). *China Aims to Spend at Least $360 Billion on Renewable Energy by 2020*. Retrieved from https://www.nytimes.com/2017/01/05/world/asia/china-renewable-energy-investment.html

GAO. (2009). *Nuclear Waste - Uncertainties and Questions about Costs and Risks Persist with DOE's Tank Waste Cleanup Strategy at Hanford*. Washington: GAO.

Gasparatos, A., Doll, C., Esteban, M., Ahmed, A., & Olang, T. (2017, April). Renewable energy and biodiversity: Implications for transitioning to a Green Economy. *Renewable and Sustainable Energy Reviews*(70), pp. 161-184.

Gielen, D., & Saygin, D. (2017). *Remap 2030 - Renewable Energy Prospects for the Russian Federation.* Abu Dhabi: IRENA.

Global Energy Monitor. (2020). *Global Coal Plant Tracker*. Retrieved from https://globalenergymonitor.org/coal/global-coal-plant-tracker/

Government of Canada. (n.d.). *Electricity facts*. Retrieved from https://www.nrcan.gc.ca/science-data/data-analysis/energy-data-analysis/electricity-facts/20068#L6

IAEA. (2016). *Country Nuclear Profiles - India*. Retrieved from https://cnpp.iaea.org/countryprofiles/India/India.htm

IAEA. (2018a). *Country Nuclear Power Profiles: China*. Retrieved from https://cnpp.iaea.org/countryprofiles/China/China.htm

IAEA. (2018b). *Energy, Electricity and Nuclear Power Estimates for the Period up to 2050.* Vienna: International Atomic Energy Agency. Retrieved from https://www-pub.iaea.org/MTCD/Publications/PDF/RDS-1-38_web.pdf

IAEA. (2019a). *Country Nuclear Power Profiles: United States of America*. Retrieved from https://cnpp.iaea.org/countryprofiles/UnitedStatesofAmerica/UnitedStatesofAmerica.htm

IAEA. (2019b). *Country Nuclear Power Profiles: Russia*. Retrieved from Country Nuclear Power Profiles: https://cnpp.iaea.org/countryprofiles/Russia/Russia.htm

IEA & NEA. (2015, September 30). *Projected Cost of Generating Electricity*. Retrieved from https://www.oecd-nea.org/ndd/pubs/2015/7057-proj-costs-electricity-2015.pdf

IEA. (2017, November). *World Energy Outlook 2017: China*. Retrieved from https://www.iea.org/reports/world-energy-outlook-2017-china

IEA. (2018a). *Country Profile: Japan*. Retrieved from https://www.iea.org/countries/japan

IEA. (2018b). *Country profile: Korea*. Retrieved from https://www.iea.org/countries/korea

IEA. (2019a, September). *World Energy Balances 2019 - Complete energy balances for over 150 countries and regions*. Retrieved from https://www.iea.org/reports/world-energy-balances-2019

IEA. (2019b). *World Energy Outlook 2019 Executive Summary.* France: International Energy Agency.

IEA. (2020, January 10). *India 2020 - Energy Policy Review*. Retrieved from https://www.oecd-ilibrary.org/energy/india-2020_9faa9816-en

IHA. (2017, May). *Russia*. Retrieved from https://www.hydropower.org/country-profiles/russia

IPCC. (2015). *Climate Change 2014 Synthesis Report.* Geneva: IPCC.

IPCC. (2019). *Global Warming of 1.5C*. Retrieved from https://www.ipcc.ch/site/assets/uploads/sites/2/2019/06/SR15_Full_Report_High_Res.pdf

IRENA. (2019). *Renewable Power Generation Costs in 2018*. Retrieved from https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2019/May/IRENA_Renewable-Power-Generations-Costs-in-2018.pdf

ITER. (2020). *What is ITER?* Retrieved from https://www.iter.org/proj/inafewlines

Joshi, A. (2019, December 31). *India has installed 84 GW of renewable energy capacity so far: MNRE*. Retrieved from https://energy.economictimes.indiatimes.com/news/renewable/india-has-installed-84-gw-of-renewable-energy-capacity-so-far-mnre/73042867

Kharecha, P. A., & Hansen, J. E. (2013, March 13). Prevented Mortality and Greenhouse Gas Emissions from Historical and Projected Nuclear Power. *Environmental Science & Technology*, pp. 4889-4895.

Kharecha, P. A., & Hansen, J. E. (2013). Prevented Mortality and Greenhouse Gas Emissions from Historical and Projected Nuclear Power. *Environmental Science & Technology, 47*(9), pp. 4889–4895.

