Challenges and Opportunities of Transition to Sustainable Electricity Generation

Miguel da Costa Rebelo Gomes Rodrigues

Dissertação de Mestrado

Orientador na FEUP: Carlos Pinho

Orientador UNESCAP: Sergey Tulinov

U. PORTO

FEUP FACULDADE DE ENGENHARIA
UNIVERSIDADE DO PORTO

Mestrado Integrado em Engenharia Mecânica

Setembro, 2020

Resumo

O consumo de electricidade tem vindo a aumentar significativamente na região da Ásia-Pacífico devido a um grande crescimento populacional, e uma grande industrialização, entre outros factores. A produção da electricidade necessária para dar resposta à procura dos consumidores nesta região é ainda muito dependente de combustíveis fósseis, principalmente carvão, que emitem uma grande quantidade de gases com efeito de estufa para a atmosfera (GEE), responsáveis pelo aumento da temperatura global da terra e consequente intensificação das alterações climáticas. O uso de carvão para a produção de electricidade é a tecnologia mais poluente neste sector, havendo alternativas maduras e com custos competitivos com impactos comparativamente muito reduzidos. Este combustível é extensivamente utilizado devido à grande disponibilidade deste recurso nesta região, o que minimiza os custos e a dependência geopolítica da mesma.

Desta forma torna-se imperativo explorar alternativas ao consumo de combustíveis fósseis no sector elétrico, dando especial relevo ao carvão. O aquecimento global é um tema que marca a atual sociedade e que, se não for abordado com seriedade, tem a capacidade de comprometer as futuras gerações, daí a sua importância e urgência.

Este relatório tem como objectivo contextualizar a situação do setor elétrico na região da Ásia-Pacifico, com ênfase na China. São apresentadas as tendências deste sector, as tecnologias produtoras de elecricidade com maior nivel de maturidade e os seus impactos, e é feita uma comparação entre as tecnologias, as suas vantagens, desvantagens e competitividade de custos.

Uma vez que o presente relatório foi realizado no contexto de uma equipa dominada por profissionais da área de economia, política e direito, fez-se um esforço por usar linguagem não demasiado técnica e dar especial relevância aos conceitos base associados à produção de energia elétrica de forma a conseguir cativar a audiência em causa, dando-lhes ao mesmo tempo uma informação tecnológica complementar.

Abstract

Electricity consumption has been increasing significantly in the Asia-Pacific region, due to a large growth in population and a broad industrialization, among others. The production of electricity necessary to meet the consumers demand in this region is still very dependent on fossil fuels, mainly coal, which emits a large amount of greenhouse gases into the atmosphere (GHG), contributing for the increase of global temperature and consequent intensification of climate change. The use of coal to produce electricity is the most polluting out of all electric power generation technologies, with mature alternatives at competitive costs and comparatively reduced environmental impacts. Due to the great availability of coal in the Asia-Pacific region, this is used extensively, which minimizes costs and the regions geopolitical dependence.

It is imperative to explore alternatives to the consumption of fossil fuels in the electricity sector, with a highlight on coal. Global warming marks the current society, and if not taken seriously, has the capacity to compromise future generations - hence its importance and urgency.

This report aims to contextualize the situation of the electricity sector in the Asia-Pacific region, with emphasis on China. This work presents the trends of the electricity sector, the most mature electricity generation technologies and their impacts. Afterwards, it is made a comparison between the different technologies, their advantages, disadvantages, and cost competitiveness.

Since this report was developed in a team dominated mainly by professionals of areas related to economy, politics and law, an effort was made to use a language not too technical and give especial relevance to the basic concepts of electric power generation in order to try to captivate the audience. However, these simple concepts might give them a complementary set of technical information.

Acknowledgments

I would like to express my grattitude for all the support given by Professor Carlos Pinho, in particular for his availability and continuous feedback.

To everyone in the Energy division of the United Nations Economic and Social Commission for the Asia and Pacific, in particular my tutor Mr. Sergey Tulinov, for all the support and for making sure that despite the current situation of the COVID-19 pandemic which made it mandatory to implement a work from home modality, I always felt integrated in the team and in constant contact with everyone.

To everyone that made part of my temporary journey in Bangkok, in particular my host family and friends, of which I grew very fond of, for all the support given throughout this abnormal period, marked by the pandemic situation, which made it especially difficult and morally challenging to be such a long way from home.

To Maria, for so much that are hardly enough words that would do it justice.

To my parents, for their incessant support throughout all my life. For giving me the opportunity to have a great education, both academically and personally. I am and will always be eternally grateful.

Table of contents

List of Acronyms

AC – Alternate Current
A-USC - Advanced Ultra-supercritical
BP – British Petroleum
CCGT - Combined Cycle Gas Turbine
CCS – Carbon Capture and Storage
CNPC - China National Petroleum Corporation
CO_2eq – Carbon Dioxide Equivalent
CPS – Carbon Price Support
DC – Direct Current
EIA – U.S. Energy Information Administration
ETS - Emissions Trading Scheme
EU – European Union
FGD - Flue Gas Desulphurization
FOLU - Forestry and Other Land Use
GDP – Gross Domestic Product
GHG – Greenhouse Gas
GWP – Global Warming Potential
HRSG - Heat Recovery Steam Generator
IEA – International Energy Agency
IPCC - Intergovernmental Panel on Climate Change
IRENA – International Renewable Energy Agency
LCOE – Levelized Cost of Electricity
LCPD - Large Combustion Plants Directive
LNG – Liquified Natural Gas
NEA – China National Energy Administration
NDRC – China National Development and Reform Commission
O&M – Operation and Maintenance
PM – Particulate Matter
PV – Photovoltaic
SC - Supercritical
SDG – Sustainable Development Goal
SI - International System of Units
UK – United Kingdom
UNESCAP - United Nations Economic and Social Commission for the Asia Pacific
UNFCCC - United Nations Framework Convention on Climate Change
USC – Ultra-supercritical
YoY – Year on year

List of Figures

List of Tables

1. Introduction

This chapter focuses on contextualising this report, its methodology and objectives.

1.1 Project context

This work performs an overview of the electric sector, in particular the most used technologies to generate electricity, both using fossil fuels and renewable sources. Moreover, it compares their advantages and disadvantages, explains their impacts on the environment, why these matter and possible pathways to minimize the negative externalities of the electricity sector. Lastly it is made an overview of the Chinese electricity sector and a collection of its latest policies.

The present report was developed as part of an internship in the Energy Division of the United Nations Economic and Social Commission for the Asia Pacific (UNESCAP) and is of relevance to promote the dialogue and share knowledge about increasing the sustainability of the electricity sector. Furthermore, it is of relevance to update the website (asiapacificenergy.org) developed by the energy division with the latest policies related to the electricity sector of China as well as provide the division with capacity building on the technical aspects related to different electricity generation technologies.

The internship was in Bangkok, Thailand, where the UNESCAP is located. Although, due to the COVID-19 pandemic, the work was developed remotely.

1.2 UNESCAP

The United Nations Economic and Social Commission for the Asia Pacific serves as a platform to promote cooperation and share knowledge within its member countries to achieve sustainable development in the region. UNESCAP provides research, analysis, policy advice, capacity building and technical assistance to governments with the aim to increase sustainability and inclusive development. The work of the energy division focuses on providing affordable, reliable, and sustainable energy for all Asia Pacific, as outlined in the sustainable development goal (SDG) number seven.

1.3 Objectives

This report has the following objectives:

- Make an overview of the electricity generation trends by region and technology;

- Analyse the technical concepts related to different electricity generation technologies;
- Comparing different electricity generation technologies, its environmental impacts, advantages and disadvantages;
- Provide an example of a coal phase out success story;
- Overview of the Chinese electricity sector.

1.4 Methodology

The elaboration of this report went through different phases although it was monopolized by research work, identifying literature about the underlying theme and interiorizing its information. Firstly, this consisted on reading different books, articles and websites about coal, natural gas, solar photovoltaic, wind turbines and hydropower, how these are used to generate electricity and their presence and growing trends around the globe. Then a lot of research was done around the Asia Pacific region, its demographics, gross domestic products (GDP), electricity growth trends and fossil fuels trade. Also, a collection of information was made on the topic of climate change, global warming, and climate mitigation. Lastly a search for the latest policies of the Chinese electricity was made, exploring several official documents, and identifying their main goals.

1.5 Report structure

This report consists of eight chapters, starting with the current one that gives an introduction and contextualization of the report itself.

The second chapter makes an overview of the electricity generation worldwide and compares it to the scenario of the Asia Pacific region.

The third chapter makes a state-of-the-art review of some of the most used electricity generating technologies. It focuses on coal and natural gas power plants and on renewables such as solar photovoltaic (PV), wind turbines and hydropower. Moreover, it identifies the growing trends of each technology installed capacity.

Fourth chapter focuses on the environmental impacts related to electric power generation, namely global warming, and air pollution. What causes it and its impacts.

Fifth chapter makes a comparison across the technologies presented in chapter three. It explores the externalities associated with each technology, advantages and disadvantages, and compares the costs of electricity production between them.

The sixth chapter focuses on the success story of the phase out of coal in the electricity sector of the United Kingdom. It explores the effects of the policies implemented and their chronology with the purpose of drawing some conclusions for possible coal phase out pathways to be implemented in other countries.

The seventh chapter provides an overview of the electricity sector of China and a review of the latest policies implemented by the Chinese government related to this sector.

The last chapter makes a deep dive on the future of electric power generation, the challenges it faces, and possible pathways for a sustainable electricity sector exploring new and different technologies that promise to be clean, reliable, and affordable.

2. Overview of the global and Asia-Pacific electricity mix

The electricity sector is a large consumer of energy because a lot of energy is required in its transformation processes. As such, this sector has great economic, social, and environmental impacts across the globe. Moreover, as of 2018, 64.2 % of the electric power generated still came from fossil fuels and only 25.1 % from renewable sources (BP, 2019). The extensive use of fossil fuels in this sector generated roughly 13 Gt of carbon dioxide (CO_2) which represents 38 % of total CO_2 emissions from energy related activities (IEA, 2019). Therefore, this sector alone is responsible for the biggest share of CO_2 emissions in the world, making it a big contributor to global warming.

A continuous population growth, fast economic and social development and a growing urbanization in developing countries are responsible for most of the increase in electricity demand worldwide. Figure 2.1 and Table 2.1 show the discrepancy of growing electricity demand in different areas of the globe. The Asia Pacific region saw the biggest increase on electricity demand driven mainly by countries such as China and India that together account for 36 % of the world's population (World Population Prospects, 2019). Furthermore, electricity consumption per capita in this region as of 2017 was only 2983 kWh which compares to a consumption rate of 6266 kWh in a developed region such as Europe (Asia Pacific Energy Portal, 2020). Moreover, electricity consumption in the Asia Pacific region is dominated by the industry sector, that has grown at a fast pace for the last twenty years, whereas the residential and commercial and public services represent a less significant portion of the electricity consumption. In developed regions such as Europe this consumption is more balanced with these three sectors having a relatively similar portion of the electricity demand. This is also a result of some industry activities being dislocated to countries with lower labour costs, a lot of those located in the Asia Pacific (IEA, 2020b).

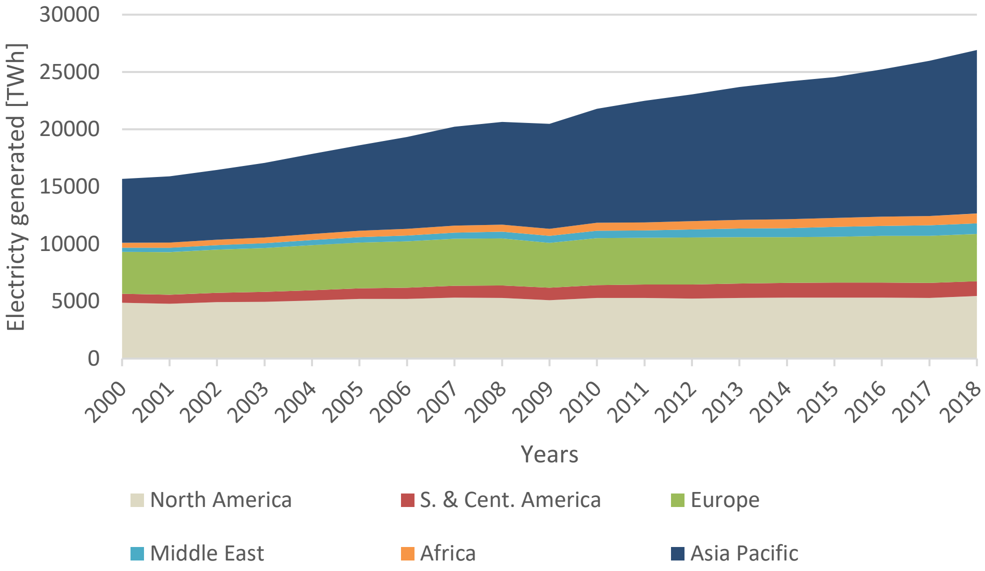

Figure 2.1 - Electricity generated by region (BP, 2019)

Table 2.1 - Electricity generated by region and growing trends (BP, 2019)

Region	Electricity Generation 2000 [TWh]	Electricity Generation 2018 [TWh]	Absolute Growth [TWh]	Relative Growth	Average growth per annum
North America	4860	5447	588	12.1%	0.7%
S. & Cent. America	808	1305	498	61.6%	2.7%
Europe	3646	4116	470	12.9%	0.7%
Middle East	351	930	578	164.6%	5.6%
Africa	440	854	414	94.0%	3.8%
Asia Pacific	5568	14265	8697	156.2%	5.4%
World	**15548**	**26615**	**11066**	**71.2%**	**3.0%**

The continuous rise of electricity consumption in developing countries demands more electric power generation capacity to be installed. On the other hand, developed countries have seen their electricity demand remain relatively flat throughout the last twenty years making it easier to reform their electricity generation fleet with a substantial share of modern renewable technologies. Developing countries struggle to reform their existing installed capacity as most of the new capacity is used to meet the growing electricity consumption. In Figure 2 is shown the power generation capacity installed worldwide and the evolution of new installed capacity each year.

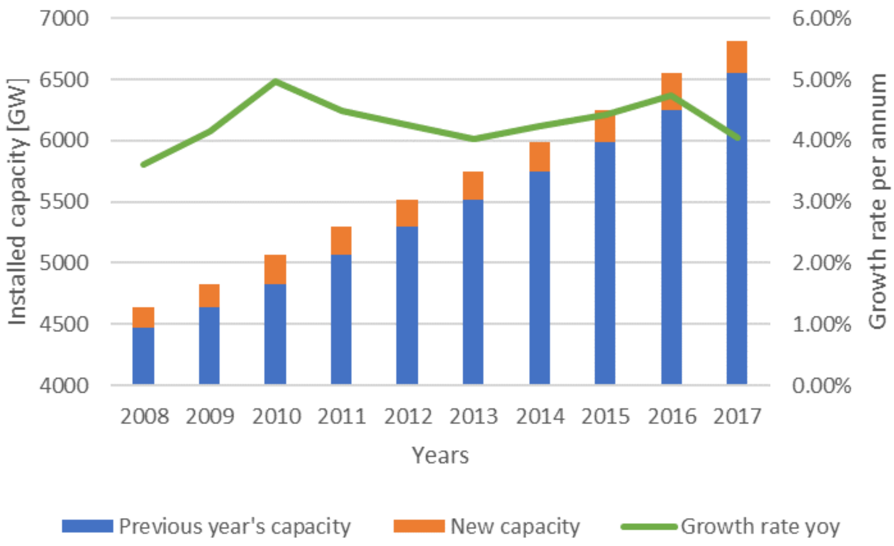

Figure 2.2 - Installed capacity of electricity generation technologies worldwide (EIA, 2018)

To better understand the relation between installed capacity and electricity generation there is an important metric to consider that is the capacity factor. This factor compares the electricity generated to its potential.

$$\textbf{Capacity Factor} = \frac{\textbf{Electricity generated}}{\textbf{Availability}\times\textbf{Installed capacity}} \tag{2.1}$$

This factor varies a lot between different technologies. In fact, renewables usually have a much lower capacity factor than fossil fuel powered power plants, as they rely on intermittent energy sources, such as wind and solar radiation, there will be frequent periods of time when the electricity generation will be zero. Fossil fuel powered power plants however depend on the fuel supplied, so as long as there is fuel available and the components are ready to operate, the power plant is capable of generating electricity. This situation, however, is not always true, thermal power plants require large amounts of water to cool its components, as well as to carry away its rejected heat, and sometimes, especially during extremely hot summers, the temperature of the water is too high requiring the power plant to be shut down. Thus, for renewables with a lower capacity factor, to achieve the same electricity output as fossil fuel powered power plants, more installed capacity is required. This subject will be discussed further in the next chapter (IRENA, 2020).

