

## Technische Hochschule Ingolstadt Faculty of Mechanical Engineering Master's course: Renewable Energy Systems

**Master's Thesis** 

# Characterization of the reaction time of different power plants

A thesis submitted in partial fulfillment of the requirements for completion of the degree Master of Science (M.Sc.) in Renewable Energy Systems

Completed By:

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## Declaration

I hereby declare that this thesis is my own work, that I have not presented it elsewhere for examination purposes, and that I have not used any sources or aids other than those stated. I have marked verbatim and indirect quotations as such.

Ingolstadt, March 10<sup>th</sup>, 2021

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#### Abstract

With the high percentage penetration of intermittent renewable energy power plants in the power system, a significant challenge has emerged to balance the demand side and supply side. To keep the stable power system needs the coordination of various units, such as the generation side. For example, the power system frequency may cause rapid decline due to the connection of large loads. In the past, the conventional power plants played prominent roles in providing the residual load to the fast response to support the power system frequency. Nowadays, renewable energy power plants, such as wind power plants and solar photovoltaic power plants, are considered potential response units to participate in the power system. However, different power plants have different attributes, such as the startup time from cold status to the minimum load, from set point one to set point two. Therefore, classifying the power plants into appropriate levels is significant.

In this thesis, the literature review regarding the power system's flexibility factors has been studied. The appropriate class of each power plant according to response time has been defined into primary response, secondary response, and tertiary response. Meanwhile, the typical power plants at present, such as thermal power plants, hydropower plants, wind power plants, solar photovoltaic power plants, biogas power plants, and energy storage facilities, have been researched. The average startup time and ramp rate of each power plant have been investigated. Moreover, a simple simulation of wind turbine pitch angle control based on the MATLAB/Simulink has been conducted. Finally, the classification of different power plants has been concluded based on their specific attributes. Furthermore, the solutions of improving the flexibility of conventional power plants are considered as future work. At the moment, the outlook for the development of renewable energy and energy storage has also been described.

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## Abbreviations

AC	Alternating current
AGC	Automatic generation control
CCGTs	Combined Cycle Gas Turbines
CO <sub>2</sub>	Carbon dioxide
DEH	Digital electro-hydraulic
FERC	Federal Energy Regulatory Commission
GCC	Grid Control Cooperation
GLEB	Guidelines on Electricity Balancing
GE	General Electric
GW	Gigawatts
IEA	International Energy Agency
GWEC	Global Wind Energy Council
LCOE	Levelized cost of electricity
OCGTs	Open Cycle Gas Turbines
OEMs	Original equipment manufacturers
PV	Photovoltaic
PTG	Power to gas
PTL	Power to liquid
RERs	Renewable energy resources
REPPs	Renewable energy power plants
TSOs	Transmission system operators
UCTE	Union for the Co-ordination of Transmission of Electricity
WWEA	World Wind Energy Association
WNA	World Nuclear Association

#### **Chapter 1 – Introduction**

#### 1.1 Research background

With the shortage of fossil energy and climate change, more and more people and authorities have realized the importance of sustainable development. A balanced and harmonious development model between human society and the natural environment has become a scientific consensus. Meanwhile, The Paris Agreement issued in December 2015 had set out a global framework to reduce greenhouse emissions and avoid the increase of average temperature to below 2°C above pre-industrial level (Paris Agreement 2015). Besides, a few countries have set a goal to become carbon-neutral countries. As the largest carbon dioxide (CO<sub>2</sub>) producer, China has promised to reach the CO<sub>2</sub> peak before 2030 achieve carbon neutrality by 2060 in September 2020 (Dennis Normile 2020). In November 2016, Germany actively published the Climate Action Plan 2050, pursuing to become a carbon-neutral nation by 2050 based on the Paris Agreement (Fabian Huneke 2016).

Sustained economic growth has also been accompanied by human dependence on electricity consumption, especially in China and some developing countries (Kerstine Appunn et al. 2020). Along with the continuous reduction of costs, renewable energies have become the potential competitive primary energy resource to replace traditional fossil energy. Wind energy and solar energy technology development have become the fastest among renewable energy in recent years. Especially in Germany, by the end of 2019, renewable energies have occupied over 40% share of energy sources in gross German power production based on IEA (International Energy Agency 2020).

However, with the high proportion penetration of the renewable energies in the grid, it becomes significant to assure the stable energy output of different power plants. On the one hand, renewable energy resources(RERs) are unstable; on the other hand, renewable energy power plants(REPPs) have different reaction times to the power grid. Therefore, there is a big challenge for the power grid system to keep stable and reliable. One ideal solution is to classify the different power plants into primary, secondary, and tertiary control based on the reaction time.

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#### 1.2 Research purpose

There are four purposes of this research. Firstly, understanding the flexibility factors of the power system and power generations. Secondly, investigating the startup time and reaction time to the power system of different power plants. Finally, classifying them into primary response, secondary response, and tertiary response; meanwhile conducting the sample wind turbine simulation based on MATLAB/Simulink.

#### 1.3 Research methodology

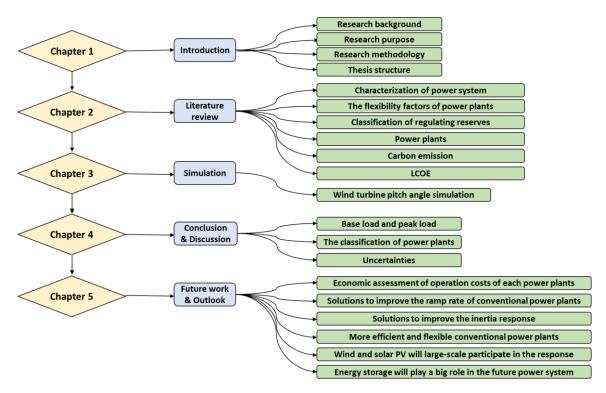


Figure 1 illustrates the research methodology structure of this thesis.

Figure 1 The research methodology structure

#### **1.4 Thesis structure**

This thesis contains five chapters and four appendices. The first chapter introduces the background of this project as well as the reason and necessity to contain the power system's stability. It then explains the purpose step by step to classify the different power plants into different response levels based on their attributes. It also illustrates the research methodology and builds the structures for this thesis.

The second chapter describes the characteristics and the flexibility factors of the power system. Meanwhile, it defines the typical three levels responses into primary, secondary, and tertiary responses. Chapter two also researches each power plant's attributes, including the basic working principle, the startup time, and the ramp rate.

The third chapter builds the mathematic model for the wind turbine control system. It also stimulates the sample pitch angle control by using MATLAB/Simulink. Besides, it plots the power graphs to show the power curve.

The fourth chapter collects all the necessary information from chapter two of each power plant. It then concludes the base load and peak load power plants based on each power plant's startup time. It also classifies each power plant into primary, secondary, and tertiary response units based on their ramp rates. Chapter four also discusses the uncertainties of the conclusion and comes up with some solutions to improve conventional power plants' flexibility.

The fifth chapter proposes some future works, such as to research the solutions to improve the flexibility of conventional power plants. Finally, it outlooks the future trend and shows the confidence of the development of REPPs and energy storage facilities.

## Chapter 2 – Literature review

#### 2.1 Characteristic of power system

An electric power system is a network that consists of the generators that produce the power, the transmission system that carries the power from the generators to the load center, and the distribution system that distribute the power to the loads, such as houses and industries. Assuming that the loads are stable so that the generators produce the constant stable power. According to the central monitoring and control system, every generator takes over a different proportion to feed the power grid. The influence of efficiency, economy, and environment must be taken into account to distribute the tasks to different generators (John Undrill 2018).

Before the widespread use of solar photovoltaics(PV) and wind power worldwide, power systems were designed with the flexibility to balance different demands and deal with the uncertainties associated with the unexpected loss of system deviation. In a traditional power system, thermal power plants such as open-cycle gas turbines, and hydropower power, play a big role to balance demand fluctuations and provide operational reserves.

The power system operators are responsible for the balance between the power supply and demand at all times. Balancing supply and demand is critical to the reliable operation of the system, otherwise, even small mismatches can interfere with the frequency of the power system and affect the reliability of the system operation. To put it simply, power system flexibility is the ability of a power system to respond to the power system deviation, no matter increase or decrease.