Laclau, B., & Brogan, A. (2018, December 12). *What's the recipe for tomorrow's energy mix?* Retrieved from https://www.ey.com/en_gl/energy-reimagined/what-is-the-recipe-for-tomorrows-energy-mix

Lazard. (2018, November). *Lazard's Levelized Cost of Energy Analysis - Version 12.0*. Retrieved from https://www.lazard.com/media/450784/lazards-levelized-cost-of-energy-version-120-vfinal.pdf

Louw, A., Boyle, R., Strahan, D., Collins, B., Kimmel, M., Giannakopoulou, E., & Becker, L. (2018). *Global Trends in Renewable Energy Investment 2018.* Frankfurt: Frankfurt School-UNEP Centre/BNEF.

Market Insider. (n.d.). *CO2 European Emission Allowances*. Retrieved from https://markets.businessinsider.com/commodities/co2-european-emission-allowances

Martinelli, L., & Filoso, S. (2008). Expansion of sugarcane ethanol production in Brazil: environmental and social challenges. *Ecol Appl*(18), pp. 885-898.

McCrary, M., Schreiber, R., McKernan, R., Wagner, W., & Sciarotta, T. (1986). Avian Mortality at a Solar Energy Power Plant. *Journal of Field Ornithology*, pp. 135-141.

Mearns, E. (2018, February 15). *Global Energy Forecast to 2100*. Retrieved from http://euanmearns.com/global-energy-forecast-to-2100/

Mitrova, T., & Melnikov, Y. (2019, August 28). Energy transition in Russia. *Energy Transit*(3), pp. 73-80.

Morrison, W. (2019). *China's Economic Rise: History, Trends, Challenges, and Implications for the United States*. Retrieved from https://fas.org/sgp/crs/row/RL33534.pdf

Narbel, P. A., Hansen, J. P., & Lien, J. R. (2014). *Energy Technologies and Economics.* Switzerland: Springer International Publishing.

Nebehay, S. (2013, February 28). *Higher cancer risk after Fukushima nuclear disaster: WHO*. Retrieved from https://www.reuters.com/article/us-japan-nuclear-cancer/higher-cancer-risk-after-fukushima-nuclear-disaster-who-idUSBRE91R0D420130228

NITI. (2015). *Report of the Expert Group on 175 GW RE by 2022.* New Delhi: Government of India.

OECD. (2016, June). *The economic consequences of outdoor air pollution*. Retrieved from https://www.oecd.org/environment/indicators-modelling-outlooks/Policy-Highlights-Economic-consequences-of-outdoor-air-pollution-web.pdf

OECD. (2016). *The economic consequences of outdoor air pollution.* Paris: OECD. Retrieved from https://www.oecd.org/environment/indicators-modelling-outlooks/Policy-Highlights-Economic-consequences-of-outdoor-air-pollution-web.pdf

Palmeirim, A., Peres, C., & F.C.W., R. (2014, June). Giant otter population responses to habitat expansion and degradation induced by a mega hydroelectric dam. Biol Conserv. *Biological Conservation*(174), pp. 30-38.

Pedroli, B., Elbersen, B., Frederiksen, P., Grandin, U., Heikkilä, R., & Krogh, P. (2013). Is energy cropping in Europe compatible with biodiversity? - Opportunities and threats to biodiversity from land-based production of biomass for bioenergy purposes. *Biomass Bioenergy*(55), pp. 73-86.

Planete Energies. (2018, August 28). *China's Overall Energy Balance* . Retrieved from https://www.planete-energies.com/en/medias/close/china-s-overall-energy-balance

Ram, M., Child, M., Aghahosseini, A., Bogdanov, D., & Lohrmann, A. (2018). A comparative analysis of electricity generation costs from renewable, fossil fuel and nuclear sources in G20 countries for the period 2015-2030. *Journal of Cleaner Production*(199), pp. 687-704.

Rensen, S. V. (2018, May). The inconvenient truth of failed climate policies. *Nature Climate Change*(8), pp. 355-358.

Rhodes, J. (2020, February 12). *Is The US Coal Industry Completely Burned Out?* . Retrieved from https://www.forbes.com/sites/joshuarhodes/2020/02/12/is-the-us-coal-industry-almost-completely-burned-out/

Ricke, K., Drouet, L., Caldeira, K., & Tavoni, M. (2018). Country-level social cost of carbon. *Nature Climate Change*, pp. 895-900. Retrieved from https://doi.org/10.1038/s41558-018-0282-y

Roser, M., Ritchie, H., & Ortiz-Ospina, E. (2019, May). *World Population Growth*. Retrieved from Roser, Ritchie & Ortiz-Ospina, 2019

Schrattenholzer, L. (1997). Energy Demand and Supply, 1900-2100. *International Institute for Applied Systems Analysis*, *I*(3), pp. 39-57.

Shelanski, H. (2013, November 1). *Refining Estimates of the Social Cost of Carbon*. Retrieved from https://obamawhitehouse.archives.gov/blog/2013/11/01/refining-estimates-social-cost-carbon

Siddayao, C. M. (1985). *Criteria for Energy Pricing Policy*. London, UK: Graham & Trotman.