The concept behind electrical power generation is similar either if it is from renewable or fossil fuel sources (exception of photovoltaic cells and some other less representative technologies). The baseline is via a working fluid that flows through a thermal engine or a hydraulic turbine, coupled to an electrical generator, convert thermal or potential energy into mechanical energy and subsequently in electrical energy. This part of the process remains the same, the main difference between different technologies is how to use a working fluid that makes the thermal engine or turbine operate for as many hours and as fast as possible in order to achieve a higher output. Here is where renewables and fossil fuel powered power plants part ways.

3. Power generation technologies and sustainability

3.1 Fossil fuels

Fossil fuels are hydrocarbons that can be found under the earth's crust, formed along millions of years from the decomposition of plant and animal matter. They are especially attractive in sectors that use heat in its processes, such as in industry and thermal electric power generation, because their combustion is exothermic. In fact, the main products of any hydrocarbon combustion are carbon dioxide, water, energy as well as other pollutants.

Generating electric power from these fossil fuels differs from most renewables because a combustion process is used to extract the energy contained in the resource. Unlike biomass, that can too be used to generate electricity via a combustion process, fossil fuels cannot be replaced at the same rate that they are consumed. In this combustion process, energy is transferred to the working fluid, increasing its temperature and pressure, and this will then pass through a turbine, where the energy contained in the fluid is converted into work, making a shaft rotate. This shaft is coupled to the generator where this mechanical energy is converted in electricity. This workflow describes the processes used in a typical large power plant, however, there are other solutions that also use fossil fuels and are mainly used in off-grid applications. These use internal combustion engines such as Diesel or Otto engines where the energy contained in the working fluid, composed by the products of the combustion, is converted to mechanical energy by moving pistons instead of turbine blades (Breeze, 2015a; Belyakov, 2019a).

Independently of the technology used, the second law of thermodynamics limits the efficiency that can be obtained, idealized in the Carnot cycle. This cycle is used to understand the maximum theoretical efficiency that could be obtained by a certain heat cycle if no irreversibility's were presented (such as friction and turbulence). This efficiency $\boldsymbol{\eta_c}$ is independent from the type of working fluid and depends only on the ratio between the temperature of the heat source $\boldsymbol{T_h}$ and the heat sink $\boldsymbol{T_c}$ that will be considered, respectively, the inlet and outlet temperatures of the turbine in Kelvin (K), as used in the international system of units (SI).

$$\boldsymbol{\eta_c = 1 - \frac{T_c}{T_h}} \quad (3.1)$$

The outlet temperature is rarely lower than the ambient temperature, therefore, to increase efficiency, the inlet temperature should be as high as possible, and the outlet temperature should be as close to the ambient temperature as possible. This cycle represents the theoretical maximum efficiency that could be obtained using these temperatures, although, due to irreversibility's present in any cycle, the real efficiency is always lower. Consequently, the closer the real efficiency is to this theoretical value, the less margin is left for technological advances.

This concept is important to understand why some technologies have higher efficiencies than others, as well as to access if they can be further improved or if they have reached or are close to reach a technical limit. Furthermore, it makes clear what is and has been the focus of technological developments in fossil fuel powered power plants, that is, achieving ever higher temperatures of the working fluid in the inlet of the turbine and lower as possible in the outlet.

The next subchapters will focus on an overview of the most extensively used fossil fuels in electric power generation, namely its general characteristics and economic evolution, as well as analysing in more detail how different power plants work and their main components.

3.1.1 Coal

Coal is characterized by its dark colour and is composed mostly of carbon and other elements such as hydrogen, sulphur, oxygen and nitrogen as well as some moisture content. This resource has been a main driver of industrialization since the 19th century, however, environmental concerns that arose mainly in the second half of the 20th century have put this fuel on the spotlight. This concern started a global discussion on the urgency to phase out coal, although, globally it still is the second most used fossil fuel losing only to oil. Moreover, this fuel is extensively used in the electricity sector, representing the largest share of electricity generation worldwide. In Figure 3.1 and 3.2 are, respectively, the evolution of electricity generated and installed capacity of coal-powered power plants.

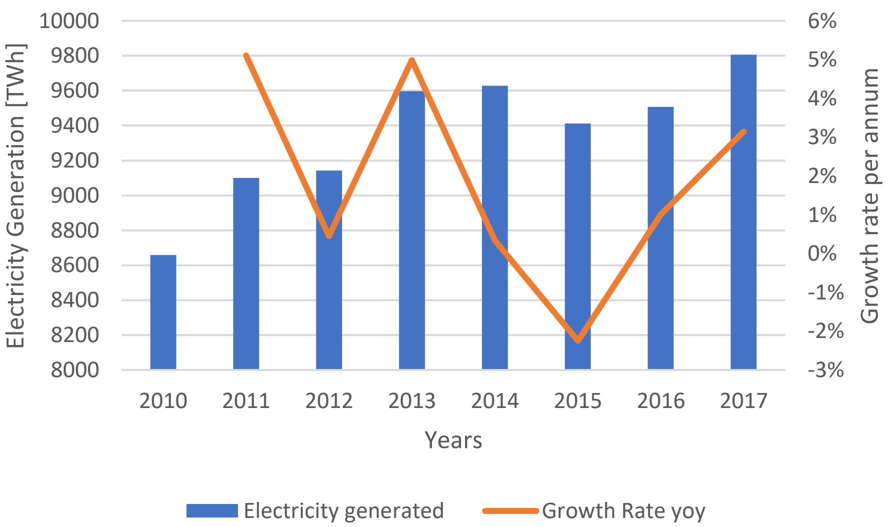

Figure 3.1 - Electricity generated from coal worldwide (EIA, 2019)

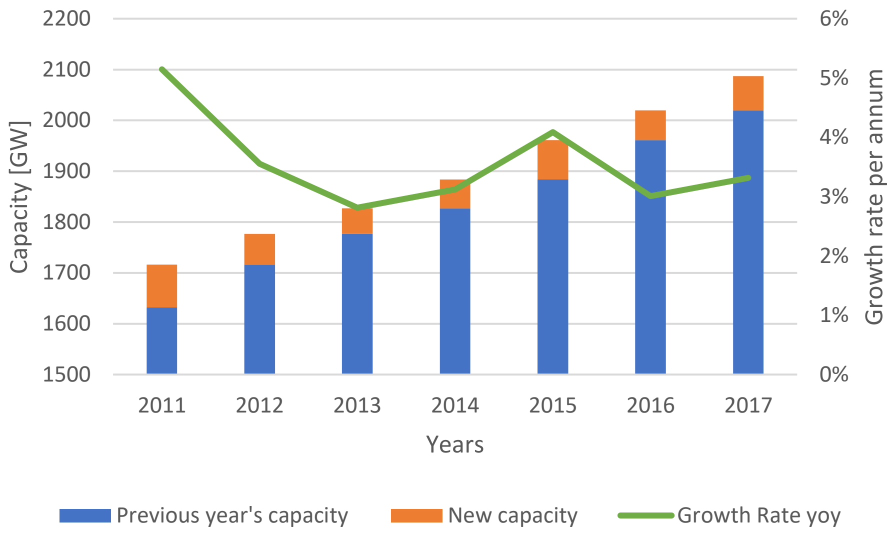

Figure 3.2 - Installed capacity of coal powered power plants worldwide (EIA, 2019)

With the values presented in the figures above it is possible to obtain the capacity factor of coal-fired power plants as seen in Figure 3.3.

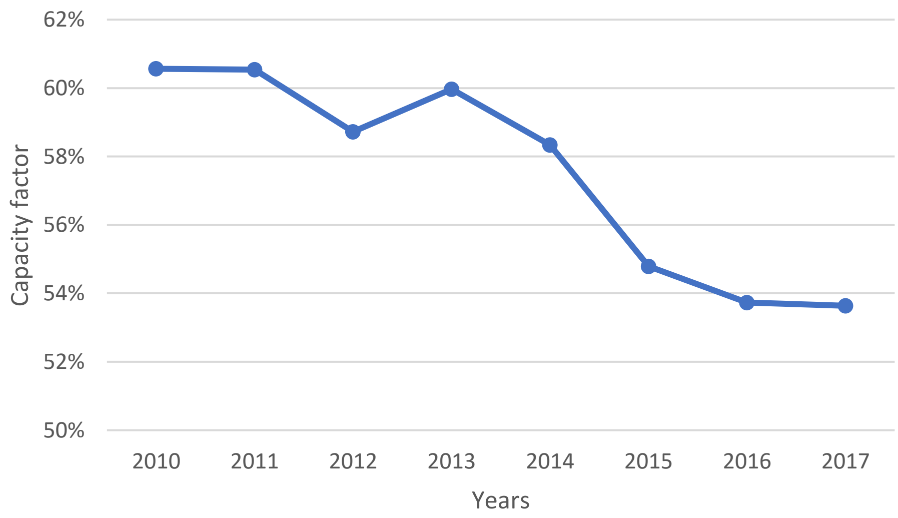

Figure 3.3 - Capacity factor of coal fired power plants worldwide (EIA, 2019)

This fuel is mined and can be found in different shapes depending on the time and conditions of formation. In Table 3.1 are the different types of coal and their characteristics.

Table 3.1 - Types of Coal (EIA, 2019)

	Formation Years	Carbon Content	Moisture	Hardness	Heat value	Reserves
Lignite	+	+	++++	+	+	++
Sub-bituminous	++	++	+++	++	++	+++
Bituminous	+++	+++	++	+++	+++	++++
Anthracite	++++	++++	+	++++	++++	+

Both lignite and sub-bituminous are lower grade coal that contain more water and ashes, are soft, have a brownish colour, a low heating value and therefore achieve lower temperatures when burned. The harder the coal is, the more difficult it is to mine as it means the mineral was subjected to higher pressures and temperatures that only occur deep under the earth's crust. Therefore, anthracite is more costly to mine than lignite and all the others. The most used by a significant margin is bituminous coal. All types of coal are used in electrical power generation however it is not common to use anthracite due to its high cost of mining, low reserves (roughly 1 % of total coal reserves) and attractiveness to other ends such as residential use (Breeze, 2015b).

Coal fired electrical power generation represented 38 % of electricity production worldwide as of 2018 (IEA, 2020a). This extensive use is mainly due to the wide availability and low cost, however, the latter is already being challenged by lower prices of renewables and natural gas. Moreover, the technology used in coal fired power plants is mature and successive upgrades have led to higher efficiencies.

Coal-fired power plants

Coal-fired power plants, although highly complex, have three core components, these are the boiler, where coal is burned and steam is produced, the steam turbine, where energy from the steam is converted into work, and the generator, where mechanical energy is converted in electricity. In Figure 3.4 are the main components of a typical coal fired power plant.

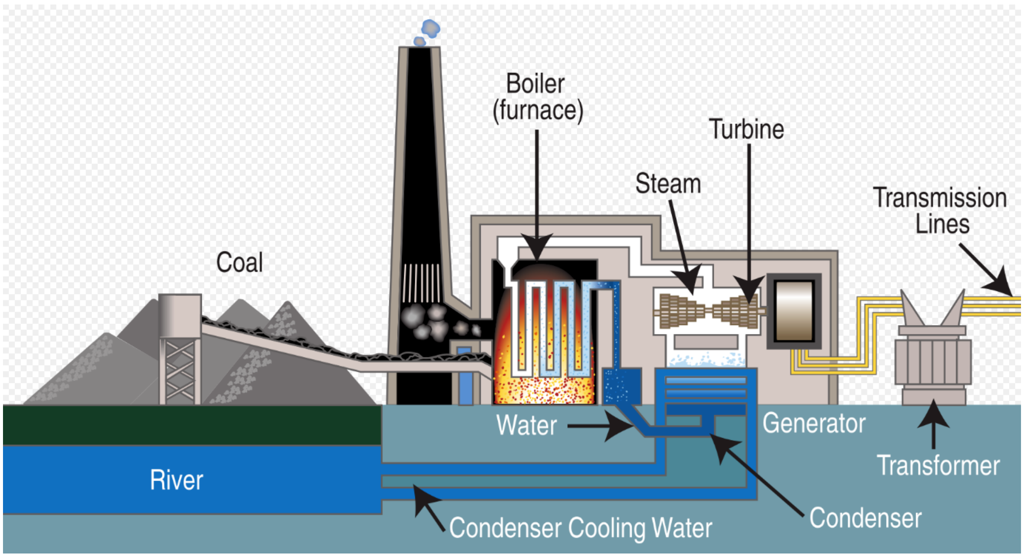

Figure 3.4 - Layout of a typical coal fired power plant (Tenesse Valley Authority)

Independently of the technologies used in any coal-fired power plant, the working fluid is the same, water. This water is heated until it becomes steam and the characteristics of that steam are used to classify different power plants as shown in Table 3.2.

Table 2.2 - Classification of coal-fired power plants using water properties (Breeze, 2015)

	Temperature [K]	Pressure [MPa]
Sub-critical	< 647.14	< 22.12
Supercritical	647.14 - 883	22.12 - 31
Ultra-supercritical	883 - 993	31 - 36

This classification uses the critical point of water to distinguish the sub-critical technology from the supercritical. In fact, the boiling temperature of water varies with pressure. At ambient pressure, water has a boiling temperature of 100 ºC, and liquid and gaseous water coexists while boiling. However, when water is heated under pressures above the ambient pressure, the boiling temperature increases as well. Moreover, when pressure and temperature rise, the properties of saturated water and saturated steam start to converge and when the critical point of 22.12 MPa and 647.14 K is reached, these begin to have the same properties and therefore can no longer be distinguished between them. Water with thermodynamic properties above this point is called supercritical steam (Breeze, 2015b). The interest in using supercritical or ultra-supercritical steam lies in the possibility of achieving higher efficiencies by using higher temperatures of the working fluid, as explained in the last subchapter.

Boiler/steam generator

This component is where the first process takes place, that is where fuel is burned producing hot combustion gases that will be used to heat the water. These can be looked at as a heat exchanger with a combustion chamber. There are different types of boilers, and these can be categorized according to certain characteristics. Some of those characteristics are presented in Figure 3.5.

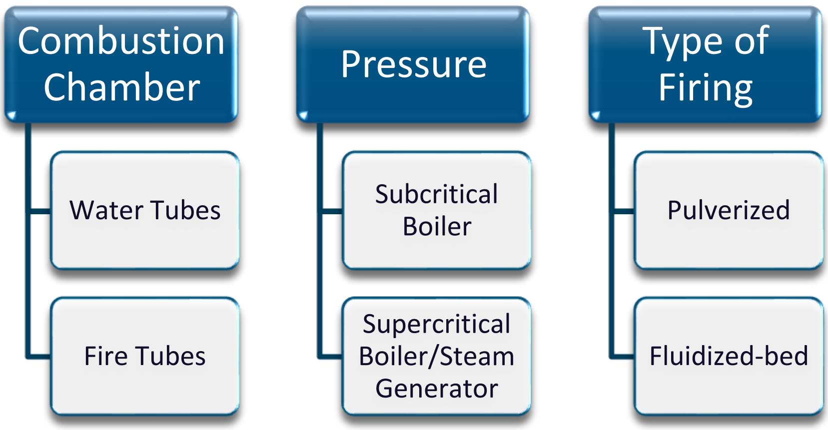

Figure 3.5 - Characteristics of different types of boilers

In coal-fired power plants the combustion chamber is usually of the water tube type because this is better suited to endure higher pressures and operating capacities. In this type of boiler water circulates in tubes whereas the combustion takes place in the furnace and hot gases circulate inside the shell of the boiler as illustrated in Figure 3.6.