#### 2.1.1 The frequency characteristic of power system

The system frequency depends on the balance between the mechanical power input, that is, the power plant input, and the various load units. Unbalance between power generation and load will immediately cause changes in the speed of the synchronous generator, which corresponds to changes in system frequency. The relationship between system frequency, power generation, and load are expressed by the following formula (Nguyen Ha Thi 2018):

$$J\omega_m = \frac{d\omega_m}{dt} = P_{gen} - P_{load}$$
 Eq.1

Where: J is the moment of inertia of the system;  $\omega_m$  is the mechanical rotational speed of synchronous generators;  $P_{gen}$  is the total generation power;  $P_{load}$  is the load power;

The load in the power system is always dynamic, therefore, the power system frequency will always change dynamically because the mechanical power of the power plant applied to the shaft of the generator cannot achieve the same rhythm as the electrical change. However, the power system frequency characteristics of a given control block should remain as stable as possible within the applied frequency range. In this case, the controller's insensitive range should not exceed ±10mHz in any case. Usually, it is in the standard condition when the system frequency ranges from ±0.1Hz, while it is called an emergency condition when the system frequency ranges from 47.5 to 51.5Hz (Pietro Tumino 2020).

#### 2.1.2 The flexibility factors and dynamic demand of power system

Figure 2 shows the flexibility factors of the power system. It does not rely on a single unit but a combination of the generation side, distribution side, transmission side, storage side, and demand side. In general, the different sides work independently. However, the stability needs comprehensive coordination with all of the sides.

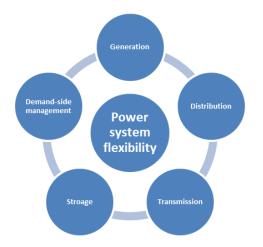


Figure 2 The flexibility factors of power system

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Demand-side management refers to the reduction or increase of load to adapt to changes in supply. Technologies that have been adopted or are being developed include sophisticated predictions of renewable energy and smart grids to best match electricity demand and supply.

Energy storage is the storage of electricity generated from renewable energy sources for later use. It includes pumping energy storage, battery storage, flywheels, and electrolysis of water to produce hydrogen. Although currently most energy storage facilities are pumped water storage, none of today's energy storage technologies is in large-scale use. In any case, energy storage solves the intermittent and non-dispatchable problems of renewable energy.

The transmission system, for example, Amprion GmbH, one of the leading German transmission system operators(TSOs), aims to balance generation and demand within their load frequency control areas at any point. The imbalance between the supply-side and demand-side must be minimized and compensated between the TSOs. Otherwise, the frequency deviation may happen, and this system's stability might be decreased (50Hertz Transmission GmbH 2020). The overall amount of balancing capacity in Germany has been reduced by the cooperation of the transmission system operators in the German Grid Control Cooperation(GCC). Besides, other European TSOs are also working together with German TSOs on the European balancing platform to establish a mutually compatible and supportive GCC for balancing energy within the framework of the implementation of the European Guidelines on Electricity Balancing(GLEB) (Amprion GmbH 2020).

Frequency is an important indicator to measure the power quality, determined by the balance between supply and demand of the power system. Because all the system devices are designed according to the rated frequency, a drop in the quality of the system frequency will affect all walks of life. When the frequency is too low, it may even make the whole system collapse, causing blackouts; besides, when the system is disturbed, the frequency can be intuitive to reflect the degree of a system disturbance (Shao Shuai et al. 2014).

#### 2.1.3 The base load demand and peak load demand

In reality, due to the electricity demand is not always stable, it will dynamically change during the hours and the days. The power grid operator needs to meet the base load demand and the

dynamic demand, including base demand and peak demand. Figure 3 shows the typical electricity demand for a summer day. The red area is a smooth upward curve, which indicates the increasing electricity demand. Thus, the continuous command must be given by the power grid operator to adjust the output of its power plants to meet electricity demand. This is the so-called "dispatching process" (John A Dutton 2018).

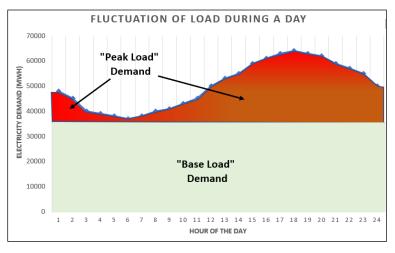


Figure 3 The typical electricity demand for a summer day

Base load, also known as continuous load, is relatively stable and refers to the minimum electricity demand within 24 hours. A home or business that needs constant electricity for more than 24 hours is a baseload. This includes equipment that requires a constant power supply, such as IT systems, alarm systems, mechanical equipment, and security lights, which cannot be turned on and off. Base load is the level at which demand does not naturally decline or the total amount of basic electricity needed (EnergiMine 2019).

Peak load is usually a short period of high demand. It is less predictable than the base load -- it peaks in the summer, for example, when heating or air conditioning is turned on, and demand tends to be highest in the late afternoon but varies by human activity, season and weather. Man's demand for electricity is changing every day. It is lowest in the early hours of the morning when most people are still asleep. Between 6 am and 9 am, many people get up to turn on electric appliances such as lights and electric cooking appliances. Electricity demand increased again around 5 pm as many people returned home from work.

The purpose of power system operation is to balance the variability and uncertainty caused by the variable demand-side and variable wind and solar PV power plants. The modern power system's significant revolution is an adjustment combination of more flexible supply resources and demand side. The power system needs more different peak operating power plants and less inflexible baseload power plants on the supply side, which brings more challenges to the flexibility of power plants.

#### 2.2 The flexibility factors of power plants

The flexibility of different power plants has drawn more attention. Figure 4 shows that the criteria of power plant flexibility.

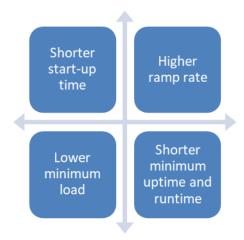


Figure 4 The criteria of power plant flexibility

- a. Startup time means receiving instructions to reach minimum load, and fast startup time also demonstrates the plant's operational flexibility. Besides, peak-load plants are being asked to start and shut down more frequently.
- b. Lower minimum loads mean more extensive load regulation, but many thermal power plants operating at lower loads face lower generation efficiency. The rate with which a plant can change its net power during operation is defined as the ramp rate (International renewable energy agency 2019).
- c. Higher ramp rates mean that power plants can respond more quickly to changes in the power output.
- d. Shorter minimum uptime and runtime means shorter mandatory time to keep running and shorter shutdown time when closed, which also means the power plant's fast reaction time.

This thesis will focus on the startup time and ramp rate. The increase or decrease in production per minute is called the ramp rate and is usually expressed as megawatts per minute (MW/min). Ramp rate is the attribute of each power plant, that a generator changes its output, reflecting the flexibility and power adjustment capability. The regulation of system load demand fluctuation relies on ramping down or ramping up flexible power generation units. Ramp rate depends on the power plant unit capacity, working conditions(startup or operating at a minimum load), and configuration. Ramping speed also depends on the number and configuration of units. For example, the 100 MW/min ramp rate is based on a multi-turbine unit design, such as the 2x1 combined cycle gas turbine (CCGT) unit (net power output 750 MW). The rated power of each gas turbine is 50MW/min.

It is important to note that this study does not consider startup costs effects, power market design, local policies, and other factors. For example, the typical cold startup cost of coal-fired is 223 €. The total yearly startup costs in the modeled German power system dramatically increase by 10% from around 86 million € in 2010 to 94 million € in 2020 and by 46% 125 million € in 2030 caused by the increase of fuel and carbon price (Schill Wolf-Peter et al. 2016).

#### 2.3 Classification of regulating reserves

The different types of generation respond differently to a transient variation of frequency. It is impossible and unnecessary for all generations to respond to the power system at the same time. Hence, the control of the power system is hierarchical based on power plants' attributes. Three types of control classes have been classified based on the Union for the Co-ordination of Transmission of Electricity(UCTE): primary control response, secondary control response, and tertiary control response (Asko Vuorinen 2020). As the following Figure 5 shows, the primary frequency response is the fundamental and autonomous support of the power grid. It will continue to force the required relationship between speed and power without inputs from any external source. Secondary control is used to compensate for the frequency and voltage deviation caused by the primary control. Tertiary control is used to optimize operation in both operating modes and power flow control in grid-tied mode.

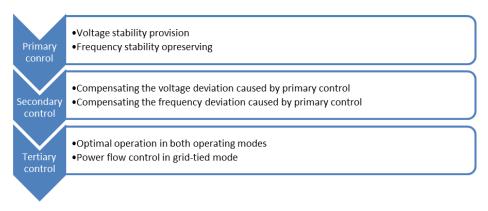


Figure 5 The hierarchical control levels

The response time requirements for the primary response, secondary response, and tertiary response is shown in Figure 6.