Sovacool, B. K. (2009, June). Contextualizing avian mortality: A preliminary appraisal of bird and bat fatalities from wind, fossil-fuel, and nuclear electricity. *Energy Policy, 6*(37), pp. 2241-2248 .

Srivastava, S. (2011, October 28). *India's Rising Nuclear Safety Concerns*. Retrieved from https://www.asiasentinel.com/p/indias-rising-nuclear-safety-concerns

Standaert, M. (2019, September 26). *Why China's Renewable Energy Transition Is Losing Momentum*. Retrieved from https://e360.yale.edu/features/why-chinas-renewable-energy-transition-is-losing-momentum

Surampalli, S. (2019, August 13). *Is Thorium the Fuel of the Future to Revitalize Nuclear?* Retrieved from https://www.power-eng.com/2019/08/13/is-thorium-the-fuel-of-the-future-to-revitalize-nuclear/#gref

Touran, N. (2009, March). *Recycling Nuclear Waste and Breeder Reactors*. Retrieved from https://whatisnuclear.com/recycling.html

U.S Fish & Wildlife Service. (2018, September 14). *Threats to Birds: Migratory Bird Mortality - Questions and Answers*. Retrieved from https://www.fws.gov/birds/bird-enthusiasts/threats-to-birds.php

U.S.NRC. (2019, August 14). *Post-Fukushima Safety Enhancements*. Retrieved from https://www.nrc.gov/reactors/operating/ops-experience/post-fukushima-safety-enhancements.html

UN News. (2019, April 26). *Chernobyl nuclear disaster-affected areas spring to life, 33 years on*. Retrieved from https://news.un.org/en/story/2019/04/1037451

Volker Quaschning. (2015, June). *Statistics Specific: Carbon Dioxide Emissions of Various Fuels*. Retrieved from https://www.volker-quaschning.de/datserv/CO2-spez/index_e.php

Wilhelmsson, D., Malm, T., Thompson, R., Tchou, J., Sarantakos, G., McCormick, N., . . . Dubi, A. (2010). *Greening Blue Energy: Identifying and managing the biodiversity risks and opportunities of offshore renewable energy*. Gland, Switzerland: IUCN.

WNWR. (2019). *The World Nuclear Waste Report 2019 - Focus Europe.* Retrieved from https://worldnuclearwastereport.org

Wolfram, C., Shelef, O., & Gertler, P. (2012). How Will Energy Demand Develop in the Developing World? *Journal of Economic Perspectives, I*(26), pp. 119-138. Retrieved from https://pubs.aeaweb.org/doi/pdfplus/10.1257/jep.26.1.119

Workman, D. (2020, April 27). *Coal Exports by Country*. Retrieved from http://www.worldstopexports.com/coal-exports-country/

World Bank. (2017). *Atlas of Sustainable Development Goals 2017 : From World Development Indicators*. Retrieved from https://openknowledge.worldbank.org/handle/10986/26306

World Nuclear Association. (2020, May). *Nuclear Power in Russia*. Retrieved from https://www.world-nuclear.org/information-library/country-profiles/countries-o-s/russia-nuclear-power.aspx

World Resource Institute. (2019, June). *Global Power Plant Database*. Retrieved from https://datasets.wri.org/dataset/globalpowerplantdatabase

Worldometers. (2016). *Russia Coal*. Retrieved from https://www.worldometers.info/coal/russia-coal/

Zubarevich, N., Florinskaya, Y., Flegontova, T., Bobylev, Y., Ponomareva, O., Kaukin, A., . . . Shel, S. L. (2020, April). Monitoring of Russia's Economic Outlook. Trends and Challenges of Socio-Economic Development (In Russian). *Gaidar Institute for Economic Policy*, pp. 1-48.