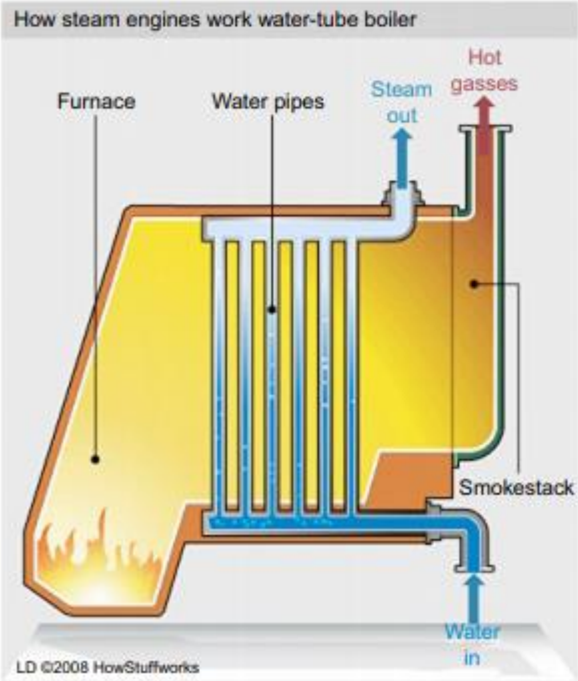

Figure 3.6 - Water tube boiler

These boilers use pre-treated coal, normally crushed until it becomes a fine powder. This powder is highly flammable and burns evenly, hence its attractiveness in this process. There are, however, different solutions of firing. Two of the most vastly used firing options are as follows:

- Pulverized coal

Coal is grinded until a flour like aspect and mixed with hot air to extract its moisture content. Only after this process takes place, the mixed stream of fine coal particles and hot air is fed to the furnace to be combusted. Once inside the furnace, the mixture receives another stream of air, just enough to guarantee a complete combustion. The air-fuel ratio is greater than the stoichiometric requirements, making it a lean fuel mixture.
This type of boiler is designed for coal within certain requirements of heating value, ash content among other characteristics and therefore is not a flexible solution (Breeze, 2015b; Pang, 2016)

- Fluidized bed

This process consists of a controlled combustion of solid particles in a bed made of sand and other materials. Pre-treated coal is fed to this bed of particles and air is forced through it allowing for a controlled combustion. This method of firing can burn coal with different heating values, and moisture and ash contents. Due to the presence of substances such as limestone in the fluidized bed, SO_2 from the combustion is extracted in this process. NO_x

emissions are also lower than in other solutions because of the lower combustion temperatures used in this process. When fuel flexibility is a priority and the coal used is of low quality this solution is attractive, however, additional costs must be taken into account as the circulation of air through the fluidized bed is energy consuming (Breeze, 2015b; Pang, 2016).

Once the coal is burned it produces a hot stream of flue gases that will circulate around the tubes containing water. Heat is transferred through these tubes to produce steam. However, depending on the type of boiler this heat transfer can happen in different ways:

- Subcritical boiler

This type of boilers, as explained before, operates with water under the critical point. Water circulates in tubes that are heated by the hot flue gases until achieving saturated water. This saturated water then goes to the steam drum where steam is separated from the liquid phase. Steam then flows out of the drum either directly to the turbine or to a reheat process in order to get superheated before going to the turbine. The water in the steam drum is then recirculated making another passage in the tubes to receive more heat and returns to the steam drum producing more steam. This is how a conventional boiler operates and these boilers are installed in most of the 20th century coal fired power plants (Breeze, 2019).

- Supercritical boiler/steam generator

This boiler does not have a steam drum, as the water characteristics are above the critical point there is no distinction between phases, which erases the need for this component. This type of boiler, also called steam generator, has a high number of small tubes passing through its shell to increase the heat transfer rate. Water is fed to each tube in the liquid phase and at the outlet, supercritical water is delivered. In order to support the pressures and temperatures involved in the process these tubes are made of special alloys. Steam generators produce steam at higher temperatures, which leads to the possibility of achieving higher power generation efficiency. On the other hand, the special materials required lead to a higher cost than the typical boiler (Breeze, 2019).

Steam turbine

This component converts the energy contained in the steam in mechanical work through its blades. In some coal fuelled power plants there are different turbines especially designed to work with steam at different pressures. This way a higher amount of energy can be extracted from the fluid thus achieving a higher efficiency.

Figure 3.7 - The blades of a steam turbine

The properties of the steam generated, presented in Table 3.3, are used to classify coal fired power plants. The most common, however slightly outdated, are subcritical plants that achieve efficiencies of around 38 % at full load (Breeze, 2019). Supercritical plants (SC) were the technology upgrade that followed, achieving efficiencies of 41 % at full load (Breeze, 2019). Further innovations led to the ultra-supercritical (USC) power plants which further increased the thermodynamic properties of the steam achieving a maximum efficiency of 47 % at full load (Breeze, 2019). Although USC technology has been around for a few decades, it only started to be commercially implemented more widely for the last years as the technology is now more mature and economically viable. At the forefront of this implementation are Asia and Europe. Research and some initial projects are underway to develop advanced ultra-supercritical (A-USC) plants that will operate with temperatures above 700 ºC aiming to achieve efficiencies as high as 55 % (Breeze, 2019).

3.1.2 Natural gas

Natural gas is a colourless, odourless, gaseous low-carbon fossil fuel, characterized by its high calorific value. This fuel is composed mainly by methane (96 %) and other hydrocarbons (Faramawy et al., 2016). This fossil fuel is formed in a scale of millions of years by decomposition of organic matter subjected to high amounts of pressure and heat that exist under the earth's crust.

This fuel was first recognized as an energy source several centuries ago in China, where the first known gas well was built. In the Western civilization this resource was first discovered in Great Britain followed by other countries such as Germany and the US, and it started to be commercialized throughout the 19th century (Speight, 2019). However, it was not until the first half of the 20th century that natural gas began to be used in electricity generation, being used in combustion boilers like the ones used in coal-fired power plants. Natural gas fired power plants saw their great breakthrough in the beginning of the Second World War with the development of the gas turbine. This component was developed as an aero engine and reached higher efficiencies than conventional steam boilers. During the second half of the 20th century, this new technology matured and started to be implemented in large-scale electricity generation. In the 21st century this technology is competing and in some cases displacing coal-fired power plants due to its higher efficiency and less significant environmental impacts (Breeze, 2016).

Figure 3.8 shows the electricity generation in the world using this fuel, Figure 3.9 the evolution of its installed capacity and Figure 3.10 its capacity factor evolution.

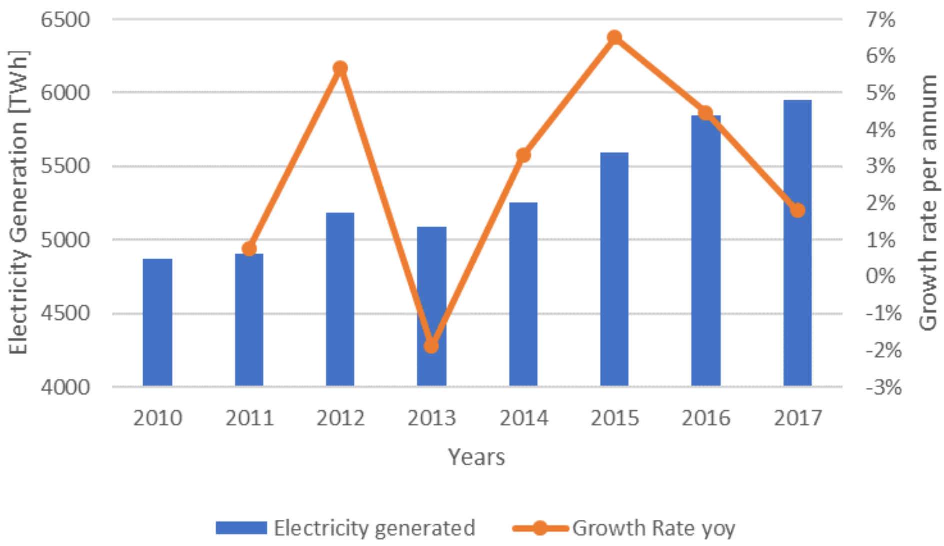

Figure 3.8 - Electricity generation by natural gas fired power plants (EIA, 2019)

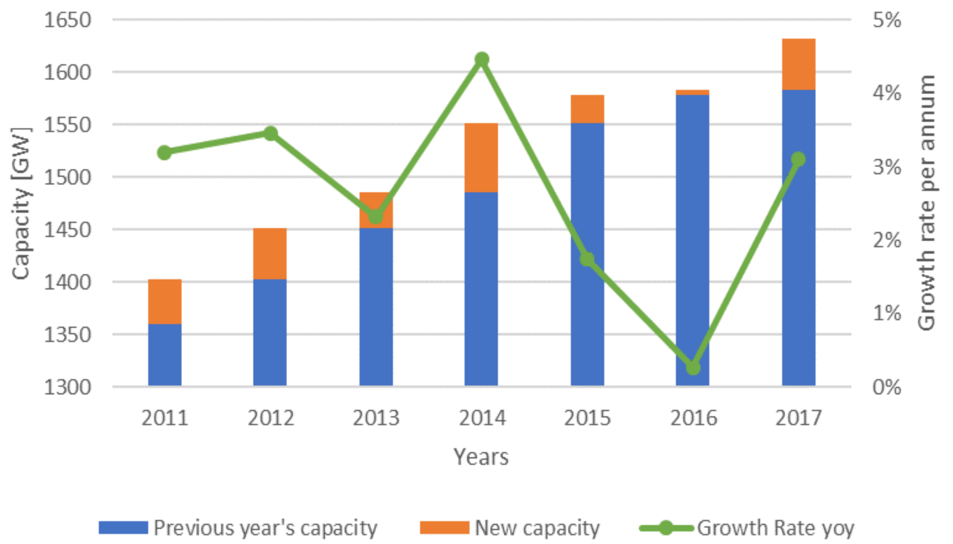

Figure 3.9 - Installed capacity of natural gas fired power plants worldwide (EIA, 2019)

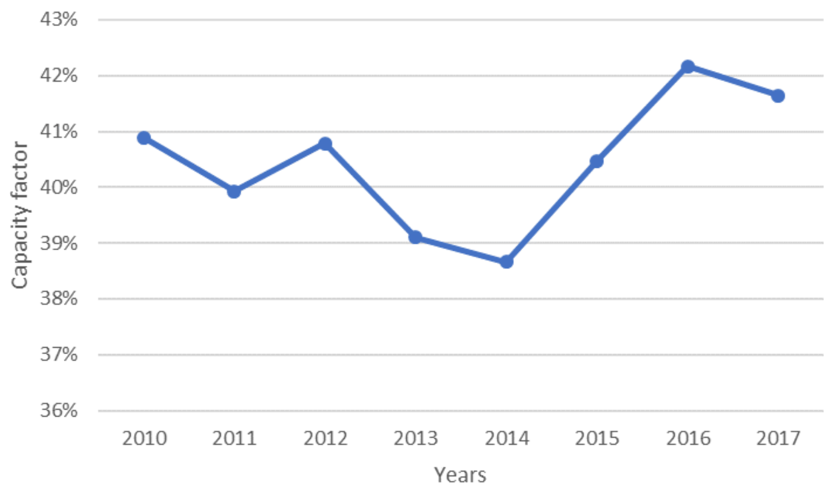

Figure 3.10 - Capacity factor of natural gas fired power plants

The capacity factor of these power plants is lower than coal fired power plants and different reasons can explain such disparity. Among them is the flexibility of natural gas power plants, these have a fast ramp rate which makes them ideal to be used more frequently on scenarios of peak demand and fuel costs. Although, these power plants are perfectly suitable to operate as baseload as well. On the other hand, coal-fired power plants are usually used as baseload power plants because they do not function at low loads, have slower ramp rates and the cost of coal is usually low and stable (Breeze, 2019)

Natural gas power plants

There are different technologies that use natural gas to produce electricity. The simplest one uses the same concept of coal-fired power plants, heat is used to raise steam in a boiler, the only difference is the fuel used in the combustion chamber is natural gas. This type of plant is not commonly used alone, due to its low efficiency when compared to other technologies that were developed throughout the second half of the 20th century.

The technology that paved the way to natural gas use in electricity generation was the development of gas turbines, idealized in the Joule-Brayton cycle. Sharing the same concept of jet engines, these turbines use the exhaust gas from the combustion as the working fluid. In fact, the process can be divided in three main stages, in the first one, air flows through a compressor increasing its pressure, after this stage natural gas is injected in the combustion chamber where it is burned with the compressed air producing high heat exhaust gases that will flow through the turbine making the shaft rotate. Figure 3.11 shows the different components of a gas turbine.

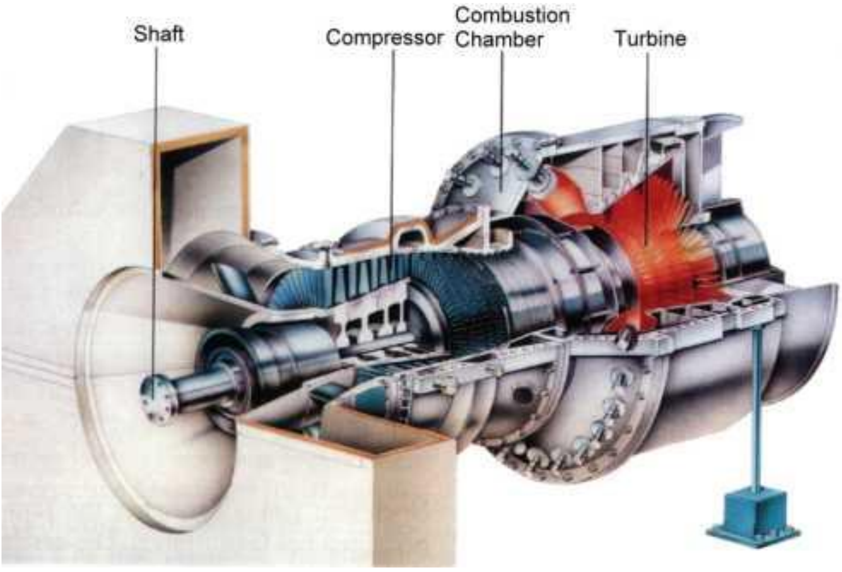

Figure 3.11 - Layout of a gas turbine

As said before, gas turbines are especially attractive to meet peak electricity demand due to its rapid start and stop capabilities. Furthermore, this solution is a lot more compact than steam generators, making it much easier to transport and install. However, one of the main disadvantages of this technology is the low thermal efficiency. In fact, the exhaust gases in the outlet of the turbine usually contain a considerable amount of energy, with temperatures in the range of 400 – 500 ºC. Power plants operating only with gas turbines are referred to as open cycle and for inlet temperatures above 1300 ºC efficiencies around 40 % can be achieved at full load (Breeze, 2016).

The thermal waste incurred when using gas turbines promoted the exploration of alternatives to capture the energy contained in the fluid at the outlet of the turbine. The solution implemented was the combined cycle gas turbine (CCGT), where the energy contained in the working fluid at the outlet of the gas turbine is used to create superheated steam in a heat recovery steam generator (HRSG). This steam then flows through a steam turbine that is connected to another generator, producing more electricity (Breeze, 2019). In Figure 3.12 is the typical diagram of a CCGT power plant.

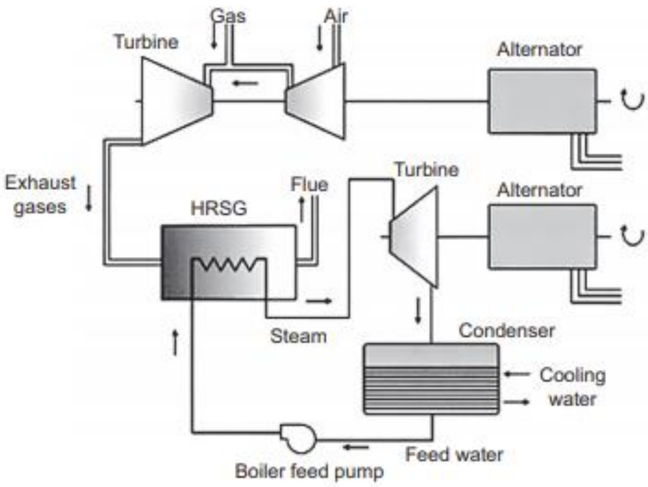

Figure 3.12 - Diagram of a typical CCGT power plant

After flowing through the turbine, the steam is cooled in a condenser and then pumped back to the HRSG to be reused. Nowadays the most advanced CCGT power plants work with inlet temperatures between 1400 and 1600 ºC, with the ones using the upper limit value slightly surpassing 60 % efficiency at full load. Research is being carried to upgrade this value to 65 % using an inlet temperature of 1700 ºC (Breeze, 2016). The limitation on the inlet temperature is posed by the materials used in the blades of the gas turbine. These are made of special alloys and coatings and must be cooled to endure such extreme conditions.

Overall natural gas fired power plants are characterized by its flexibility. In fact, these have fast ramp rates and can be quickly adjusted to different loads if electricity demand varies. Moreover, CCGT power plants have high efficiencies over a wide range of loads, which also makes them suitable for baseload operation while minimizing emissions as less fuel needs to be burned to achieve a certain output.

3.2 Renewable Energy

Renewable electricity is produced using resources that can be replenished within a human's lifetime. This type of electricity is characterized by the lower impact in the environment when compared to fossil fuel originated electricity as well as by the abundance of the resources used. The main types of renewable energy are wind, solar, geothermal, biomass and hydro. Although most use a working fluid in its natural state, taking advantage of earth's characteristics (gravity, meteorology, internal activity) and producing no emissions while operating, others such as biomass use a combustion process and therefore produce CO_2. This resource, made of organic matter from animals or plants, unlike other renewable sources it is not considered a clean fuel per se, as it emits greenhouse gases (GHG). However, using the example of wood as a biomass source, this is considered a renewable fuel as the CO_2 emitted to the atmosphere when burned was CO_2 previously absorbed by a tree during its lifetime. Therefore, CO_2 is only returning to where it was stored before being absorbed, resulting in net zero emissions. Despite this, the combustion of biomass produces other atmospheric pollutants therefore it cannot be considered a clean fuel. The case with fossil fuels is different because new amounts of CO_2 are being added to the atmosphere.