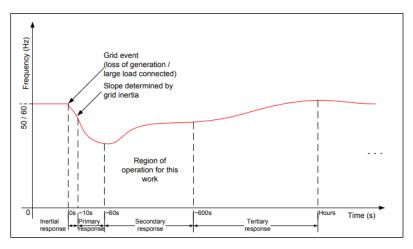


Figure 6 Type of frequency control(Source: Pietro Tumino 2020)

It is worth noting that the inertial response reacts before the primary response, which is the immediate response when the loss of generation or large load is connected. The energy to compensate for this load increase comes from the kinetic energy of the rotating generators, decreasing the velocity. After this, the speed controller called the "governor" of each generator acts to increase the generated power to recover this speed decreasing and clear the imbalance (Pietro Tumino 2020). Inertial response plays a critical role in power systems because it reduces the rate of frequency change after perturbation, which can avoid low-frequency load reduction or worse problems, including blackouts. A conventional synchronous generator naturally provides an inertial response through the energy stored in the rotating mass of the turbine. Wind turbines can provide an inertial response by storing energy on rotating blades or capturing more energy from

converters(Ela Erik et al. 2012). Solar PV power plants do not store the mass of the rotation axis, so it needs additional auxiliary energy to provide an inertial response. Table 1 shows the typical inertia constants of different power plants(Nguyen Ha Thi 2018).

Time (s)	
2-4	
2.4-6.8	
3-9	
5-8	

Table 1 The typical inertia constants of different power plants

#### 2.3.1 Primary response

A variety of interference or random deviation to destroy the balance of power generation and demand will cause frequency deviation. The central controller involved in the generator set's primary responsibility will respond to the frequency deviation at any time. The primary response is the control reserve, which is a local automatic control that adjusts active power generation and consumption to quickly restore load and generation balance and quickly offset frequency variations. Primary response actions are fast, it is measured in MW/seconds (Illian Howard F. 2010). Primary frequency control is mainly used for frequency stabilization after severe power generation.

Table 2 shows the need for primary control reserves in some typical regions:

Table 2 The demand for primary control reserves from some typical regions (Source: Asko Vuorinen2020)

Regions	Primary control reserves	Deployment time
Continental Europe	3.000MW or two 1.500MW	1.500MW in 15s
		3.000MW in 30s
North Europe	1.000MW	300MW in 5s
		1200MW in the 30s

Generally, the response time of primary control reserves ranges from 5 to 30 seconds. The power plants should generate the necessary power and keep it for at least 15 minutes, which depends on the TSOs requirement.

All generators located in the synchronous zone and matched with the governor automatically conduct primary frequency modulation. The demand side also participates in primary frequency control through automatic regulation of frequency-sensitive loads such as induction motors, or the action of disconnecting or connecting a frequency-sensitive relay to a load at a given frequency threshold.

#### 2.3.2 Secondary response

The secondary response also named the automatic generation control(AGC) is the temporary increases(regulation-up) or decreases (regulation-down) in generator active power output. Regulation-up and regulation-down are based on the system frequency changes. Suppose the system frequency falls below the nominal value 50Hz or above the nominal value 50Hz. In that case, the AGC system sends a regulation-up or regulation-down signal to increase the active power or reduce generation (Rebello Eldrich et al. 2018).

Secondary frequency control is a centralized automatic control that adjusts active power generation to restore frequency and interchanges with other systems to target values after imbalance. In other words, the primary control limits and prevents the frequency shift, and the secondary control makes the frequency renege on the target value. Only the generator set located in the area where the imbalance occurs participates in the secondary frequency control and maintains the load and generation balance. It should be noted that the load usually does not participate in secondary control. In contrast to primary frequency control, secondary control is not required. Therefore, secondary frequency control three times. However, because manual control is inefficient in maintaining tie line overruns, secondary frequency control is used in all large interconnected power systems.

Secondary frequency control actions are slower than primary frequency control actions(Illian Howard F. 2010). It should respond between 20-600 seconds, i.e. within 10 minutes, and can last 120 minutes. Table 3 shows the demand for secondary control reserves in some typical regions:

Regions	Secondary control reserves	Deployment time	
Continental Europe	3.000MW system 100MW=3%;	5 minutes	
	10.000MW system 200MW=2%;		
	60.000MW system 600MW=1%		
USA	Forecasted day peak load 1.1%;	5 minutes	
	Forecasted night peak load 1.1%		
North Europe	No specific requirement given	10 minutes	

Table 3 The demand for secondary control reserves from some typical regions (Source: Asko Vuorinen 2020)

#### 2.3.3 Tertiary response

Tertiary response refers to manual changes in generator set scheduling and unit combination. The third frequency control is used to restore the primary and secondary frequency reserve, manage the transmission network congestion, and make the frequency and power exchange return the target value when the secondary control fails. Some aspects of tertiary control relate to energy trading used for target balancing.

#### 2.3.4 Summary

Table 4 below shows a summary of three control reserve levels and the main features of each (Pietro Tumino 2020).

**Duration time** Hierarchy **Response time** Operation 5-30 seconds 15 min Primary response Automatic Secondary response 20-600 seconds 120 min Automatic >600seconds Indicated by TSO Tertiary response Upon request

Table 4 A review of the three regulation levels

#### 2.4 Power plants

#### 2.4.1 Thermal power plant

#### 2.4.1.1 Gas turbine power plant

The basic working principle of the gas turbine is based on the Brayton Cycle, a thermodynamic cycle that works in inhaled jet engines. Figure 7 shows the basic framework of the gas turbine, firstly, the fresh air flows into the compressor, where produces the air with a higher pressure. Secondly, the fuel, natural gas, or petrol will then be sprayed and mixed with compressed air into the combustion chamber, where the fuel will be ignited to produce the flow at a high temperature. Finally, the high-temperature pressurized flow enters into the turbine to drive the turbine blades to spin fast. Where the thermal energy is converted into mechanical energy to drive a turbine and the compressor. The exhaust gases come out from the turbine into the atmosphere. However, considering the economy and environment, the exhausted gases will also be reused to heat the water and produce the steam to drive the turbine.

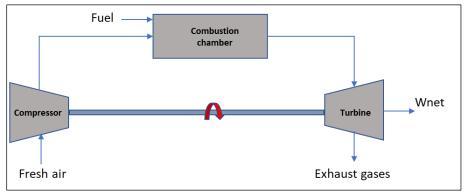


Figure 7 The basic framework of a gas turbine

There are two types of gas turbines: open cycle gas turbines(OCGTs) and combined-cycle gas turbines(CCGTs). OCGTs mean the exhausting gases come out directly into the atmosphere, while in CCGTs, the exhausted gases will be used again to combine with a small steam engine power plant, the so-called Combined Heat Plant(CHP). It leads to the decline of flexibility as a result of the CCGTs must run at a specific capacity to produce heat. OCGTs have a lower efficiency compared with the CCGTs. However, OCGTs usually can react and supply the power system faster than CCGTs. The startup time of OCGTs and CCGTs from command to full load is 5-6 minutes and 30-240 minutes respectively (Carlos Perez Linkenheil et al. 2017). Table 5 shows the technical

parameters of different heavy-duty gas turbines from different original equipment manufacturers(OEMs), including General Electric(GE), Siemens, Mitsubishi (Kamal Abudu et al. 2020). The ramp rate of each gas turbine differs from different OEMs, from 7MW/min to 40MW/min in terms of the technologies and size. In general, the larger size, the bigger the ramp rate.

OEM	Model	Power output	Ramp rate	Ramp rate
		(MW)	(MW/min)	(%/min)
GE	9F.05	314	24	8
GE	7F.04	198	30	15
GE	6F.03	88	7	8
Siemens	SGT6-5000F	360	40	11
Mitsubishi	M50IF	185	12	6
Mitsubishi	M70IF	385	38	10

Table 5 The technical parameters of different gas turbines from different OEMs

In general, due to the high flexibility of the heavy-duty gas turbines, its operation load is from 20% to 40% of rated capacity at the minimum load level, which has the lowest fixed cost, while lowest operation efficiency and approximately 15% loss in power plant efficiency (Carlos Perez Linkenheil et al. 2017). The economic factors and anti-risk factors must be taken into account when installing a wide range of gas turbines because a few countries control the export of gas and oil, Saudi Arabia, Russia, Canada, and the price varies with the geopolitical landscape, so it is cost and benefit are uncertain. Nevertheless, with the development of hydrogen production technology, fuel sources for gas turbines have become more diverse.