Appendix

Parts of the main data source

Country	CapacityMW	PowerSource	ConnectionYear	Region	CloseYear
United States of America	408.00	Hydro	1964	USA	2044
United States of America	6.30	Hydro	1948	USA	2028
United States of America	5.00	Solar	2013	USA	2038
Switzerland	100.00	Hydro	1932	OECD	2012
China	640.00	Coal	2006	China	2046
United States of America	1.60	Waste	2010	USA	2050
China	400.00	Coal	2010	China	2050
China	150.00	Coal	2001	China	2041
United States of America	6.40	Waste	2007	USA	2047
Austria	75.00	Hydro	1975	OECD	2055
United States of America	1.60	Gas	1990	USA	2020
United States of America	3.20	Oil	1998	USA	2038
United States of America	20.00	Solar	2016	USA	2041
United States of America	93.60	Gas	1990	USA	2020
United States of America	5.00	Solar	2015	USA	2040
United States of America	50.40	Wind	2009	USA	2034
United States of America	84.80	Gas	1969	USA	1999
Netherlands	485.00	Nuclear	1973	OECD	2033
United States of America	361.90	Hydro	1953	USA	2033
Poland	4.00	Hydro	1914	OECD	1994
United States of America	1.80	Hydro	1913	USA	1993
Germany	22.00	Gas	1994	OECD	2024
Germany	11.06	Gas	1992	OECD	2022
United States of America	264.00	Wind	2008	USA	2033
United States of America	150.00	Gas	2000	USA	2030
Brazil	2.96	Oil	2008	Rest of the World	2048
China	700.00	Coal	2014	China	2054
United States of America	5.00	Solar	2017	USA	2042
China	600.00	Coal	2015	China	2055
India	1110.00	Coal	1995	India	2035
United States of America	51.60	Gas	1994	USA	2024
United States of America	1138.30	Nuclear	1987	USA	2047
United States of America	1116.00	Coal	1980	USA	2020
United States of America	3.90	Solar	2015	USA	2040
United States of America	1.90	Solar	2016	USA	2041
Ireland	32.50	Wind	2011	OECD	2036
United States of America	1.40	Solar	2016	USA	2041
Sweden	10.50	Wind	2006	OECD	2031
Brazil	29.52	Hydro	1958	Rest of the World	2038
India	100.00	Nuclear	1972	India	2032
Switzerland	54.00	Hydro	1921	OECD	2001
United States of America	4.60	Oil	2003	USA	2043
United States of America	3.00	Biomass	2011	USA	2051
Algeria	600.00	Gas	2015	Rest of the World	2045
United States of America	3.00	Wind	2010	USA	2035
United States of America	199.70	Wind	2010	USA	2035
Kazakhstan	2450.00	Coal	1972	Rest of the World	2012
United States of America	4.80	Waste	2009	USA	2049
China	2400.00	Coal	2004	China	2044
Ireland	66.70	Wind	2015	OECD	2040
United States of America	1.60	Waste	2013	USA	2053
United States of America	2.00	Solar	2013	USA	2038
United States of America	1960.40	Nuclear	1980	USA	2040
Laos	1878.00	Coal	2016	Rest of the World	2056

United States of America	1.40	Hydro	1986	USA	2066
United States of America	4.00	Solar	2014	USA	2039
United States of America	1.20	Gas	2010	USA	2040
Greece	134.00	Gas	1998	OECD	2028
United States of America	3.90	Solar	2017	USA	2042
Germany	15.60	Waste	2009	OECD	2049
Germany	12.80	Hydro	1955	OECD	2035
Brazil	30.00	Wind	2014	Rest of the World	2039
United States of America	6.00	Storage	2016	USA	2046
Bangladesh	71.00	Oil	2011	Rest of the World	2051
United States of America	4.20	Solar	2017	USA	2042
United States of America	63.60	Oil	1970	USA	2010
United States of America	1.50	Solar	2016	USA	2041
United States of America	301.50	Gas	1983	USA	2013
Libya	65.00	Oil	1985	Rest of the World	2025
United States of America	5.00	Solar	2016	USA	2041
United States of America	7.10	Oil	1971	USA	2011
Russia	12.00	Oil	1934	Russia	1974
Saudi Arabia	102.00	Oil	1982	Rest of the World	2022
China	270.00	Coal	2007	China	2047
United States of America	2.00	Solar	2017	USA	2042
United States of America	2.00	Oil	1980	USA	2020
United States of America	1.00	Solar	2015	USA	2040
United States of America	16.00	Oil	1992	USA	2032
United States of America	38.00	Waste	1992	USA	2032
United States of America	4.80	Gas	1995	USA	2025
India	90.00	Hydro	1988	India	2068
Brazil	18.90	Wind	2014	Rest of the World	2039
Sweden	10.20	Wind	1983	OECD	2008
Iran	972.00	Gas	2014	Rest of the World	2044
United States of America	3.00	Wind	2017	USA	2042
Netherlands	213.30	Wind	2009	OECD	2034
United States of America	5.00	Waste	1983	USA	2023
United States of America	2.20	Oil	2010	USA	2050
Portugal	2.20	Solar	2008	OECD	2033
United States of America	1.10	Solar	2012	USA	2037
Philippines	59.00	Solar	2016	Rest of the World	2041
United States of America	2.10	Wind	2008	USA	2033
United States of America	19.00	Oil	1968	USA	2008
India	412.02	Hydro	2013	India	2093
United States of America	14.00	Oil	1964	USA	2004
United States of America	10.20	Waste	2003	USA	2043
United States of America	84.20	Biomass	1991	USA	2031
Austria	1272.00	Gas	2009	OECD	2039
United States of America	2.90	Solar	2017	USA	2042
United States of America	19.00	Solar	2013	USA	2038