The following sub-chapters will explore the concepts behind the fastest growing technologies used to generate electricity from renewable sources. In particular, hydro, wind and solar photovoltaic.

3.2.1 Hydropower

This source of energy is one of the oldest known to humans. In fact, evidence shows that thousands of years ago water was already used to turn wheels that would grind wheat and flour (Breeze, 2018a). This technology, as with most renewables, indirectly depends from solar energy. Solar radiation is used in evaporation processes that will result in large amounts of water vapor to accumulate in the atmosphere. This vapor will eventually be precipitated in the form of rain, completing what is widely known as the water cycle (Belyakov, 2019b). Hydropower in electricity generation started to be vastly implemented in the beginning of the 20th century and since then it became the most mature and widely used renewable energy source. In Figure 3.13 is the evolution of electricity generation from hydropower since 2007, Figure 3.14 the installed capacity evolution and Figure 3.15 its capacity factor.

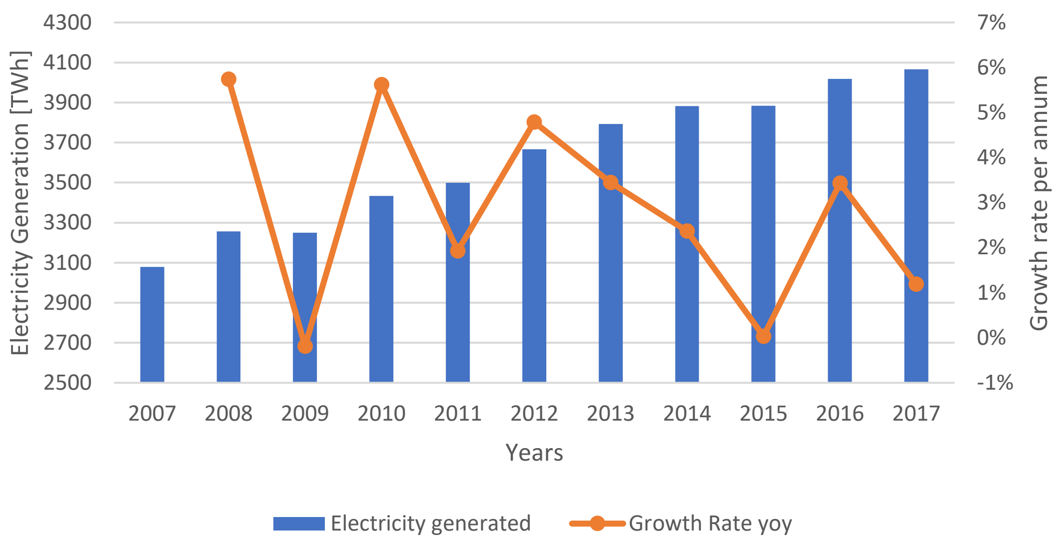

Figure 3.13 - Electricity generated using hydropower worldwide (BP, 2019)

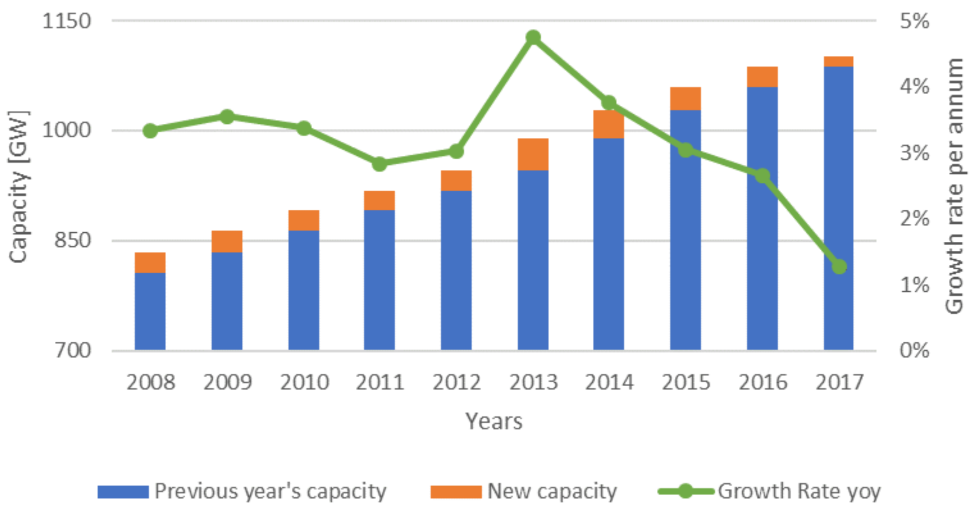

Figure 3.14 - Installed capacity of hydro generation worldwide (IRENA, 2018)

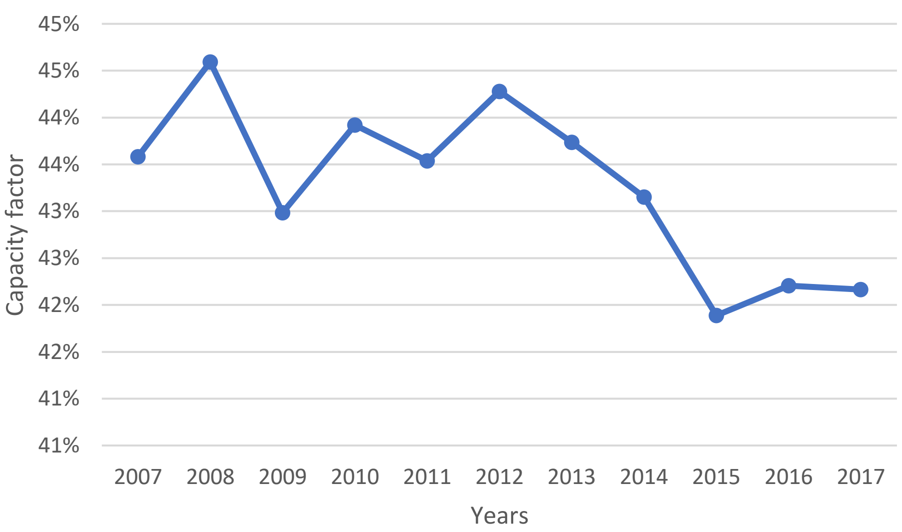

Figure 3.15 - Capacity factor of hydro generation worldwide

Hydroelectric power plant

There are different solutions to capture hydric energy to generate electric power, however, all of them extract the energy contained in the water due to the difference in its elevation. To capture this energy, depending on the characteristics of the site and the river, several concepts can be adopted. One of the most common is to build a barrier, a dam, that will block the flow of the river creating a water reservoir in the upper side. Water from this reservoir will be used at will via a duct that leads to the turbine and is then delivered back to the river. In Figure 3.16 is a scheme of this solution. As said before, this technology extracts the potential energy contained in the water, therefore more electricity is produced if larger volumes of water with higher elevations between the top of the reservoir and the inlet of the turbine are used. The power capacity using hydropower technology is ruled by the following equation.

$$\boldsymbol{P} = \boldsymbol{\rho} \times \boldsymbol{Q} \times \boldsymbol{g} \times \boldsymbol{H} \tag{3.2}$$

Where the output capacity, $\boldsymbol{P}$, depends on two intrinsic variables, the water density $\boldsymbol{\rho}$ that varies little, and the gravitational acceleration constant $\boldsymbol{g}$. The other two variables are determined by characteristics of the river, the dam's location and size will determine the height of the water drop $\boldsymbol{H}$ and the operator will control, in part, the volumetric water flow rate through the turbine $\boldsymbol{Q}$ (Breeze, 2018b). Again, the blades of the turbine will extract the energy contained in the water and convert it in mechanical energy making the shaft, connected to a generator, rotate. This generator will then convert this energy in electricity.

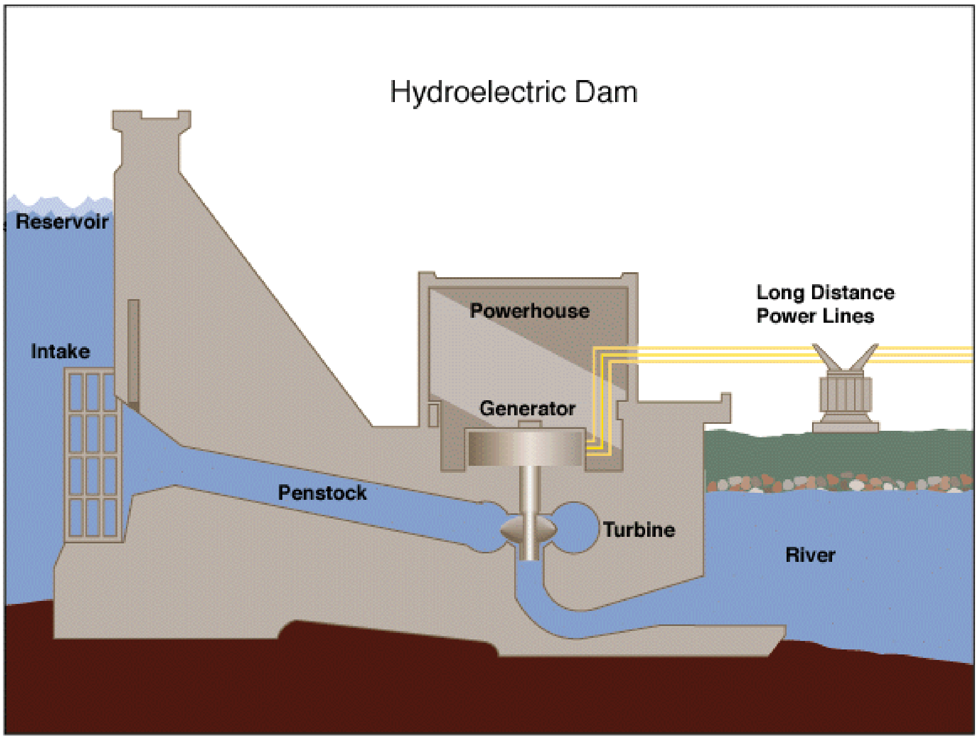

Figure 3.16 - Layout of a typical large hydroelectric power plant (EIA, 2019)

Reservoir hydroelectric power plants achieve a relatively constant power output as the water reservoir enables to operate with a relatively constant water flow, do not produce any gases, however, the resources used depend on precipitation and have to be carefully managed to allow other activities that depend on this resource to satisfy their needs. On the other hand, this solution is capital intensive and drastically influences the habitat where is located, sometimes requiring the displacement of indigenous population.

Other popular solution is the pumped storage hydroelectric power plant. This technology is equipped with hydro turbines that can work as pumps. This way, when electricity demand is low, water is pumped to the upper reservoir to be reused when electricity demand is higher. This technology serves the same purpose as a battery and is of great use in integrating renewables in the electric grid (Belyakov, 2019b).

Lastly, the run-of-river concept is used in small hydroelectric power plants. This solution consists of a small barrier, although it does not block the flow of the river as is the case with the reservoir dam, instead it diverts a portion of the river stream to a powerhouse after which it returns to the river. This technology can be implemented in rivers with relatively low water flows and its impacts on the habitat are considerably lower than the other solutions (Killingtveit, 2014).

3.2.2 Wind energy

Wind is a form of solar energy. The solar radiation unevenly heats the atmosphere, that together with the rotation of the earth creates wind flows. However, wind varies greatly in intensity and direction with time and location (US Department of Energy, n.d.).

The technology to extract energy contained in the wind using turbines was developed in the middle of the 20th century and started to be vastly implemented in the beginning of the 21st century, with Europe in the frontline. Soon after, other countries saw success in this technology and started to implement it as well. Therefore, since the beginning of the current century, electricity generated and installed capacity started to grow at a considerable pace as seen in Figures 3.17 and 3.18, respectively. Also, in Figure 3.19 it can be seen the low capacity factor of this technology when compared to the ones abovementioned, mainly due to its intermittence associated with the unpredictability of wind flows. The values presented are total values considering onshore and offshore wind turbines.

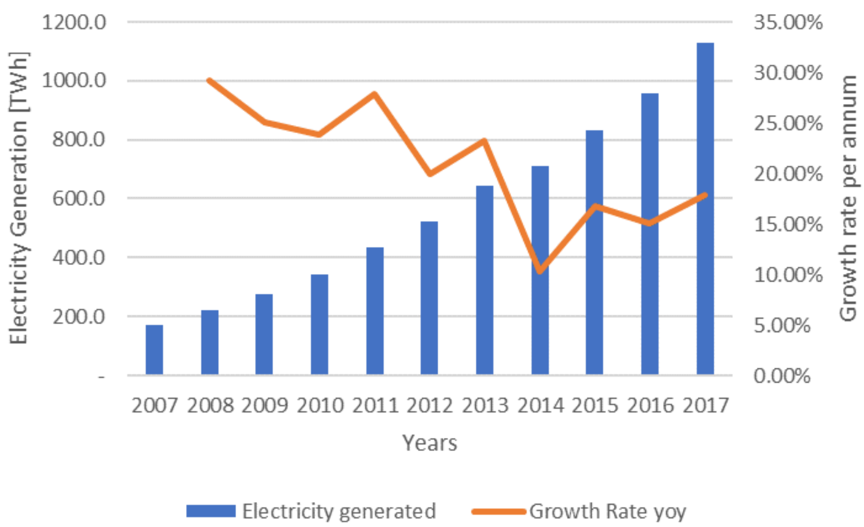

Figure 3.17 - Electricity generated by wind turbines (BP, 2019)

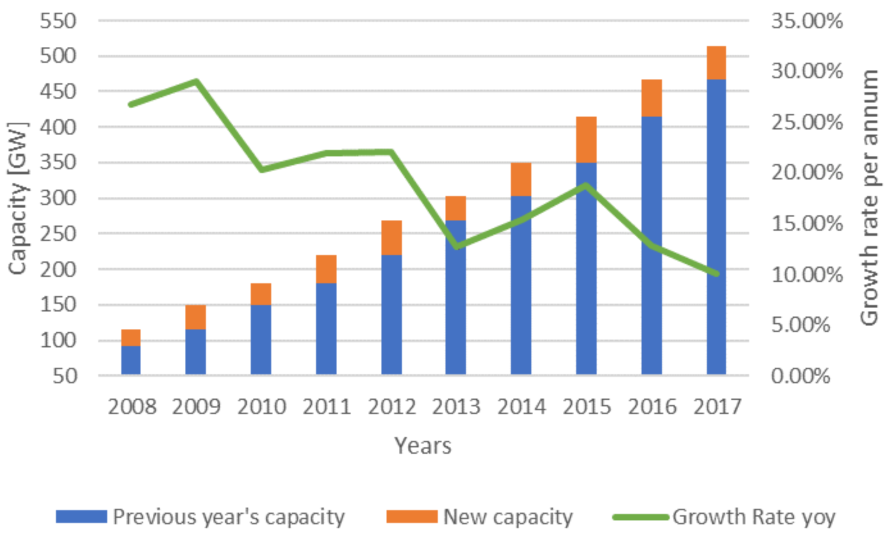

Figure 3.18 - Installed capacity of wind turbines worldwide (EIA, 2019)

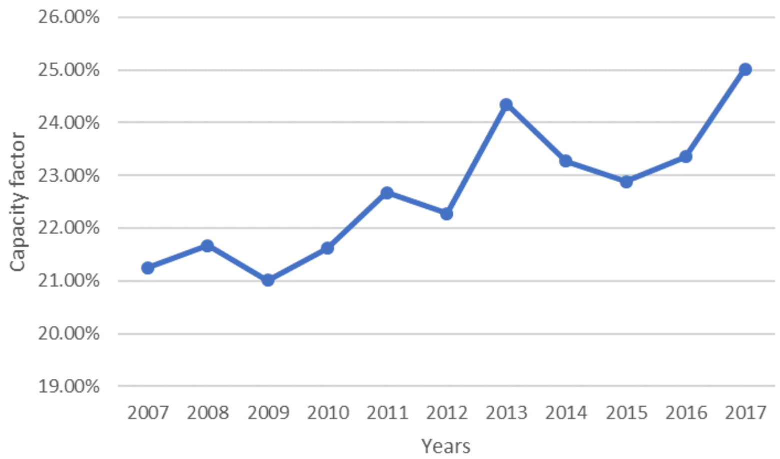

Figure 3.19 - Capacity factor of wind turbines worldwide

The growing capacity factor can be attributed to a diverse set of reasons, among those is a better assessment of locations to install wind turbines, another is simply from more windy years. In fact, wind availability is not constant, as such, there will always exist years with more availability and others with less. However, there are several wind previsions models that try to minimize the uncertainty of this resource using historical data from various sources (Deign, 2018).