#### 2.4.1.2 Gas engine power plant

The gas engine is an internal combustion engine that burns natural gas and blast furnace gas based on the Otto Cycle's working principle. This is also applied in the motorcar engine, i.e., the so-called four-stroke engine. It consists of four steps, as Figure 8 shows down below. Firstly, the suction stroke absorbs the air into the engine. Secondly, the compression stroke compresses together the fuel and the air to atomize the fuel. And then the atomized fuel and air are ignited by the spark plug, resulting in the heat to raise the piston. Finally, the exhausted gases, mostly water vapor, and carbon dioxide are released. The gas engine's power output relies on the mixed amount of gas-air mixture inside the cylinder. Once a command issue, a specific gas-air mixture will be added into the cylinder, and the engine will work at a constant speed.



#### Figure 8 The necessary working process of gas engine

At present, gas turbine occupies the leading market share in large industrial sites with high heat and steam demand, although the gas engines have relatively higher efficiency than gas turbines. Gas engines can be easily interconnected to form large generating sets. The gas engine power plants have been verified that having the flexibility to perform the start-stop cycle quickly and steadily. The startup time of gas engine power plants from command to full capacity is just 1-5 minutes (Carlos Perez Linkenheil et al. 2017). A gas engine power plant consists of several engine units, the ramp rate per unit varies from different suppliers. For example, the loading rate of one Wärtsilä 18V50SG engine is 24 MW/minute. If combining 20 Wärtsilä 18V50SG engines in one operation power plant, it can fast respond to the power grid regulation. The average minimum load of a gas engine power plant is 30% of its full capacity. Meanwhile, it can ramp from 30% to 100% load within 1 minute when it is already under operation, i.e., the ramp rate is 100+%/minute of its full capacity (Joseph Ferrari 2014). The advantages of the gas engine power plant are its long service duration and maintenance-friendly engine, and low fuel consumption. Besides, it is also available as a container "plug and plays" unit for quick installation to supply emergency issues in industries, hospitals, and military bases.

#### 2.4.1.3 Coal-fired power plant

#### 2.4.1.3.1 The history and status quo

Nowadays, fossil-fuel-based power stations still account for the majority of electricity worldwide. Most of the electricity is produced through the steam turbine globally, such as coal-fired power plants, which consist of hard coal and lignite coal. The efficiency of a coal-fired power plant depends on the turbine size, load condition. The efficiency of large-size coal-fired power plants can reach up to 50% meanwhile having a lower cost. The basic working principle of the coal-fired power plant is based on the Second Law of Thermodynamics and Carnot's Theorem. Carnot's Theorem states that a turbine's maximum thermal efficiency depends only on the hot reservoir temperature and the cold reservoir. In other words, the higher the steam temperature, the greater power plant efficiency. This follows the Second Law of Thermodynamics, which illustrates that "Energy is irreversible". In all energy exchanges, if no energy enters or leaves the system, the potential energy of the state is always less than the potential energy of the initial state". Figure 9 shows that, virtually, the steam turbine first works to convert the chemical energy into heat energy, i.e., heating the water to too high-temperature steam, which is so-called superheated steam. Then the superheated steam flows past a turbine's spinning blades, where the steam expands and cools. Through the turbine, the heat energy is turned into kinetic energy by rotating the blades. The turbines are connected to generators with an axle.

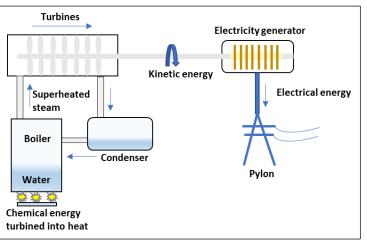


Figure 9 Thermal Power Plant

#### 2.4.1.3.2 The flexibility of coal-fired power plant

In general, the coal-fired power plants have relevant longer reaction time from command to the full load. The hot or warm start is in the range of 1-10 hours. Because of the output's long-term stability, coal-fired power plants are used to supply the baseload. However, some reasons are showing below that the coal-fired power plants participate in the frequency response widely.

#### --The large installed capacity

By the end of January 2021, china operates the largest coal-fired power plants, which is 1.042GW, 49% of the total electricity resources. The total installed capacity of coal-fired power plants in India

is 229GW, which is 55% of the total electricity resource. The coal-fired power plant is the fourth major source of electricity generation in Germany, accounting for 15.89% of total output in January 2021 (Statista 2021).

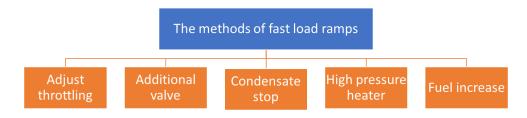
Table 6 shows the ramping capacity of coal-fired power plants in India (Powerline 2019). We can see that although it has the 1% assumed ramp rate, with a large size and high installed capacity, it can also provide a large amount of power output up to 860MW/minute. Capacity on the bar is that the number of units on the bar in 15 Minutes Blocks (Minus Normative Auxiliary Consumption) (Southern Regional Power Committee 2016).

Unit size (MW)	Capacity	Capacity	Assumed	Ramp rate
	utilization(%)	on the bar(MW)	ramp rate(%)	(MW/minute)
<150	40	4.073	1	41
200-210	80	25.824	1	258
250-360	80	30.885	1	309
500	80	37.276	1	373
600-800	82	86.043	1	860

Table 6 Analysis of the ramping capability of coal-fired power plants in India

#### --Advanced control strategies

However, due to most of the coal-fired power plants are large, and still dominate the share of the main electricity resource globally, it plays a vital role to regulate the fluctuation of dynamic frequency of the power grid to stabilize the grid frequency by adjusting the steam inlet valve of the digital electro-hydraulic(DEH) control system and use the boiler heat storage. DEH is the core of the turbine control system, with the advanced control system the turbine can adjust the power output up and down easily. This kind of frequency control happens fast and in a few seconds. DEH is the most crucial functional subsystem of the steam turbine generator. It includes many parameters, such as over-speed protection, thermal stress, the start-stop command control, etc. In general, there are several measures to adjust the power output. Figure 10 shows the five methods of fast load ramps provided by Siemens AG (Dr. Andreas Feldüller 2017).



# Figure 10 The methods of fast load ramps

The steam turbine unit's regulating system directly and automatically adjusts the turbine's regulating valve to complete the power grid's load compensation and correct the fluctuation of the power grid frequency. The turbine's primary frequency modulation function's electromechanical control system is usually to convert the difference between the turbine speed and the rated speed into power signal compensation or flow compensation.

# --The low average minimum load

Large coal-fired power plants are more flexible in terms of their minimum and maximum load, which is average required 30% of its full load. Figure 11 shows the average load factor of coal-fired power plants in Germany in the past two decades based on the research deriving from Deloitte in 2019. It is worth noting that the rapid decline that happened in 2008 is because of the global financial crisis. While the rapid decline from 2013 until now is due to the increase of REPPs. The average load factor is 44% and the minimum load factor is 35% in the past two decades. According to the Fraunhofer Institute, in 2019, the maximal output from hard coal power plants was just 17.4 gigawatts(GW), which was considerably lower compared with its total installed capacity of 23.7GW, in the first half of 2019, the fleet averaged 25% of its potential output (Karsten Capion 2019).

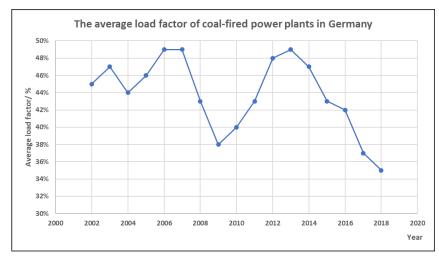


Figure 11 The average load factor of coal-fired power plants in Germany

Therefore, from the above evidence, we can see that the coal-fired power plants have a wide range to ramp up or down the load. They are operating to go through more and more operating cycles even during the days (Carlos Perez Linkenheil et al. 2017). With the rapidly growing share of renewable energies in the power system, the thermal power plant's start-stop cycle has also dramatically increased. The research reported that the total number of start-stop of a thermal power plant in Germany grows 81% based on predicting the RES will be expected to rise from 14% in 2013 to 34% in 2030 (Schill Wolf-Peter et al. 2017b).