Wind energy converter

The machine used to extract the energy contained in the wind is made of several components. The most visible is the wind turbine, composed by long blades that are driven by the air flow, this is the component that captures the wind energy and converts it in mechanical energy by driving a shaft at low speeds. This low speed shaft is connected to a gearbox that will multiply the rotation speed converting it in a high-speed rotation shaft that is connected to the generator. Figure 3.20 is a representation of the wind turbine and the components responsible for the energy conversion inside the nacelle.

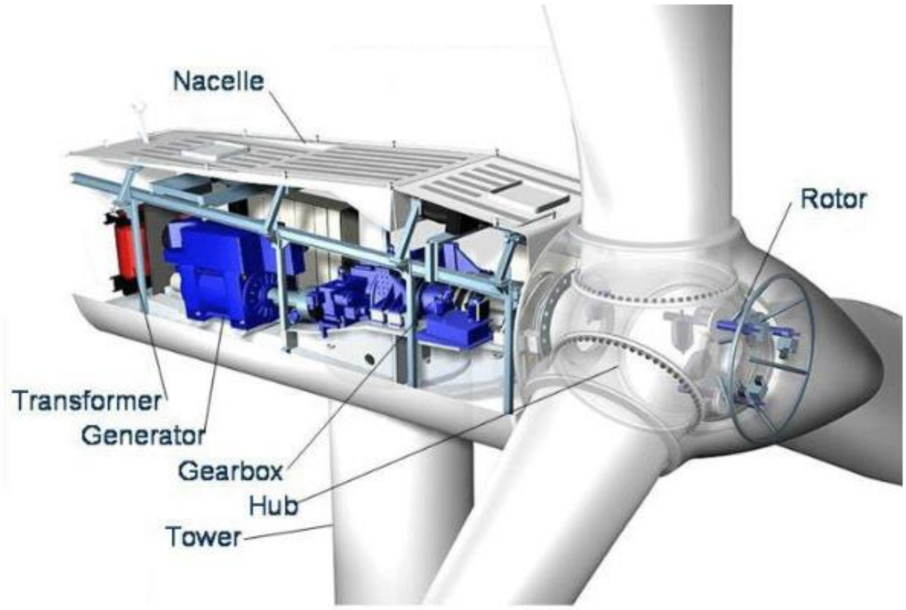

Figure 3.20 - Representation of a typical wind converter

The wind turbine and the nacelle are supported by a tower and inside the nacelle, there are motors responsible for rotating the group nacelle plus wind turbine in order to align the latter with the direction of the wind flow. This maximizes the extraction of the energy contained in the wind.

The power output of a wind turbine $\boldsymbol{P}$ is defined by the following variables:

$$\boldsymbol{P} = \boldsymbol{Cp} \times \frac{\mathbf{1}}{\mathbf{2}} \times \boldsymbol{\rho} \times \boldsymbol{V}_{\infty}^{\mathbf{3}} \times \boldsymbol{A_R} \quad (3.3)$$

Where $\boldsymbol{Cp}$ is a coefficient that represents the ability to extract energy from the wind and is a characteristic of the installed wind turbine, it is therefore, a measure of efficiency. $\boldsymbol{\rho}$ is the density of the air. $\boldsymbol{V}_{\infty}$ is the speed of the air flow in the swept area of the blades. This variable is cubed and therefore has a big impact on the power output of the wind turbine. Lastly is the swept area $\boldsymbol{A_R}$, that depends on the length of the blades used in the wind turbine. Wind turbines, to achieve higher power outputs, need a higher tower and longer blades to maximize both $\boldsymbol{V}_{\infty}$ and $\boldsymbol{A_R}$. One of the biggest wind turbines in the world has a nominal capacity of 12 MW, a rotor with 220 meters of diameter and a tower with a height of 260 meters (Ganguly, 2018; General Electric, 2019).

To understand the intermittence of electricity generation associated with wind turbines it is necessary to further explore the influence of air speed. In Figure 3.21 there is a chart with the typical relation between air speed and power output in a wind turbine.

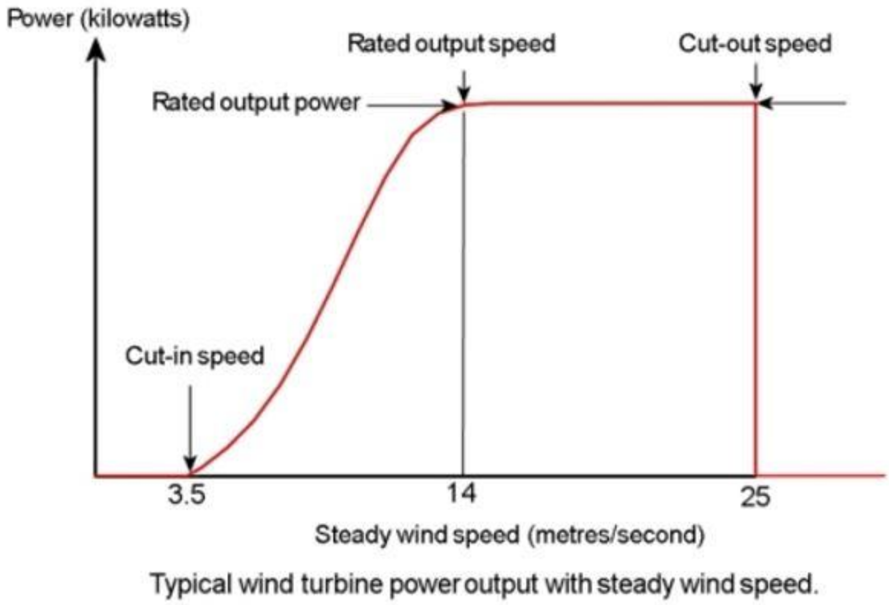

Figure 3.21 - Relation between air speed and power output of a typical wind turbine (Dvorak, 2017)

It is visible from Figure 3.21 that the optimum wind speed is between 14 and 25 m/s, more than this leads to possible structural problems or even an overheating of the generator, therefore the emergency system is activated, stopping the wind turbine. Less than 3.5 m/s will not be able to rotate the blades, and between this speed and the optimum value the power output increases almost linearly with an increase in the wind speed. This way, for a wind turbine to achieve a capacity factor of 100%, the wind would need to always flow at a speed within the optimum values when the wind turbine is operating (Beig and Muyeen, 2016).

3.2.3 Solar photovoltaic

Photovoltaic technology converts solar energy directly into electricity. It was developed in the middle of the 20th century but only started to be used in a larger scale in the beginning of the 21st century as it became more developed and economically viable. This technology depends on solar radiation, which is a plentiful and democratic resource, the sun shines in every single corner of the world. Furthermore, it is largely available in areas of the globe dominated by developing countries, which creates an opportunity for poorer economies to build up their energy security and capacity. Electricity generated using this technology has experienced a rapid growth as seen in Figure 3.22. Figure 3.23 shows the installed capacity of PV panels and Figure 3.24 the evolution of its capacity factor.

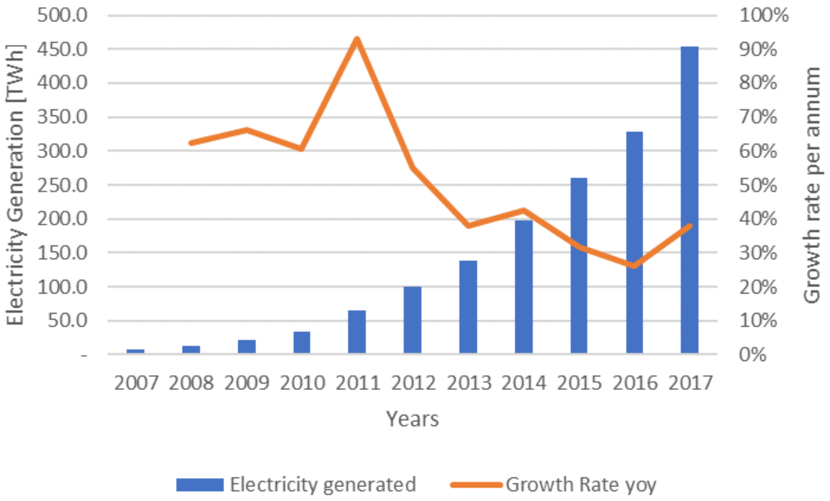

Figure 3.22 - Electricity generated from solar PV panels worldwide (BP, 2019)

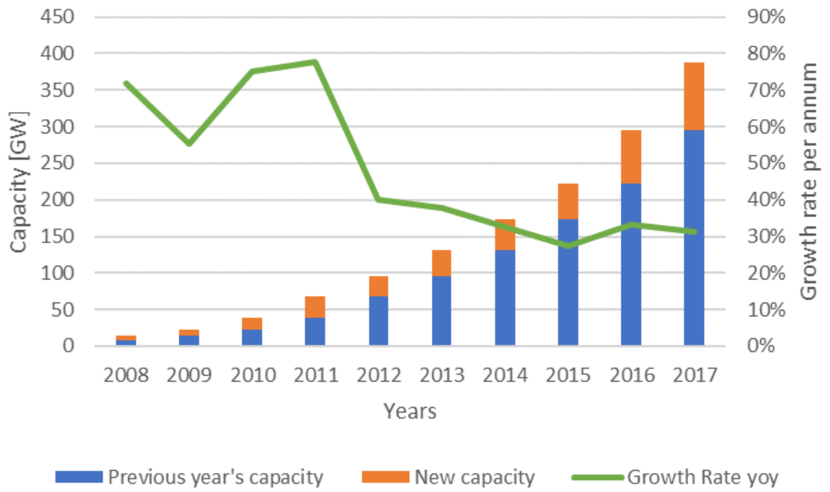

Figure 3.23 - Installed capacity of solar PV panels (EIA, 2019)

This technology is indeed experiencing a fast growth, the fastest among every electric power generation technology (IEA, 2020b). However, as observed in Figure 3.24, the capacity factor of PV systems is also the lowest of all technologies. PV panels do not generate electricity during the night and even when the sun is up the amount of electricity produced can vary significantly. The low capacity factor implies that to generate the same amount of electricity with photovoltaic panels when compared to other technologies, there is a need to have a considerable higher installed capacity of PV panels.

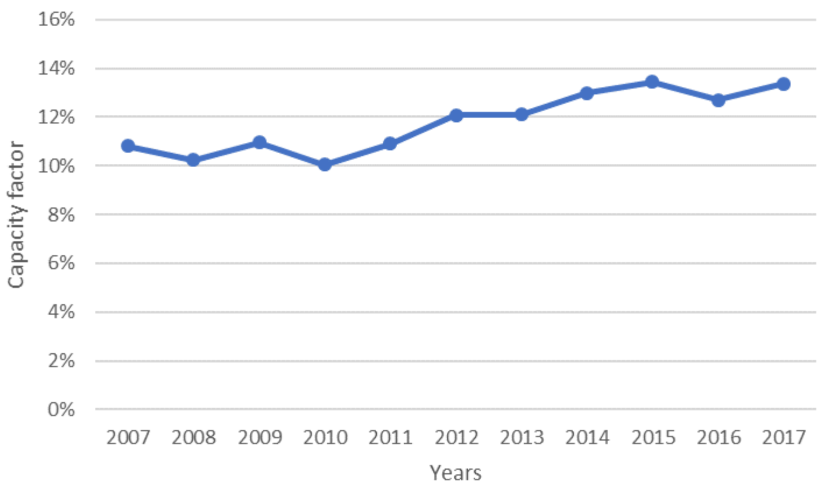

Figure 3.24 - Capacity factor of PV solar panels

This technology differs from all the others as it does not use a turbine nor a generator. This can be looked at as an advantage in that fewer moving parts usually mean less maintenance is required. Instead, photovoltaic cells are made of semiconductors such as silicon that absorb the energy contained in the photons of the incident solar radiation. The received photons, when containing enough energy, excite electrons that are expelled creating an imbalance and thus an electric field. The output is a direct current (DC), and as across most households the electricity consumed is alternate current (AC), an inverter is used to make this transformation (EIA, 2020).

Figure 3.25 - PV solar panel composed of several PV cells

The power output of a PV module depends on the incident radiation and the temperature of the PV cells. To better understand the relation between these variables and the power output it is important to remember the following relation,

$$\boldsymbol{P} = \boldsymbol{V} \times \boldsymbol{I} \tag{3.4}$$

The power output $\boldsymbol{P}$ depends on the voltage $\boldsymbol{V}$ and the current $\boldsymbol{I}$, therefore, to achieve a maximum power output it is important to maximize the product of these variables. An analysis on the influence of incident radiation and cell temperature in both these variables is very important to better understand how the power output of a PV module varies. In Figure 3.26 is the I-V curve and the corresponding power curve for a typical PV module at standard conditions of 1000 W/m^2 of incident radiation and a cell temperature of 25 ºC.

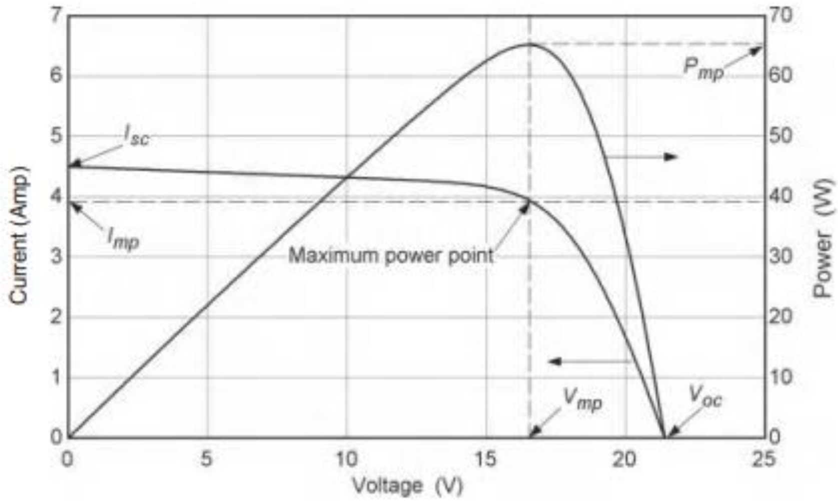

Figure 3.26 - Power curve of a typical PV module (Duffie and Beckman, 2013)

As observed, the maximum power point corresponds to a compromise between current and voltage. For the same PV module with the same incident radiation, the I-V curve changes with the temperature of the PV cell, as observed in Figure 3.27. In fact, although current remains similar, the open circuit voltage (maximum voltage) decreases with higher cell temperatures, and vice versa.

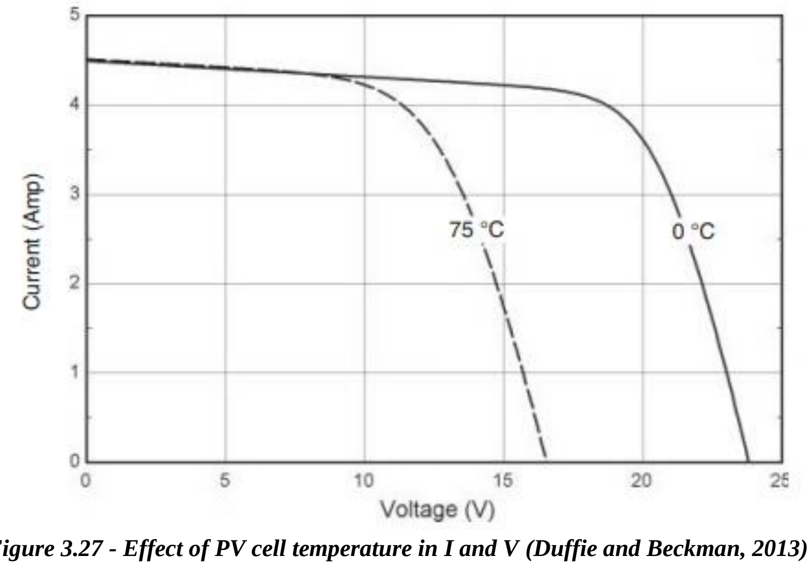

Figure 3.27 - Effect of PV cell temperature in I and V (Duffie and Beckman, 2013)

On the other hand, current is highly affected by incident radiation, as observed in Figure 3.28, with a similar PV module and a cell temperature of 25 ºC.

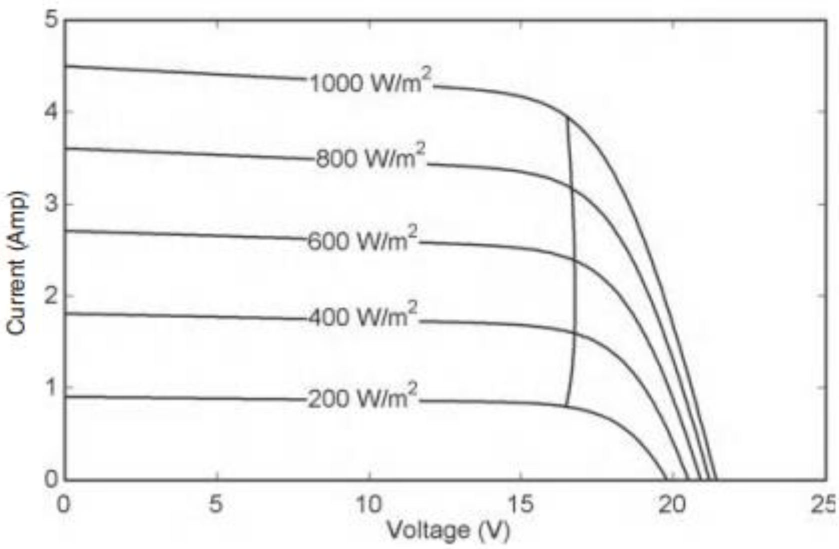

Figure 3.28 - Effect of incident radiation in I and V (Duffie and Beckman, 2013)

To achieve the highest power output possible, the most favourable conditions are a high incident radiation in cold environments. Warm climates will see a lower output and consequently less efficient PV modules due to the higher temperatures of the cells leading to lower voltages. When analysing a location to install PV solar panels both these variables need to be extensively analysed. Incident radiation varies greatly with location, meteorological conditions, and time. It will be higher with a clear sky and radiation perpendicular to the panel and will be null in the night-time. Cell temperature depends on the ambient temperature and the amount of incident radiation converted to heat in the PV panel (Duffie and Beckman, 2013; Solar Electric Power Company, 2018).

4. Environmental aspects of power generation

4.1 Global warming

Electric power generation using fossil fuels generates gases that have negative impacts on the environment. These can present themselves in different ways, either directly or indirectly, in the present or in the future, but in any case, consequences are real and severe.

Global warming is one of the main indirect impacts of burning fossil fuels. The increase of GHGs present in the atmosphere, responsible for trapping and absorbing solar radiation and then converting it into heat, contributes to higher temperatures being registered all around the globe. The main GHGs, produced mainly by human activity, are carbon dioxide (CO_2) and methane (CH_4), with others such as nitrous oxide (N_2O) and fluorinated gases (F-gases) representing a smaller, although not negligible, share of these gases in the atmosphere. Furthermore, one of the most important GHG is water vapour, this gas is essential to keep the earth at a temperature suited to human life. This gas is responsible for most of the greenhouse effect however, as it is considered a good and natural type of greenhouse gas it is not considered as GHG emissions. This is ruled by the water cycle so if the global temperature rises as a consequence of others GHGs emissions, more water will evaporate producing more water vapour thus creating a positive feedback that will accelerate the rise of global temperatures (IPCC, 2014).

Since pre-industrial times the world has already warmed by about 1 ºC due to the high level of human activity, derived substantially from energy related activities associated with burning fossil fuels (Allen et al., 2018). In 2015 the Paris agreement was outlined and agreed upon by 197 countries. The signed document clearly states in article 2 the goal to keep the global average temperature below 2 ºC and an effort to push this limit to 1.5 ºC relative to pre-industrial levels (United Nations, 2015). Failing to meet such targets poses a threat to the current way of life. Heavy rainfalls, wildfires, melting ice sheets and glaciers and an increased sea level rise are some of the consequences from the increase of the global average temperature. Also, global warming is an inequality amplifier, affecting poor populations in a more intense and direct way.

The warming effect of greenhouse gases varies with their capacity to absorb energy and their lifetime in the atmosphere, as such, in order to compare global warming impacts of different GHGs the global warming potential (GWP) was developed. This method compares the warming potential of different GHGs in relation to CO_2 over a certain period, in particular, how much energy one ton of a certain gas will absorb compared to 1 ton of CO_2. This metric is widely used to assess the global warming effect and the 100 years' timeframe was adopted by the United Nations Framework Convention on Climate Change (UNFCCC) and its Kyoto Protocol. In Table 4.1 are the GWP values of some of the main GHGs both in a 20 (GWP_{20}) and 100 (GWP_{100}) years' timeframe as well as the lifetime of the GHG in the atmosphere.

Table 4.1 - GWP and atmospheric lifetime of most common greenhouse gases (IPCC, 2014)

Gas	Formula	Atmospheric lifetime (years)	GWP 20 Years	GWP 100 Years
Carbon Dioxide	CO_2		1	1
Methane	CH_4	12.4	84	28
Nitrous Oxide	N_2O	121	264	265
Perfluoromethane	CF_4	50000	4880	6630

In fact, GHGs with a shorter lifetime will have a higher GWP if a shorter timeframe is considered. An example of this situation is the GWP_{20} and GWP_{100} of methane. This gas has a short lifetime in the atmosphere therefore its effects on global warming are more intensively felt in the short-term. In contrast CO_2 is believed to remain in the atmosphere from centuries to thousands of years resulting in a GWP equal for all timeframes. Other gases such as N_2O and most F-gases absorb more energy when compared to both CO_2 and CH_4 and their atmospheric lifetime varies considerably from gas to gas. Although CO_2 is the GHG that absorbs the least amount of energy per unit of gas, it is responsible for the majority of the GHGs emissions as it is produced in great amounts. As of 2010, CO_2 represented 72 % of all GHGs emissions using a GWP_{100}, with 62 % related to fossil fuels and industrial processes and 10 % to forestry and other land use (FOLU). Methane represented 20 % of all GHGs and the remaining share is attributed to N_2O and F-Gases, all using a GWP_{100} (IPCC, 2014).

Most of the GHGs emitted in the electricity sector are CO_2 and CH_4. CO_2 is produced when burning fuels that contain carbon and the amount of emissions depends on the carbon content of the fuel as well as on the efficiency of the power plant. On the other hand, CH_4 is not produced through a combustion process, instead it is unwillingly emitted along the supply chain of the different fossil fuels (Kholod et al., 2020; Alvarez et al., 2018).

The power sector has a key role to play in climate mitigation. This sector is one of the energy related areas with viable, mature, and cost competitive solutions to decarbonize the energy sector. Furthermore, other energy related activities such as transportation are following the trend of electrification paving the way for a faster decarbonization of a sector that is currently dominated by the carbon intensive fossil fuel that is oil.

4.2 Air pollution

One of the more directly felt impacts of burning fossil fuels to produce electricity is the air pollution caused by some gases produced in the combustion process. Among those it is important to highlight the negative impacts of the SO_2, NO_x and PM. The first is released when fuels containing considerable amounts of sulphur in its composition are burned and is responsible for acid rains that can contaminate aquatic systems and forests. NO_x is produced at high temperature combustions and also contributes to acid rains. Nitrogen dioxide (NO_2) is a type of nitrogen oxide responsible for health complications, namely several pulmonary diseases. Particulate matter (PM) is a mixture of extremely small particles made of different components that usually fall under two different categories. PM_{10}, that have diameters between

2.5 and 10 micrometres and $PM_{2.5}$ that have diameters smaller than 2.5 micrometres. The smaller ones are the ones emitted in greater amounts in power plants and are particularly dangerous to human health as they easily penetrate sensitive areas of the respiratory tract. The negative externalities caused by air pollution are vast and among those, health implications are of special concern as several premature deaths are attributed to this pollution. It is estimated that ambient air pollution kills about 3 million people annually, affecting more intensely areas such as the South East Asia and Western Pacific regions (World Health Organization, 2016).

5. Comparing electric power generation technologies

5.1 Coal and natural gas fired power generation

All technologies presented in Chapter 3 have a series of positive and negative characteristics associated. A basic overview of the fossil fuel powered technologies and renewables can be made to better understand those characteristics.

The advantages of fossil fuel powered power plants, among others, are their reliability, predictability of its output, the possibility of adjusting its load and the need of small areas of terrain for a power plant with a high installed capacity. On the other hand, there is a great number of disadvantages such as the reliance on fossil fuels that are scarce, finite, and heterogeneously distributed worldwide. Also, as said on Chapter 4, there is a great number of negative externalities associated with the gases produced on the combustion of the fossil fuels. However, as explained on Chapter 3, not all fossil fuels are equal which makes it important to analyse the differences between each other. In this case, since the subject at hand concerns electric power generation, where the most used fossil fuels are coal and natural gas, a focus will be given to both these fuels. Considering the most advanced technologies announced on chapter 3 the CO_2 intensity for each technology can be obtained, as observed in Table 5.1. The values for the low heating value (*LHV*) and emissions factor are from Pinho (2017).

Table 5.1 - CO_2 emissions per MWh of coal and natural gas fired power plants

	Coal	Natural Gas
LHV [MJ/kg]	25.8	45.1
Emissions Factor [kgCO_2/GJ]	94.5	64.1
Efficiency [%]	44	60
Emissions per unit of electricity [kgC0_2/MWh]	773.2	384.6

Moreover, when burned, natural gas emits NO_x, SO_2 and PM on the order of 10 %, 1/682 and 1/1479 of those emitted when burning coal (Zou et al., 2018). Natural gas emits less CO_2 and air pollutants than coal when burned, however, this gas faces a lot of criticism due to methane leakages on the exploration and transportation process. As mentioned in Chapter 4, methane has a bigger impact on global warming than CO_2, therefore it is important to account the leakages of methane along the natural gas and coal supply chains in order to find the real emissions of CO_2eq per unit of electricity attributed to each type of power plant. To analyse this a lot of measures and estimates of methane leakages have been made, however, these vary a lot and their uncertainties are high. The International Energy Agency has estimated that when considering the full lifecycle emissions of coal and natural gas, including methane emissions, the latter produces on average 50 % less CO_2eq emissions than coal when used to generate electric power. Furthermore, since burning natural gas emits considerably less air pollutants than coal it is estimated that accident and air pollution related deaths from using natural gas to produce electricity are around 10 % of those associated to coal per unit of electricity produced (Markandya and Wilkinson, 2007).

This way natural gas can play an important role in integrating a higher share of renewables in the grid while phasing out the use of high GHG emitters such as coal, and it can also play a role in integrating new non fossil forms of energy, namely biomethane or the so called green hydrogen. The technology for this invisible fuel is mature, readily available and cost competitive.

This fuel is already used in electricity generation to a large extent in developed countries. In most of the Asia-Pacific region, however, this fuel represents a negligible share of the power mix. This region has a high domestic production of coal and only a few countries are significant natural gas producers. Therefore, imports are a main driver of the natural gas supply. This resulted in the highest prices of natural gas being traded in this part of the globe, and a heavy dependence on supplies from other countries, which makes the use of natural gas a less attractive transition fuel. Despite this, current events are moulding a new reality. The US shale gas boom began a new liquified natural gas (LNG) era, making pressure on other natural gas producers to accelerate their LNG trade. This competition puts stress on prices and increases the number of exporting countries, two factors that are beneficial for Asia-Pacific countries that rely heavily on imports. Moreover, the current COVID-19 pandemic, made oil prices achieve historic lows and, as natural gas prices in this region are mostly oil-indexed, this fuel also followed the trend. This created a window of opportunity to affordably increase the use of natural gas fired power plants to transition away from coal and increase the share of renewables while providing existing electric grids with the required flexibility (Mcglade et al., 2014; Grigas, 2017; IEA, 2020c)

Although there is some room for natural gas power generation to grow, new generation capacity must be meticulously calculated, due to the risk of locking GHGs emissions in the long term. A typical CCGT power plant takes 2-3 years to build and has a typical operational lifetime of 30 years, therefore, new projects will operate until 2050. In contrast a coal-fired power plant usually takes 4 years to become operational and has a lifetime of 40 years, thus the urgency of cancelling all coal projects on the pipeline and new ones in order to meet the goals established on the Paris agreement (IEA, 2020a).

Countries that have a large coal-fired power plants fleet and are still building new ones have diverted a lot of attention to Carbon Capture and Storage (CCS) technologies that capture close to 90 % of the CO_2 emissions present on the flue gases of a power plant and then inject the captured carbon in old oil and gas wells. This technology is not yet mature, it is still not economically viable, and it is power consuming which results in a decrease in the power plant efficiency, therefore more fuel must be burned to achieve the same power output. To date there are two large-scale CCS power projects installed in coal-fired power plants, Petra Nova in the United States, and Boundary Dam in Canada. These projects cost over one billion dollars each, together have a capture capacity of 2.4 Mt of CO_2 per year, and this CO_2 is used in enhanced oil recovery (EOR) (Jenkins, 2015; Preston et al., 2018) . Although this technology has been receiving funding and being advertised as one of the main solutions to offset CO_2

emissions in the short to mid-term, to comply with the Paris Agreement, it also faces a lot of scepticism regarding the safety of the underground containment of CO_2 that will be subjected to the tectonic movements of the earth's upper crust (Zoback and Gorelick, 2012).

5.2 Levelized Cost of Electricity

It is important to compare the costs of each electric power generation technology to better understand its viability. To make this comparison the Levelized Cost of Electricity (LCOE) is used and represents the price at which the operator of a project needs to sell its electricity to breakeven on its investment. This metric accounts for capital costs, fuels costs, fixed and variable operations and maintenance (O&M) costs, financing costs and an assumed utilization rate for each technology. For projects such as hydro, wind and solar electric generation technologies, there are no fuel costs and O&M costs are small, instead, the LCOE of these technologies relies heavily on capital and financing costs. On the other hand, fossil fuelled power plants have lower initial capital costs but fuel and O&M costs throughout the lifetime of the power plant represent the largest portion of the costs. Figure 5.1 shows the range of LCOE for different technologies worldwide.

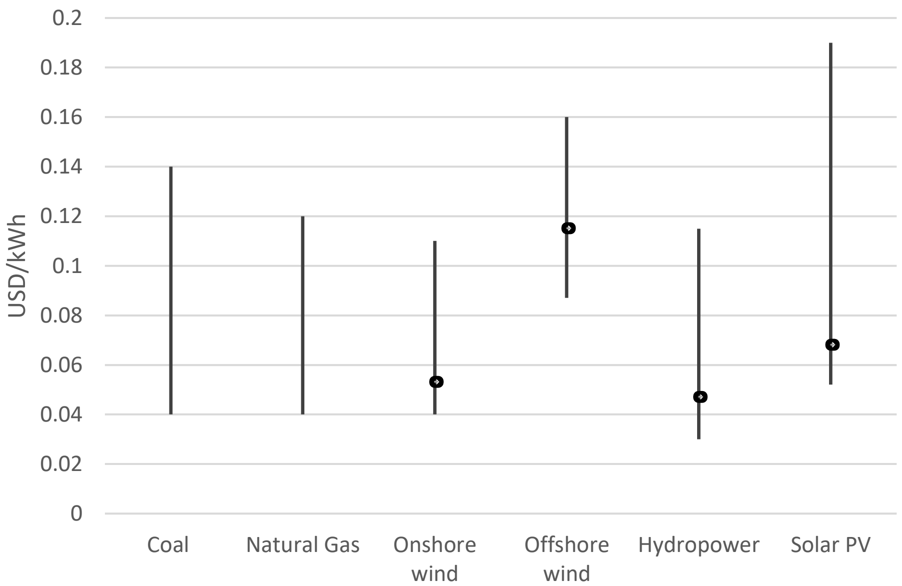

Figure 5.1 - LCOE interval of different electric power generation technologies (Belyakov, 2019; IRENA, 2020)

From Figure 5.1 it is clear that all renewables are cost competitive with electric power generation from fossil fuels. The dot on the interval line of the renewable technologies represents the weighted average LCOE for that technology. It is worth to highlight that coal-fired power plants with the lowest LCOE are mostly located in the Asia-Pacific region, and hydropower, onshore wind and solar PV projects with the lowest LCOE are found in China and India (IRENA, 2020).

It can be noted that even without accounting all the negative externalities associated with burning fossil fuels, renewable projects are already competitive and, in some cases, cheaper than fossil fuelled electric power technologies. As such, the challenge of increasing sustainability and decarbonising the electricity sector can no longer be justified by the costs of renewables (IRENA, 2020).

6. Coal phase-out success story

Most countries once relied heavily on coal to generate electricity, however, nowadays, this fuel is experiencing a decline, especially in developed countries, with a group of countries leading the way on phasing it out almost entirely of the power mix. A good example of such a country is the United Kingdom (UK). The land where the industrial revolution took place and once the biggest producer and consumer of coal has committed to phase out coal fired power generation completely by 2025. However, in 1990 coal represented a share of roughly 65 % of the electric power mix. Therefore, this case study can be used to extract some conclusions and to better understand the effect of different policies in promoting this phase out (Littlecott et al., 2018). In Figure 6.1 is represented the evolution of the UK power mix and in figure 6.2 the electricity demand from 1990 to 2018.