# --Case studies:

a. China

A study analyzed characteristics of primary frequency modulation action of the thermal power unit in power grid fault (Haihua Song et al. 2015):

At 0:25 on March 22, 2012, a wide range of power grid frequency fluctuation occurred due to a circuit trip in Central China Power Grid. The lowest value of power grid frequency reached 49.82Hz, and the duration of the low frequency of the whole power grid was about 5min.

At the initial moment when the power grid failure occurs, the primary frequency modulation function of the thermal power units in Hunan Province quickly acts, and the total frequency modulation power reaches 117.1MW(about 1.76% of the active power at startup) at the moment when the network frequency reaches the lowest point (6s after the failure), which provides strong support for the initial stability of the power grid frequency and the effective prevention of the expansion of the power grid accident.

# 2.4.1.4 Nuclear power plant

# 2.4.1.4.1 The history and status quo

According to the International Atomic Energy Agency, until April 23, 2014, 450 nuclear power plants were operating in 31 countries worldwide. Nuclear power plants are highly efficient energy construction, with almost zero greenhouse gas emissions and carbon dioxide. However, after the Fukushima nuclear power plant accident in Japan in 2011, many countries are gradually planning to shut down existing nuclear power plants. France, as the electricity resources highly rely on nuclear power, nearly 72% of its electricity needs, are determined to reduce the rate to 50% by 2030 or 2035. 12% of Germany's electricity resource is from the nuclear power plant, but it has vowed to shut down all 17 reactors by the end of 2022. China is one of the few regions with growing nuclear power plants after the Fukushima nuclear accident. They are currently 49 operable reactors, 47.498MWe total installed capacity, 16 reactors, and 15.906 MWe capacity are under construction. According to the National Energy Administration, nuclear plants supplied less than 5% of China's annual electricity needs in 2019. However, this share is expected to grow as the air pollution, and China plans to become carbon-neutral by 2060.

The startup of a nuclear power plant from shut-down condition to a required load is a complicated process. The critical step is to generate a controlled nuclear fission chain reaction, which is highly required to be safe, professional, and precise at any time. Figure 12 shows the process of nuclear fission. The uranium atoms are the main nuclear fuel resource. Considerable energy will be released when a neutron crashes with a uranium atom and splits during nuclear fission. At the same time, more neutrons and other lighter elements will also be released. These released neutrons will continue to crash with other uranium atoms so that the energy is keeping producing. This process is repeating during a fission chain reaction. This reaction can be controlled by moving the control rods in nuclear power plant reactors to produce certain electricity.

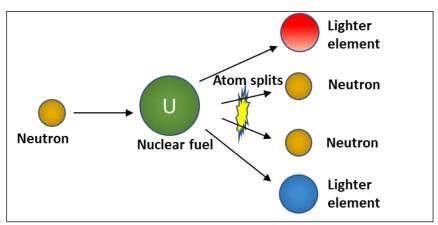


Figure 12 The process of nuclear fission

Figure 13 shows the nuclear power plant's key components consist of a nuclear reactor, control rods, pressurizer, steam turbine, generator, and condenser. The nuclear power plant is a thermal power station that uses nuclear fission to produce heat resources. And then, the heat passes into the primary cooling water. The water is heated and passed through the steam generator in the containment building to produce superheated steam, fed into the steam turbine where it spins the turbine and the generator to produce electricity.

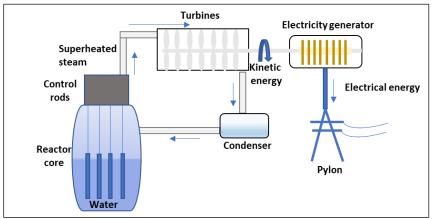


Figure 13 The working mechanism of nuclear power plant

The nuclear power plant is much cleaner and neater compared with other thermal power plants. Besides, a significant number of nuclear fuel resources can be found around the world. Meanwhile, just a small amount of fuel can produce a large amount of electricity. Therefore, it can continuously supply reliable energy. However, they are still some concerns about its initial costs and safety. The capital cost, including the reactor core and nuclear fuel installation cost, is prohibitive than other thermal power plants. Although the modern nuclear power plant already pays more attention to the safety protection system to avoid radioactive pollution, there are still concerns about nuclear contamination and radiation.

# 2.4.1.4.2 The flexibility of nuclear power plant

The normal cold startup of a nuclear power plant can take several days or less than a week. For example, a boiling water reactor takes 4 to 6 hours to reach the critical point where achieve a continuing nuclear chain reaction and then around 12 hours to approach rated temperature and pressure. After that, it takes another 12 hours to heat the water to steam to spin the turbine to start producing electricity at the minimum load point. Since then, it takes 2 to 3 days to reach full power. Due to its extended startup attribute and reliable energy output, it is always be used to set as the based load unit.

Technically speaking, nuclear power plants can participate in frequency modulation. Nuclear energy appears as the only large-scale, non-weather-dependent low carbon technology capable of demonstrating on a large scale that it can contribute to the electrical system's stability by adapting to changes in demand and balancing the intermittency of variable renewables. Also, nuclear power plants have characteristics that allow a relatively high power change rate when operating at a low load capacity. Therefore, the load dispatcher can use this operating feature to supply generation control during deviation of the power grid by taking out one or several control rods to increase the power output and move the control rods into the core to reduce the power output. According to the report from International Atomic Energy Agency(IAEA), the premise for nuclear power plants to provide frequency is as following (IAEA 2018):



Figure 14 The premises for nuclear power plants to provide frequency response

Table 7 shows the frequency response requirement in different countries (IAEA 2018). The nuclear power plants are in France play an important role. Therefore, it is given a higher mission to participate in the primary response and the second response(Dr. Robert Peltier 2019). In Belgium, where nuclear power plants are currently participating in the secondary response in a limited range, more requirements are under researching to allow large-scale load increase and reduction. Although it has a high share in the USA, it is not required to provide frequency response, most of the nuclear power plants are operated under their nominal power due to the expensive fixed costs. The share in China is relatively low, but in the local province, Guangdong is relatively high, where it is required to provide the primary control reserve.

Share of nuclear power plants	Frequency response type
70%	Primary, secondary
47%	Secondary
18%	Primary, secondary
19.7%	No
5%	No
15%	Primary
	70% 47% 18% 19.7% 5%

Table 7 The frequency response requirement in different countries

In conclusion, whether to participate or not depends on the share, grid dispatch, and market rules. Modern nuclear reactors' load-tracking capabilities help balance a high proportion of solar or wind penetration in few countries. However, in real life, they are bound by specific technologies and security constraints that do not provide the same flexibility. Meanwhile, not all new reactors will operate flexibly at the plant level, which requires good design, operational skills, and regular maintenance (Agora Energiewende 2015). Generally speaking, the ramp rate of the nuclear power plant is considerably lower than any other power plant, around 2% of its full load per minute (Gonzalez-Salazar Miguel Angel et al. 2018). In reality, nuclear power rarely participates in grid fast frequency modulation due to slow ramp rate, safety, and economic considerations. Therefore, It can be set as the tertiary response unit.

# --Case study

Table 8 shows the main electricity sources in the EU and Germany. We can see that conventional power plants still dominate the market. Technically, all thermal plants, such as gas, coal, lignite,

and nuclear, can provide all three reserve types when they are already under operation (Sebastian Just 2015).

Power plants	Nuclear	Gas	Hydro	Lignite	Hard Coal
EU	25.00%	20.00%	13.00%	7.00%	6.00%
Germany	3.80%	12.62%	6.33%	8.32%	7.57%

One study indicated that the hydropower plant would largely provide the primary response in Germany and the EU when the REPPs have a high penetration rate in the power system (Ibrahim Nassar et al. 2014).

A. Scenario one: 0% renewable energy in operation in both Germany and the EU power system

Table 9 Primary re	esponse plants v	vith 0% renewa	ble energy	in EU and	d Germany
Primary response plants	Hard coal	Lignite coal	OCGT	CCGT	Hydropower
EU	16%	16%	28%	32%	7%
Germany	15%	15%	33%	37%	-

B. Scenario two: 60% renewable energy in operation in both Germany and the EU power system

Table 10 Prima	ry response p	plants with 60	% renewa	ble energy	in EU and Gern	nany
Primary response plants	Hard coal	Lignite coal	OCGT	CCGT	Hydropower	Nuclear
EU	23%	25%	6%	6%	23%	18%
Germany	37%	28%	-	9%	-	-

C. Scenario three: 77% renewable energy in operation in both Germany and the EU power system

Table 11 Primary response plants with 77% renewable energy in EU and Germany

Primary response plants	Hard coal	Lignite coal	OCGT	CCGT	Hydropower	Nuclear
EU	10%	10%	2%	2%	59%	18%
Germany	10%	10%	-	5%	76%	-

## 2.4.2 Hydropower plant

### 2.4.2.1 The history and status quo

It has been centuries since humans first harnessed river flows' kinetic energy to irrigate and process grain. Since the world's first hydropower plant opened in the United States at the end of the 19th century, hydropower plants now provide roughly 16% of the world's electricity. A hydropower plant consists of reservoirs, dams and turbines, and generators. Water from the river is stored in reservoirs where dams can be freely switched on and off to control water flow, spinning through turbines to drive generators at the other end. The generation of electricity depends on the pressure and flow of water through the turbine. The world's largest hydropower plant in China's Three Gorges on the Yangtze River, which has 32.700MW installed capacity. Germany is rich in river resources and has a long history of hydropower development. By 2019, the total installed capacity of hydropower power is 11.022MW. 8.1% of electricity production was from hydropower in renewable energy electricity in 2019 (Federal Ministry for Economic Affairs and Energy 2020).

The power output of the dam is calculated using the potential energy of water and can be found using the following hydropower formula:

$$P = \rho * \eta * g * h * Q \qquad \qquad Eq.2$$

Where:

P is the power output, measured in Watts;  $\eta$  is the efficiency of the turbine;

 $\rho$  is the density of water, taken as 998kg/m<sup>3</sup>;

*g* is the acceleration of gravity, equal to  $9.81 \text{m/m}^2$ ;

h is the head, or the usable fall height, expressed in units of length;

Q is the discharge, also called the flow rate, calculated as Q=A\*v;

 $\hat{A}$  is the cross-sectional area of the channel;

v is the flow velocity;

The above equation shows that the hydropower plant's power output relies on the usable height flow rate in the reservoir. Figure 15 shows the layout of a turbine flow control system. Because of the coupling between flow and pressure changes in the penstock, a fast rise in the flow comes at the price of a sharp decrease in the pressure. The water level in the upper reservoir will produce different pressure on the penstock. Therefore, if the digital control system can monitor the level transmitter's information about the water level in the upper reservoir, the opening time limiter will adjust the flow control device through the injector to keep a stable dynamic response.

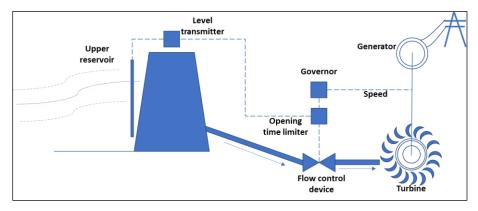


Figure 15 The layout of a turbine flow control system

# 2.4.2.2 The flexibility of hydropower plant

The start-up time of hydropower plant from command to full load to the power grid is just 25-300 seconds (Carlos Perez Linkenheil et al. 2017). Meanwhile, it can work at a shallow load level, i.e., around 5% of its full capacity. The average ramp rate of a hydropower plant is 15%/min (Gonzalez-Salazar Miguel Angel et al. 2018). The most crucial use of hydropower plants in the power system is frequency modulation. Hydropower station relative to other types of power stations in the frequency modulation aspect has the innate advantage, the turbine can quickly adjust the speed, also can quickly adjust the active generator power and reactive power output, to quickly balance the grid load. As long as the power grid's active power balance is right, the voltage is relatively stable. Therefore, hydropower stations' contribution to the power grid's frequency stability relatively large (Yu Chen 2012).

Hydropower stations have different properties and reserve capacities. Most hydropower stations have limited capacity to manage storage. Therefore, they can only be used to provide primary reserves, as primary control relies more on adjusting flexibly up and down rather than generating more or less energy over a period, which is essential for secondary and tertiary reserves (Sebastian Just 2015). Nowadays, hydropower power plants in primary frequency control have become critical due to the grid's more complex structured intermittent renewable sources (Yang Weijia et al. 2016).

# 2.4.3 Wind power plants

### 2.4.3.1 The history and status quo

The wind is generated by the sun, the sun irradiates the earth, the different thicknesses of the atmosphere, the unevenly heated mountains, valleys, and planets that orbit the sun create the wind to balance the uneven pressure in space. Figure 16 shows the working mechanism of the wind turbine. The wind generator is the wind energy through the fan blade absorption to drive the generator rotor rotation to generate electric energy equipment.

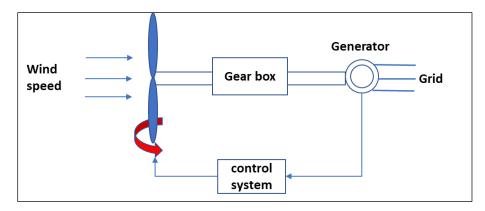
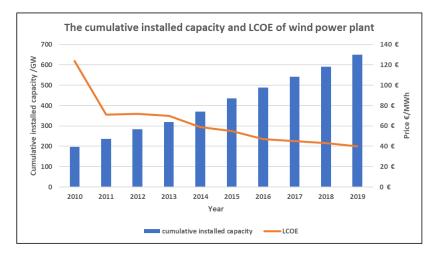


Figure 16 The working mechanism of wind turbine

Wind power is one of the pioneers in the energy transition around the world. According to the World Wind Energy Association(WWEA), the total installed capacity of wind power plants(WPPs) worldwide has reached 650 GW by the end of 2019, covering 6% of the global electricity demand. It is estimated that the global wind energy market will continue to grow at 8.5% annually and historically reach 1.000 GW by the end of 2025. China is the largest market holding around 36% of the total installed capacity so far. Germany leads the onshore and offshore wind power installing capacity in Europe for a long time, and it is also the biggest market in the region. Around 29.546 onshore wind turbines, 55 GW cumulative installed capacity are under operation across the country by July 2020. Meanwhile, around 1.501 offshore wind turbines, 7.76 GW cumulative installed capacity are under operation (Sören Amelang and Benjamin Wehrmann 2020). The total electricity production from onshore and offshore covered 35% of its entire net electricity production in 2019. Looking ahead to the next decade, the Global Wind Energy Council(GWEC) predicts that Europe's offshore wind market will continue to grow strongly, as new offshore wind projects are cheaper to build and operate than new nuclear and gas-fired power plants, helping

Europe reach its carbon-neutral target by 2050. The German Federal Cabinet has approved an amendment to the offshore "Wind Power Law" in June 2020. The bill increases the 2030 offshore wind target from 15 GW to 20 GW and establishes a long-term goal of reaching 40 GW by 2040.

The decline of the Levelized cost of electricity(LCOE) is with the rapidly increasing installed capacity. Figure 17 shows the cumulative installed capacity and LCOE of the WPPs during the last decade. The LCOE dropped dramatically from  $600 \in /MWh$  in 2010 to  $40 \in /MWh$  in 2019 (Statista 2020).



*Figure 17 The cumulative installed capacity and LCOE of the wind power plant*(Source: Statista, 2019)

# 2.4.3.3 The flexibility of WPPs

The startup time of a wind turbine usually takes few minutes to reach the full load under the rated wind speed. The ramp rate of the wind turbine can be easily controlled by adjusting the torque or pitch angle. The operation can be done independently for each turbine or the entire wind farm according to the power system requirement.

Worldwide, although WPPs are not widely involved in frequency regulation of power systems due to their relatively low penetration ratio and high fixed cost. However, in some countries and regions with high penetration of WPPs, are being asked to perform more and more the frequency of the conventional power plant control tasks, to improve the frequency stability, the European power transmission system operator network released the network coding, that is to say, a wind farm in continental Europe and the rated power is higher than 50 MW, WPPs in the UK and the rated power is higher than 10 MW, WPPs in Ireland and the rated power of above 5 MW. These WPPs must be equipped with frequency responsive auxiliary control services (Nguyen Ha Thi 2018).

The ramp rate of WPPs varies from different countries. In Germany, the ramp rate for WPPs is maximal 10%/min of its full load. North Germany: over 4.000 MW (58% of capacity) decrease within 10 hours, extreme negative ramp rate of 16 MW/min (0.2% of capacity) happed on 24th December 2004. In Ireland, the average ramp rate is required for 8%/min, i.e., between 1MW/min and 12MW/min. The ramp rate requirements in the UK depend on the size of the WPPs. There is no limit for WPPs until 300MW capacity. It has to provide a 50MW/min ramp rate as long as the size is between 300MW and 1.000MW, and 40MW/min if the size is over 1.000MW. However, Denmark has the more flexible and aggressive requirement within the range of 10-100%/min due to the high penetration rate (WindPrimControl 2020).