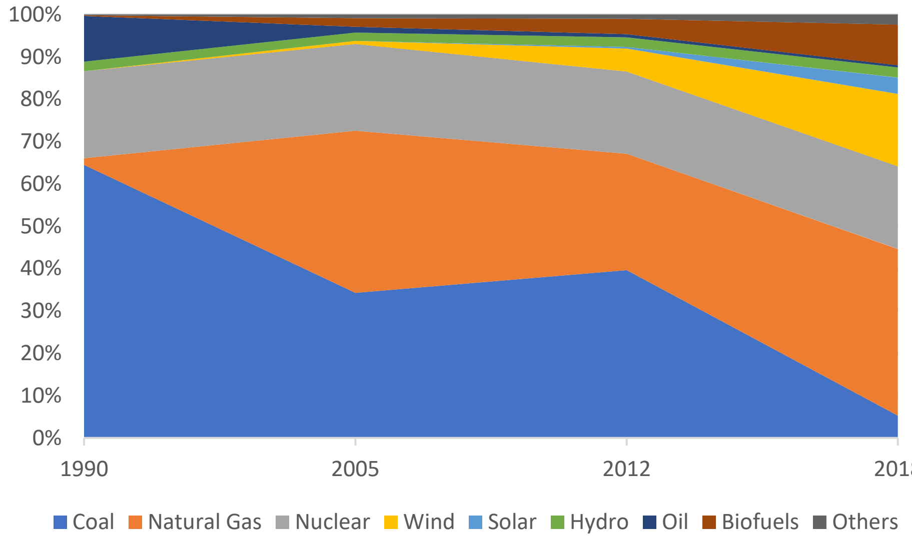

Figure 6.1 - Evolution of the UK power mix (IEA, 2019)

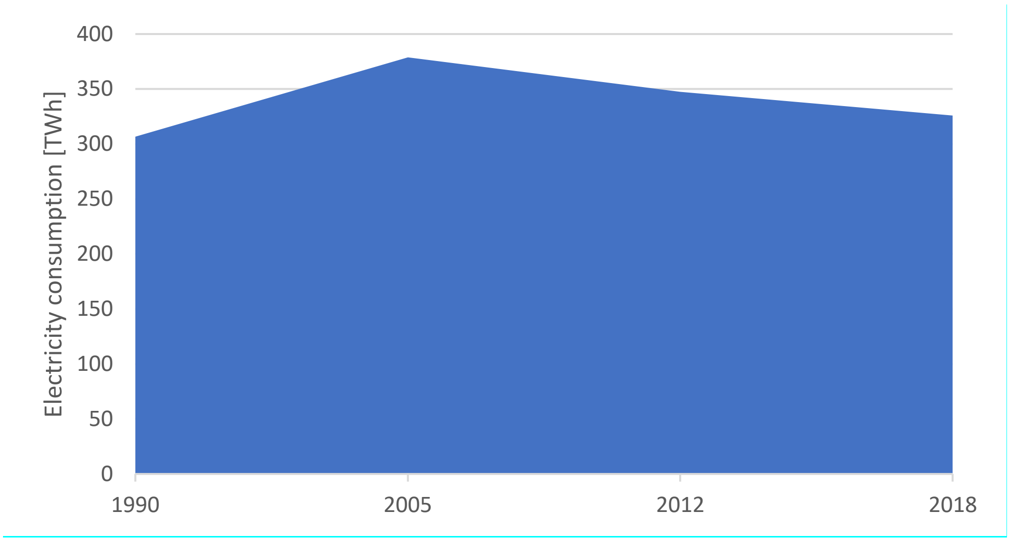

Figure 6.2 - Evolution of the electricity consumption in the UK (IEA, 2019)

In 1991 the European Union (EU) lifted restrictions on using natural gas for power generation, and with a domestic offshore oil and gas industry in the North Sea, natural gas supply was plentiful in the UK, promoting a switch of a considerable share of the power mix from coal to gas. Furthermore, the electricity sector had just been privatized in 1990, and since gas fired power plants require less initial investment than coal, several companies opted for the cheaper option (Littlecott et al., 2018).

The period from 2002 to 2009 saw high prices of natural gas, which promoted investments to prolong the life of existing coal power plants (at this stage most of the coal power plants had already surpassed 30 years of operation). In this period, it was suggested to build new and modern coal power plants to replace old and inefficient ones. However, with the passage of the UK's climate change act in 2008, that introduced multi-year carbon budgets and advised that any new coal fired power plants would need to be retrofitted with CCS by the early 2020's, in order to comply with those carbon budgets, resulted in none of the proposed projects to be implemented.

From 2008 onwards several coal power plants were closed in part due to tighter pollution control standards, in particular because of a EU legislation, the large combustion plants directive (LCPD), that required all coal power plants to be installed with flue gas desulphurization (FGD) technologies by 2015. Another policy that contributed to make coal power less economically viable was the start of the EU emissions trading scheme (EU ETS) in 2005. This policy intended to put a price on carbon emissions. However, the price of CO_2 emissions remained relatively low which resulted in an insignificant influence on the economics of coal and gas fired electric power generation. To compensate this, in 2013, the UK carbon price support (CPS) was introduced with the purpose of increasing the price of CO_2 emissions and therefore discourage the use of fossil fuels that emit high amounts of CO_2. This policy had a big impact on the economics of coal power generation, making it unattractive for operators (Littlecott et al., 2018). This impact can be observed in Figure 6.1 by the drop of almost 30 % of the share of coal in the power mix since this policy was put in place.

Moreover, several policies were implemented aiming to promote low carbon technologies such as feed-in-tariffs and contracts for difference. These played an essential role in promoting wind and solar energy when costs were still not competitive with fossil fuelled power generation.

As such, coal capacity fell from 23 GW in 2012 to 13 GW in 2017, mainly due to the LCPD, which would require significant investments to be made on the already old coal power plant fleet, and to the high price of CO_2 that put coal fired power plant operators under pressure and struggling to achieve profits. The decline of the coal share of the power mix was replaced mainly with renewables such as wind, solar and biomass and with natural gas fired power generation (Littlecott et al., 2018).

The UK proved that coal can be phased out of the power mix in a relatively short timeframe if serious commitments are made, especially when taking into consideration the negative externalities of fossil fuel combustion. Moreover, policies that promoted the competitiveness of low carbon technologies have been of great importance to level the playing ground on the costs of electricity. Although throughout the second decade of the 21st century, costs of modern renewables, in particular solar and wind have experienced a sharp decline making a stronger case against fossil fuel powered electricity generation.

The UK power grid is a lot more flexible today, in part due to the relatively small share of inflexible technologies that are more suitable to be used at a constant output, such as nuclear and coal powered technologies that together accounted for 25 % of the power mix in 2018. The remaining share is composed of mainly CCGT power plants that are used as baseload or as peak generation providing the grid with the required flexibility to better integrate intermittent technologies such as wind and solar, that together represent 22 % of the power mix as of 2018. Furthermore, connectivity with neighbouring countries is being used to increase the flexibility of the grid. As of 2018, 4 GW of electrical interconnectors are in operation, connecting the UK with four countries, representing a share of roughly 5 % of the total generation capacity. Several projects are being discussed to increase connectivity with neighbouring countries and it is projected that in 2025 the UK will have 11 GW of interconnectors linking it to a total of seven countries (Office of Gas and Electricity Markets n.d.). The interconnection with neighbouring countries is of great relevance because it allows countries to explore each other’s resources, in particular natural ones. This way more flexibility is provided to the electrical grid of a country allowing to compensate for periods of peak demand or low electricity production of renewable sources (European Union, 2015).

This success case of coal phase out can be used to understand the effect of different policies in increasing the sustainability of the electric power sector. Although conclusions have to be interpreted in a case-by-case assessment because different countries, especially developed and developing ones face different challenges, the abovementioned policies ought to be scrutinized in order to better comprehend their impacts. Nonetheless, one main conclusion that can be extracted from such a success story is that a decarbonisation commitment must come from governments. In fact, the UK government understood the urgency of economy decarbonisation and found a fast track to implement it in the electricity sector announcing in 2015 that coal fired electric power generation will be phased out entirely by 2025 including with CCS (Department for Business Energy & Industrial Strategy 2020). Such an announcement sat the future trend of the electricity sector in this country providing the private sector with essential information to better decide on future investment decisions.

7. National policies for increasing sustainability of electricity generation in China

To increase the sustainability of the electricity sector, renewables must be widely adopted, and to meet the Paris agreement, they must be installed at a faster pace while decommissioning the biggest contributors of CO_2 emissions. Therefore, coal phase out in the electricity sector is a topic of important relevance today. As was mentioned along the report, coal fired power plants are responsible for the biggest carbon footprint of any energy related sector. This chapter will give an overview of the countries of the Asia Pacific region that have a significant share of electricity generated from coal, and then make a deep dive on the electricity sector of China as well as making a collection of the latest policies related to electricity generation implemented by the Chinese government.

Coal dominates the electric power generation sector worldwide, representing 38 % of the electricity production as of 2018 (IEA 2019a). However, this reality changes abruptly when it comes to the Asia-Pacific region where a share of roughly 52 % of the electricity comes from burning coal. Composed mainly by developing countries, this part of the world is home for 60 % of the world's population, which combined with a high domestic supply of coal and constantly increasing electricity demand, made the use of this resource on the electricity generation sector both attractive and straightforward. Figure 7.1 shows the countries of the Asia-Pacific region with more than 30 % of electricity generation from coal.

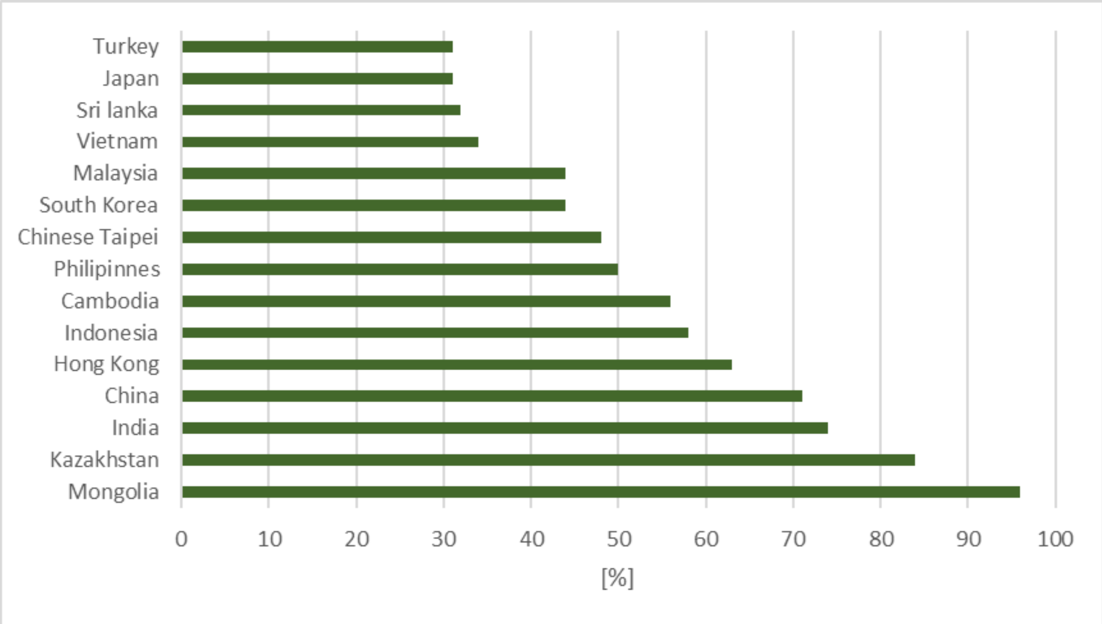

Figure 7.1 - Share of electricity generated from coal in countries of the Asia-Pacific region with a share larger than 30 % (IEA, 2019)

China produces more electricity than any other country. As of 2018 it consumed 7111.8 TWh of electricity from which 66.5 % or 4732.4 TWh came from burning coal. The remaining share is produced mainly by hydropower and modern renewables such as wind and solar PV. Figure 7.2 shows the electricity generation mix as of 2018 and Table 7.1 the trends of electricity generation from different sources.

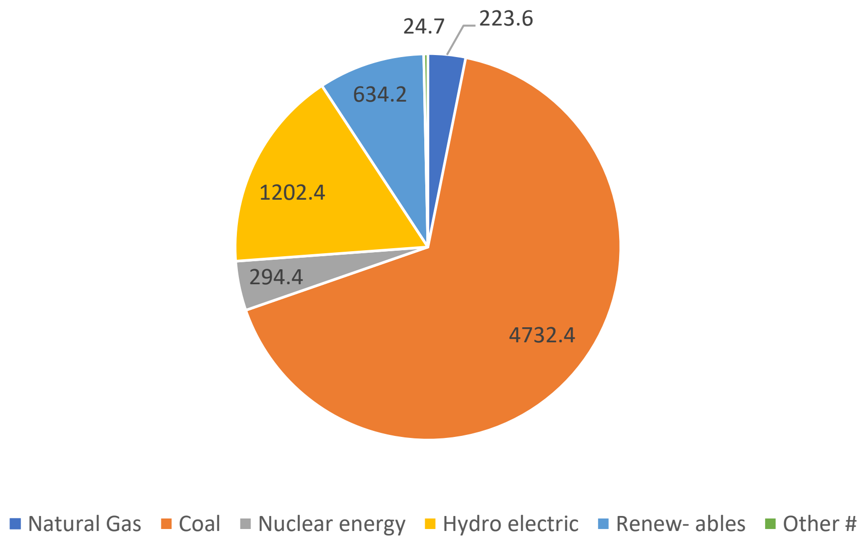

Figure 7.2 - Electricity generation mix of China in 2018, values in TWh (IEA, 2019)

Table 7.1 - Trends of electricity generation in China (IEA, 2019)

	Year 2000 [TWh]	Year 2017 [TWh]	Relative growth	Absolute growth [TWh]	Average growth year on year
Coal	1,060	4,485	323 %	3,425	9 %
Natural gas	6	183	3072 %	177	23 %
Nuclear	17	248	1382 %	231	17 %
Hydropower	222	1,157	420 %	935	10 %
Modern Renewables	0.644	426	66006 %	425	47 %
Other	50	103	106 %	53	4 %
Total	1,356	6,602	387 %	5,246	10 %

Electricity demand has grown at a fast pace, as observed in Table 7.1. This is explained mainly by the growth of the industry sector that grew more than 400 % since 2000 and as of 2017 it represents more than 55 % of all electricity consumption in China. Other sectors such as residential and commercial and public services also grew considerably, however, they represent a considerable smaller share of electricity demand when compared to the industry sector (IEA, 2019a).

Coal has been the fuel of choice used to meet most of the electricity demand growth in China. This use is in part due to the large production of domestic coal, the combination of a predominantly state controlled coal mining and transportation sector allied with a public electric sector which allows electricity prices to be kept low. During the 21st century, China has continuously set ambitious GDP targets, which resulted in higher energy consumption across all sectors. Electricity plays a great part on this economic growth, and China now provides electricity access to 100 % of its population (World Bank, n.d.). However, as discussed before, coal-fired power plants are the most prejudicial to the environment out of all the electric power generation technologies. This extensive use of coal in electricity generation has, on recent years, resulted in approximately 11 % of global CO_2 emissions coming from Chinese coal-fired power plants (César et al., 2018). Moreover, in 2018 China had roughly 1000 GW of coal-fired power plants installed capacity, having experienced an average addition of 50-60 GW each year between 2006 and 2016. Since then, the growth has slowed to roughly 30 GW in 2017 and 2018 (Sandalow, 2019).

Natural gas use in China has experienced a significant growth since the beginning of the 21st century. In fact, as of 2018 China is the third largest consumer of natural gas, only behind the USA and Russia. However, most of this resource is used in industry and residential and commercial buildings, with only around 20 % of natural gas consumption being used in electric power generation. Although natural gas use in the power sector has grown significantly from 2000 to 2017, this is still very low, with the electricity generation from natural gas as of 2018 representing only about 3 % of total electricity generation (IEA, 2019a). Despite this, natural gas has been used to displace coal-fired power generation in some provinces, mainly motivated by high levels of air pollution, as was the case in Beijing, where the last large coal-fired power plant was suspended in 2017 and the electricity generated in thermal power plants now comes from burning only natural gas (Chen, 2017).

Hydropower is the most used renewable energy in China. In fact, China has more installed capacity of hydroelectric power plants than any other country, with roughly 28 % of all installed capacity worldwide. At the end of 2018 it had 352 GW of installed capacity producing roughly 17 % of all its electricity generation (IEA, 2019b; Sandalow, 2019).