The WPPs can provide an inertial response. Thanks to the direct coupling between the rotor speed and the system frequency, the induction generator with fixed speed can provide limited inertial response. WPPs can provide an inertial response similar to that of conventional generations by using energy stored in the rotating blades or capturing more energy from converters (Muljadi et al., 2012). The power electronics-based converters' controls sense the frequency drop and determine the appropriate increase in power output. The fixed-speed wind turbines with rated power above 1 MW have an inertial constant of 3–5 s. The stored energy in each turbine is unrelated to wind speed, and the cumulative kinetic energy of a wind power plant increases with the number of turbines connected.

When equipped with governor-like control, wind turbines can contribute to grid frequency through torque or pitch control. The wind power plant's primary frequency regulation is usually activated within tens of seconds and sustained for up to 15 mins (Wu et al., 2018). They can provide primary frequency response to the power system, which requires a power increase or decrease, only when operating below maximum output levels. Such curtailment of energy production could have a significant economic impact on WPPs due to the remaining expensive capital costs.

Although the primary frequency response from WPPs is not widely required, different countries have different regulations. In China, grid-connected generating units, including WPPs with 30MW

and above, must have a primary frequency response function (National Energy Administration 2020). Germany requires the system frequency to be greater than 50.2Hz and new energy to participate in the frequency modulation. For every 1Hz increase in the system frequency, the available real-time output of new energy will be reduced by 40% (Dawei Zhao et al. 2019).

Technically speaking, WPPs can respond to secondary control to provide regulation service, although they do not typically do so today. In the same way, wind turbines can provide primary frequency response, and their blades can be pitched to increase or decrease output rapidly.

#### 2.4.4 Solar PV power plant

#### 2.4.4.1 History and status quo

Solar PV is a solar power technology for generating electricity using semiconductor devices silicon known as solar PV cells. The PV cell is doped with a semiconductor silicon material to form a P-N segment structure as the internal electric field. P-type (positive) silicon tends to give up electrons and gain holes, while N-type (negative) silicon tends to accept electrons. When the sun radiates into a cell, photons in the solar radiation excite some of the semiconductors' electrons to become electron-holes or positive-negative pairs. Under the power plant's action inside the P-N node, the electrons move towards the negative pole, and the holes move towards the positive pole. The wires are then connected in series to form a circuit that generates current for the external load. That is how PV solar cells work.

In general, as Figure 18 shows, the main parts of a solar PV power plant consists of the following units: firstly, installed solar panels located toward the sun to absorb the maximal radiation and enhance the efficiency; and then using cables connect each panel and the inverter to turn the direct current into the alternative current; a transformer is needed to increase the voltage to connect with the power grid. The switchgear is necessary to power down equipment to allow work to be done and clean up downstream faults, which is directly related to the electricity supply's reliability. Also, the off-grid and family-rooftop solar PV systems have to install a set of batteries as a backup so that the electricity can be released when the lack of sun radiation.

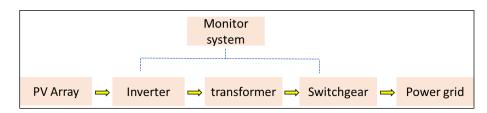
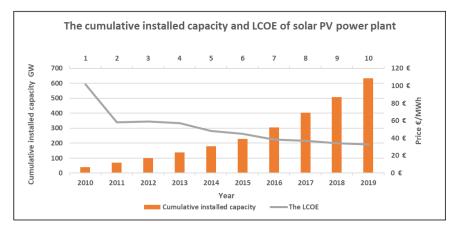
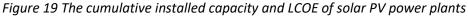


Figure 18 The basic units of solar PV power plant

When PV panels were first created 50 years ago, the amount of energy required to produce a single PV panel exceeded the amount of energy the panel could produce in its lifetime. Solar PV was initially used only in space exploration because of its high price and low power generation efficiency. The efficiency was just 14% in the space program in 1960, with around  $82 \in$  per watt. Thanks to improved technology and production, the efficient solar PV has reached 20%, with a lower average cost of  $0.41 \in /W$  (Vivint solar 2019).

In the past ten years, the payback period has been reduced to 3-5 years by improving solar panels and manufacturing methods based on sunlight conditions in the installation area. Figure 19 illustrates the cumulative installed capacity and the change of LCOE of utility-scale solar PV over the past ten years.





From the above figure, we can see that the falling prices have made PV more competitive, and so installations have exploded over the past decade. According to the International Renewable Energy Agency, the global solar PV cumulative installed capacity has reached 633 GW, including 3.4 GW off-grid solar PV by the end of 2019, 23% of the total renewable energy installed capacity worldwide. China is leading the world, holding 204 GW solar PV capacity. Although Germany is not

one of the countries holding abundant solar resources worldwide, it is the pioneer to develop solar PV. It already has a cumulative solar PV capacity of roughly 49 GW by the end of 2019, covering 8% of its total electricity consumption. In April 2020, due to the plenty of sun intensity, the share of solar PV reached a new daily record of 28% of its total electricity consumption (Benjamin Wehrmann 2020) historically.

It has to be noted that the LCOE dropped rapidly from  $102 \in /MWh$  in 2010 to  $33 \in /MWh$  in 2019, which is approximately approach to the capital costs of the coal-fired power plant. For the longer-term view, technology progress in the PV industry will continue with an expectant range for further cost reductions soon. To some extent, solar PV installation will keep rising at over 20% growth rate globally.

Although the solar PV system still has expensive initial costs, it highly relies on weather and solar radiation while maintaining a large land resource scale. One of the crucial advantages of solar PV is that it is flexible and easy to assemble for individual families, hotels, hospitals, rural areas, etc. In this case, people can reduce the electricity bills, and some remote areas that cannot connect to the power grid can be accessible to the electricity service.

# 2.4.4.2 The flexibility of solar PV power plants

The solar PV power plant takes only a few seconds to start up from zero loads to its full load under the rated sun radiation. One studies says that the ramp rate of the solar PV power plants is between 8.3%/min to 16.7%/min (George Dickeson et al. 2017)or at the average level of 200MW/minute (Alejandro Hoese 2016), which is even significantly faster than a hydropower power plant. Recent operational experience in La Ola Island has shown that the ramp rate of solar PV power plants can be as high as 63%/min of the rated capacity, while the aim is to limit the ramp rate to 30%/min. In New South Wales, where solar PV power plants are limited to 50%/min, Australia's Commonwealth Scientific and Industrial Research Organization report that PV capacity can rise at rates of up to 8%/s. A study conducted on a system in Mesa del Sol, New Mexico, recorded a solar PV power plants in distribution systems, the high ramp rate variation will bring significant voltage fluctuations. Therefore, to improve the penetration level of solar PV in the power system, it is necessary to adopt a ramp rate control strategy to reduce the fluctuation of solar PV power plant's output and the ability to respond to the frequency fluctuation of the power system.

Countries with high solar PV penetration have limits on the output power of solar PV power plants connected to the grid and requirements on frequency modulation capabilities. For example, the Puerto Rico Power Authority regulates that the output power of solar PV power plants changes at a rate of 10%/min. Similarly, in Germany, where transmission system operators require solar PV power plants to provide a forward ramp rate of 10%/min, solar PV power plants can only inject a maximum of 70% of their rated capacity into the grid. This allows energy storage systems and PV inverters to respond to fluctuations in output power(Mahmood Reaz Sunny and Nabid Faiem 2015).

Unlike wind turbines, PV modules do not have rotating masses, so they cannot provide an inertial response. However, the inverters are capable of frequency control. They respond much faster than the main frequency responses currently in use. In a way, they are about as fast as one can get except for battery storage power stations. On the one hand, the output can be reduced and increased through smart inverters or by simply disconnecting some of the inverters. On the other hand, the generation of energy is directly converted from solar energy to electricity, unlike traditional thermal and hydroelectric power plants, which have complex processes that require converting energy from different forms to mechanical energy or heat energy and finally convert to electricity. If needed, the inverter can respond quickly to restore the frequency so that the initial supply and demand imbalance cannot be detected. Of course, the fast frequency response of a solar PV power plant only occurs when the solar PV plant is under low load,

There are two main technical ways to use inverters for frequency control: grid-following or grid-forming (Christia Roselund 2019).