Among modern renewables, the two most representative technologies are wind and solar energy. The first had, as of 2018, an installed capacity of 185 GW, representing roughly 5 % of the electricity generation mix and 10 % of installed electric power capacity. In 2018 alone, China added 20 GW of new wind energy capacity, confirming its role as the leader in wind power deployment (China Energy Portal, 2019).

Solar power, in particular solar PV, representing 99 % of total solar power installed capacity in China, has experienced a continuous fast growth. In 2018, it had 175 GW of installed capacity, producing roughly 3 % of all electricity generation and accounting for 9 % of all installed power capacity (National Energy Administration, 2019). 2018 was the first year that a solar project sold electricity cheaper than the benchmark price of electricity from coal-fired power plants (Sandalow, 2019).

Nuclear power had an installed capacity of roughly 40 GW as of 2018 and China is by far the country that installed more nuclear power capacity in the last five years. As of 2018 this technology represented 4 % of the electricity generation. Moreover, the Chinese government plans to expand the use of this technology because it allows to offset carbon emissions while producing electricity at a constant output (IEA, 2019a; Sandalow, 2019).

In Table 7.2 there are some of the targets sat by the Chinese government related to the energy and electricity sector that aim to increase the country's commitment with climate mitigation.

Table 7.2 - Policies related to the energy sector to promote climate mitigation

Document	Target	Observation
China's Energy Supply and Consumption Revolution Strategy 2016-2030	Peak CO_2 emissions must occur in 2030 or earlier	As committed in the nationally determined contributions (NDC)
	By 2050, more than 50% of primary energy consumption to come from non-fossil energy	
	By 2030, 50% of total electric power generation to be from non-fossil sources	
	By 2030, at least 20% of total primary energy consumption to come from renewable sources	

Table 7.3 presents a collection of policies published by the Chinese National Energy Administration (NEA) related to coal-fired power plants.

Table 7.3 - Collection of most relevant policies related to coal-fired power plants

Document	Target	Observation
China's Energy Supply and Consumption Revolution Strategy 2016-2030	By 2030, 80% of the coal fleet to be ultra-low polluting coal-fired power plants	
Strategic Action Plan for Energy Development (2014-2020)	By 2030, 80% of the coal fleet to be ultra-low polluting coal-fired power plants	
13th Five Year Plan (2016-2020)	Coal fired power installed capacity in 2020 under 1100 GW	
Mid-term Evaluation and Optimization of the "Thirteenth Five-Year Plan" for Electric Power	Coal fired power installed capacity in 2030 under 1300 GW	

The following Tables 7.4, 7.5, 7.6 and 7.7 present the policy documents that determine the installed capacity targets until 2020 for natural gas fired power plants, hydro, wind, and solar power respectively.

Table 7.4 – Most relevant policy related to natural gas fired power plants

Document	Target	Observation
Mid-term Evaluation and Optimization of the "Thirteenth Five-Year Plan" for Electric Power	Natural gas fired installed capacity to reach 95 GW in 2020	

Table 7.5 - Most relevant policies related to hydroelectric power plants

Document	Target	Observation
13th Five Year Plan (2016-2020)	380 GW of hydropower installed capacity in 2020	
Mid-term Evaluation and Optimization of the "Thirteenth Five-Year Plan" for Electric Power	Strive to reach 480 GW installed capacity in 2035	

Table 7.6 - Most relevant policies related to wind power

Document	Target	Observation
13th Five Year Plan (2016-2020)	210 GW installed capacity in 2020	
Mid-term Evaluation and Optimization of the "Thirteenth Five-Year Plan" for Electric Power	220 GW installed capacity in 2020	

Table 7.7 - Most relevant policies related to solar power

Document	Target	Observation
13th Five Year Plan (2016-2020)	110 GW installed capacity in 2020	Achieved before planned in 2017
Mid-term Evaluation and Optimization of the "Thirteenth Five-Year Plan" for Electric Power	200 GW installed capacity in 2020	

According to the several targets imposed by the NEA and the China electricity council, coal remains the fuel of choice for electricity generation for many years to come. Coal fired power capacity is posed to increase by roughly 200 GW until 2030, after accounting for planned retirements of older coal fired power plants. A typical coal fired power plant has a lifetime of no less than 30 years, therefore, every project that starts operation this following decade will only retire well after 2050. Despite this, China is pushing for a fleet of “green” coal, dominated by modern USC power plants. This “green” coal, although it can prevent higher emissions that would happen if older coal power plants were used, is far more pollutant than other technologies such as CCGT natural gas-fired power plants or even more when compared to renewable technologies such as hydropower, wind and solar (Hart et al., 2017; IEA, 2019a).

China is at the same time the largest producer of electricity from coal and the largest producer of electricity from renewables, namely hydro, wind (onshore) and solar PV. It has more installed capacity of these technologies than any other country and new projects of wind and solar PV are being installed at a fast pace. This growth has been so fast that the existing grid has been unable to fully answer demand. Most renewable projects are in the west and southwest of the country, but most urban areas are in the east and south-east of the country creating the need to transmit this electricity across long distances. Although a lot of investment is being allocated in improving the existing grid this upgrade has been slower than the installation of new renewable projects which led to an alarming curtailment rate of roughly 12 % in 2015, that has since decreased to around 7 % in 2018 (César et al., 2018; China Energy Portal, 2019).

Grid infrastructure improvement plays an essential role in allowing new renewable projects to be implemented, as it allows operators to sell most of their electricity, therefore, making the economics of the project less risky. Moreover, as China moves to end subsidies for most renewable projects from 2021 onwards this case becomes even more important for renewable projects operators (Hang, 2019).

In Table 7.8 are the latest policies related to electricity generation published by the NEA and the National Development and Reform Commission (NDRC) and their main goals.

Table 7.8 - Collection of latest policies related to electricity generation and transmission

Document	Date	Observation	Link
Circular on 2023 risk and early warning for coal power planning and construction	26/2/2020	Determines which regions can and cannot approve new coal power plants projects in 2023	[1]
White paper on the development of "New Infrastructure Construction"	19/3/2020	Guidelines on the development of new infrastructure including upgrading the power grid with new ultra-high voltage lines	[2]
Circular on matters relevant to the construction of wind and PV power generation projects in 2020	5/3/2020	Guidelines for approving new wind and solar projects in 2020	[3]
2020 Wind power investment monitor & 2019 PV Market environment monitor	30/3/2020	Determines which regions can and cannot approve new wind projects in 2020 and the PV projects situation in 2019	[4]
Notice on Relevant Issues of the Photovoltaic Power Generation Tariff Policy in 2020	31/3/2020	Guidance on feed in tariffs for solar PV projects	[5]
Energy Law of the People's Republic of China (draft for comments)	3/4/2020	Strategy for the Chinese energy sector	[6]
Notice on matters related to the preparation of the 14th Five-Year Plan for renewable energy development	9/4/2020	Guidance for the development of renewable under the 14th five year plan with the aim to achieve targets in place	[7]
Circular on the issuance of 2020 renewable electricity consumption quota for provincial-level administrative areas	1/6/2020	Establishment of renewables quotas for each province in 2020	[8]
Key tasks for resolving excess capacity in coal-fired power generation in 2020	18/6/2020	Guidelines to address coal fired power generation overcapacity	[9]

China's electricity mix is dominated by technologies suited to deliver a constant output, usually called baseload technologies, such as coal-fired power plants, hydropower and nuclear power plants. Both coal and nuclear power plants take long to start up and are slow to adjust to different loads. Hence their use as baseload generation. Hydropower on the other hand is more flexible but is normally used as a baseload technology or in the case of pumped hydro, used to meet peak electricity demand. The higher penetration of intermittent renewables such as wind and solar PV comes with a certain unpredictability on the supply side which creates a need for more flexible technologies that can easily and rapidly adjust to this variation, therefore guaranteeing that electricity demand is always met. Several technologies can be used to increase this flexibility of the grid, such as natural gas power plants, different forms of storage and a high rate of connectivity, both internally and with neighbouring countries. Therefore, it remains somewhat clear that in order for China to achieve its targets on renewable power generation all of these three tools have to be escalated to add the so needed flexibility to the grid that will allow curtailment rates to be kept to a minimum (César et al., 2018; IEA, 2019a).

Electric power generation from natural gas is projected to more than triple by 2030 to 722 TWh confirming that natural gas power will have a more significant role in the integration of intermittent renewables on the grid (IEA, 2019a). Moreover, according to the policy on new infrastructure presented in Table 7.8 there are several ultra-high voltage lines under construction that will facilitate renewable electricity to be transmitted from rural areas to urban ones, where demand is higher.

According to the state-owned China National Petroleum Corporation (CNPC) electric power demand forecast from 2019, a base case scenario based on the policies and targets currently in place is presented in Figure 7.3.

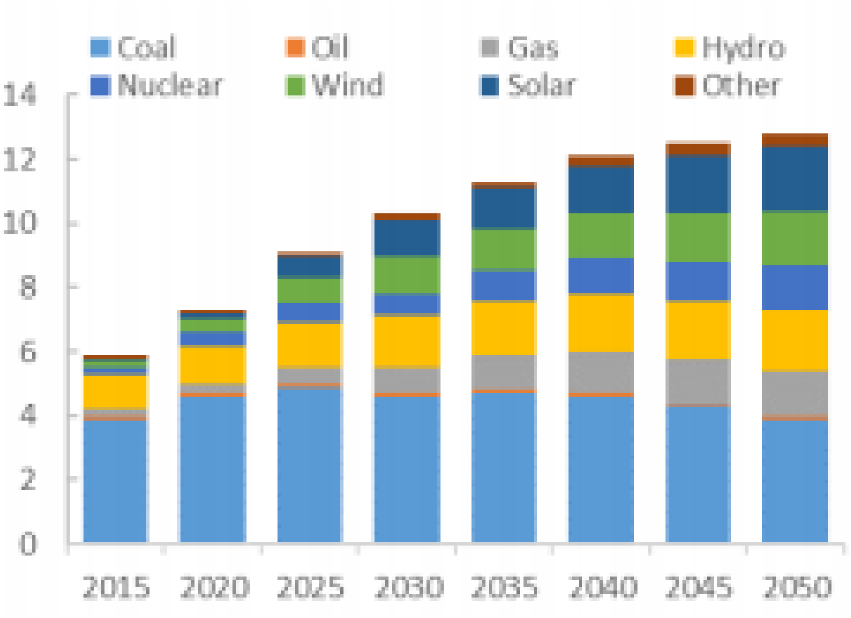

Figure 7.3 – Electric power generation forecast by source under current policies scenario (CNPC, 2019)

According to this forecast new electricity demand will be met mainly by non-fossil fuel sources. Electric power generation from coal will peak at around 2025 and will decrease from there onwards, although at a slow pace if more ambitious policies are not implemented. With the current scenario, the coal share of the power mix will decrease throughout the years, but it will still be the main source of electricity production in 2050, which falls short of complying with the Paris Agreement. It is worth to highlight the following targets projected by the CNPC:

- Electricity demand will be around 10500 TWh in 2030 and 12200 TWh in 2050;
- CO_2 emissions expected to peak at 10 Gt between 2025 and 2030;
- Natural gas share in the power sector of 10 % and 13 % in 2035 and 2050;
- Electricity generation from coal expected to peak at 4900 TWh in 2025.

8. Conclusions

This work aimed to make an overview of the electricity generation sector exploring the trends of electricity demand and making a detailed analysis of the most used fossil fuel powered and renewable technologies used to generate electricity. This analysis was focused on the technical aspects and limitations of each technology with the goal of providing capacity building to the team of the energy division of the UNESCAP. The internship in the UNESCAP was completed fully remotely due to the circumstances imposed by the COVID-19 pandemic, which dictated a type of work more directed towards literature review and capacity building.

As already referred in the introduction, this text was written taking into account that its main readers, the staff from the energy division of the UNESCAP, was mainly formed by economists, lawyers and politicians, whose main cultural background was far from the engineering area. The adopted light technical approach was, thus, required, under such circumstances.

The electricity sector is the energy related area responsible for the biggest portion of GHGs emitted to the atmosphere, therefore, making it a priority in the path towards climate mitigation. Moreover, it is urgent to increase the sustainability of this sector so that future generations can have their electricity demands met with sources other than fossil fuels that are finite.

Coal needs to be phased out entirely of the electricity generation mix in order to comply with the goals established in the Paris Agreement, however, it is observed that developing countries, especially in the Asia-Pacific region are still using this resource in large scale, and have coal fired power plants on the pipeline and new projects under approval. It is therefore unlikely that coal will be phased out in this region before 2050. To make up for this scenario a push to deploy CCS technology in coal-fired power plants is underway. This movement should be met with some scepticism due to the still high costs of this technology, the dangers associated with seismic activity and the amount of effort and investment that will be directed to a technology that does not contribute to the increase of sustainability of the electricity sector given the fact that it is directed to technologies that burn fossil fuels that will eventually run out.

The focus should rely on a strategy that achieves the full sustainability of the electricity generation sector in the long-term. At the same time, it would be unreal to believe that this transition can happen from day to night, instead, this process must happen gradually but at a steady pace. A first step towards this goal is to increase the share of renewables as fast as possible, and use natural gas fired power plants to provide the electrical grid with the needed flexibility. Also, smart grids will have an essential role in predicting the electrical grid demand which will be of great importance to combine intermittent technologies with storage and therefore safely answer the consumers needs. At the same time coal-fired power plants should be decommissioned with priority for the most outdated and more polluting ones. Also, other technologies such as nuclear fission power plants can be used to replace coal as a baseload technology while curbing GHGs emissions in the short to medium term.

Once the electricity demand growth of developing countries starts to slowdown all fossil fuelled power plants should be replaced with renewables, mainly wind and solar technologies that still have the largest unexplored potential. It is still unclear and subject to a lot of debate the role that nuclear energy will play at this stage. To some this technology is a source of clean, cheap, reliable and safe electricity while others defend that the possibility of an accident from a nuclear core meltdown, the danger of allowing nuclear technology to be misused by some nations and the issue of safely dealing with the radioactive waste makes it a high risk path to follow. Ideally, nuclear fusion technology would mature and provide a safe and infinite source of electricity, however, developments have been slow, and it is unlikely that it will be commercially available at least for the next couple generations.

To promote the phase out of coal, governments must put in place policies that account for all the negative externalities associated with burning this fuel. As seen in Chapter 6, it is possible to phase out coal almost entirely of the electric power mix in a relatively short time frame if serious commitments are made. The price on carbon, for instance, can have a significant impact on making coal-fired electricity less economically viable for operators, and this way diverting investments to other electricity generation technologies. Also, strong regulations related to air pollutants can accelerate the decommissioning of old coal-fired power plants. It is therefore clear that coal phase out is real and possible, it is up for each government to elaborate and commit to a particular strategy.

Developed countries that have some of the highest electricity consumption per capita and have mostly relied on fossil-fuelled electricity generation throughout the 20th century have been able to increase their share of renewables, mostly because their electricity demand kept relatively constant throughout the last 20 years. Developing nations, on the other hand, are only now experiencing a fast increase on electricity demand which makes it harder to meet the new demand using only renewable power generation technologies. Developed countries should then provide financial and technical support to accelerate the uptake of renewable technologies in poorer nations and this way avoiding new projects of power generation technologies that emit high amounts of GHGs.

Overall, stronger commitments must be made in increasing the share of renewable electric power generation technologies, in line with the SDG 7, to comply with the Paris Agreement and therefore limit the increase of the global average temperature to well below 2 ºC above pre-industrial levels.

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Annex A: Media news and key findings related to China

Media News

- "China must cancel new coal plants to achieve climate goals: study" – outlines that China must cancel all new coal projects to achieve peak CO_2 emissions in 2030 and keeping the temperature rise in 2050 below 1.5 ºC. China has over 1000 GW of coal fired power generation capacity and 112 GW do not meet environmental standards. Currently 121 GW are under construction (reuters.com);
- China leads on public funding for overseas coal fired power plants having committed $21.5 billion (bn) with an additional $14.6 bn in proposed funding for 102 GW of capacity in 23 countries (theguardian.com);
- "China to make national carbon trading 'breakthrough' by year-end: official" (reuters.com).

Key Findings

- New policies must promote a stronger pace on the phasing out of coal;
- The 14^{th} Five-year plan (2021-2025) to be presented and approved in the beginning of 2021 will be crucial to achieve targets;
- Implementation of the national carbon market essential to discourage new investment in coal and promoting carbon free and low carbon technologies;
- Natural gas a good short-term solution to aid the transition to renewables however due to the high reliance in imports it is imperative to develop a strong strategy, investing in storage and importing from different sources;
- Transition from coal fired power plants will be mainly towards non-fossil fuel technologies whereas natural gas will play a secondary role however a lot more relevant than it is today.