- a. Grid-following inverters actively measure the grid voltage and frequency and input the realtime active and reactive power needed by the grid.
- b. Grid-forming inverters create a local voltage and frequency and then try to adjust this voltage so that the real-time active and reactive power needed by the grid flows into the grid.

Although primary frequency response from solar PV power plants is not widely required, few countries already issued the frequency regulation requirement for solar PV power plants. In China, grid-connected centralized solar PV power plants with 30MW and above must have a primary frequency response function (National Energy Administration 2020). Germany requires that once the power system frequency is more significant than 50.2Hz, the solar PV power plants have to participate in the frequency modulation. For every 1Hz increase in the system frequency, the available real-time output of new energy will be reduced by 40% (Dawei Zhao et al. 2019). In 2009, the Federal Energy Regulatory Commission of the United States published a bill, which requires both large and small solar PV power plants to "install, maintain, and operate equipment capable of providing primary frequency response as a condition of interconnection" to mitigate the potential reliability impact of the increasing solar PV and WPPs(Christia Roselund 2019).

#### 2.4.5 Biogas power plant

#### 2.4.5.1 The history and status quo

Humans have been using biogas for centuries. Evidence suggests the earliest use of biogas back to the Assyrians in the 10th century (Homebiogas 2020). As fossil fuels price increased since the early 20th century, various industrial and small-scale biogas systems began to emerge. Since then, small household biogas fermenters have been widely used in rural areas of China and India. Corn, weeds, other organic matters, and poultry and family members' excrement are all fermentation sources. This provides locals with a more significant fuel source than burning charcoal, reducing health problems and environmental pollution.

The biogas production is based on biological fermentation in an anaerobic digester to produce methane and carbon dioxide. The mixture is typically 60% methane and 40% carbon dioxide, similar to natural gas—99% methane. The organic matter comes from the brewery, distillery waste, animal slurry, manure, meat packing waste, human excreta, etc. 1kg cattle dung can produce 40 liters biogas specific temperature and pressure. The daily biogas production can be calculated by using the following equation (International renewable energy agency 2016):

$$G = C * V_d * S * \left(\frac{k}{1+kR}\right)$$
 Eq.3

#### Where:

G is the biogas production in m<sup>3</sup>/kg;

C is the unique attribute of each feedstock, which represents the amount of biogas that can be produced by 1kg of volatile solids in  $m^3/kg$ ;

 $V_d$  is the digester volume in m<sup>3</sup>;

S is the initial concentration of volatile solids in the slurry in kg.m<sup>3</sup>;

R is the feedstock retention time in days;

k is a constant value meaning the rate of gas production at a given temperature;

Figure 20 shows the modern biogas power plant, which consists of manure collection into the tank, anaerobic digester, effluent treatment, biogas storage tank, and electricity-generating equipment. The waste of livestock and poultry is stored in the collection tank before being treated to the homogenization tank, equipped with a stirrer to facilitate the waste stream homogenization. The evenly mixed waste is obtained in uniform size through a dipping machine and then pumped into an anaerobic digester of appropriate volume, where the organic waste is stabilized. The bacteria decompose at the right temperature to convert organic matter into methane and carbon dioxide. The missed gas will be passed into the gas tank, where it will be filtered to get the pure methane. The methane will flow into the generation unit to produce electricity and heat. The rest of the fermented slurry will be treated as fertilizer.

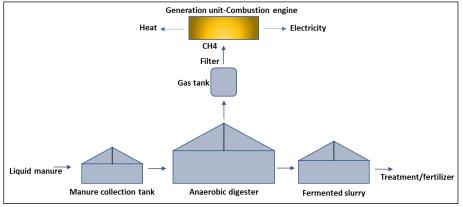


Figure 20 The structure of biogas power plant

Biogas has been developed as a high-quality technology in the world. The total installed capacity of the biogas power plant has reached 139GW by the end of 2019. Germany is one of the leading countries of the high-quality components and good knowledge required for electricity-generating biogas plants. Currently, they are 8.9GW biogas power plant installed capacity are operation in

Germany. The biogas power plant is also popularly used in China. China leads the market using biogas energy, which pushes itself holing the significant share of the world's 16% total capacity.

We can see many advantages of the biogas power plant. Firstly, it is clean and renewable. There is roughly no pollution during the biogas generation. Besides, The rest matter of fermentation is nutrient-rich natural organic fertilizer. Whereas food poisoning and water pollution are caused by a large amount of commercial fertilizer used today. Moreover, small family-biogas stations in most rural areas in the world provide an alternative solution for local people to cook instead of burning wood. However, the low efficiency of biogas power plants today is one of the points. So far, we cannot see a very innovative technology to simplify the process and make it much more efficient and economical. Besides, large-scale biogas power plants rely on raw materials. Meanwhile, the fermentation process produces pungent gases that make people uncomfortable. Therefore, the biogas power plant is appropriately located in rural and suburban areas.

### 2.4.5.2 The flexibility of biogas power plant

Unlike wind power and solar PV plants, which depend on unpredictable climate factors, biogas production can be relatively well controlled by the amount of substrate fed to the biogas plant. In reality, biogas production can only meet long-term demand. Because the biogas reactor contains sensitive microorganisms, short-term fluctuations are difficult to offset. Most biogas power plants operating in Europe are currently designed as base-load plants that continuously convert biogas into electricity and heat in cogeneration units, typically operating for more than 8.000 full load hours per year (Saracevic Ervin et al. 2019). Biogas can also be stored temporarily and turned into electricity later. The combination of biogas power generation and the electrical and thermal efficiency of the energy conversion of cogeneration units are necessary for demand-oriented flexible power generation. Biogas can be stored in-situ at the plant through internal or external biogas storage units, or it can be filtered and stored in a gas grid that removes carbon dioxide and impurities. However, biogas storage requires additional financial outlays due to investment and maintenance costs.

Ideally, the technology of fuel cells can directly convert biogas into electricity. Using fuel like biogas in a fuel cell avoids burning gases or pollutants from combustion-based power plants. However, the fuel cell requires relatively clean gas, and the costs are pretty high. Therefore, using the

37

combustion engine becomes an excellent solution to convert biogas into electricity. Biogas is higher knock resistance than natural gas and can also be used in combustion motors with high compression rates. The production of electricity from biogas could be a very efficient process as long as the generator's rest heat can be captured and used appropriately. The CHP is widely used to improve efficiency. It can achieve 80% energy conversion efficiency.

Because some microorganisms in anaerobic sludge are sensitive to growth conditions and thus reproduce slowly, the start-up time of a biogas plant can be much longer than that of other power plant processes. The process of anaerobic fermentation of microorganisms may take at least a few weeks or even 1-4 months (Bernhard Drosg 2013). Controlling anaerobic fermentation allows microorganisms to grow and multiply to a certain amount to achieve the optimal state of biogas production. Therefore, the time of anaerobic fermentation must be calculated scientifically. It is supposed to be not too long or too short. Otherwise, the production of biogas will be affected, and profits will be reduced. It can be concluded that enough biogas storage is a prerequisite to ensure the stable power output of biogas power plants.

The minimum load of a biogas power plant is 20%, the maximal ramp rate is 6%/minute of its full load (Deloitte 2019). Considering the long process of anaerobic fermentation, biogas power plants usually provide the mid-term and long-term frequency response.

### 2.4.6 Energy storage

To solve grid stability caused by the large-scale access of wind power and solar PV power plants, energy storage technology has been paid more and more attention by enterprises, governments, and research institutions. Energy storage facilities can store power generated when resource conditions are abundant, but demand is low and respond quickly to grid demand during peak loads. For example, when the wind resource is abundant on a hot summer night, the wind power plant produces a large amount of excess electricity, which can be stored. When it is hot in the day and many electrical types of equipment, such as air conditioners and refrigerators, are turned on, the energy storage can quickly respond to the load demand and release electricity.

Although we can see quite often the news about the implementation of utility-scale energy storage, such as in 2017, Tesla the world's largest utility-scale 250MW energy storage facility in

Hornsdale, South Australia (Julian Spector 2020). After that, the facility has played an important role in supplying, stabilizing, and balancing the unreliable local grid. This application has convinced people to apply large-scale energy storage cooperating with renewable energy plants, such as wind and solar PV power plants. However, the large-scale application still heavily relies on policy support as a result of the expensive costs. According to the IEA, the installed capacity of energy storage facilities will increase to 1.095GW by 2040 from 9GW in 2018. The market for residential energy storage is experiencing a rapid increase around the world. There are 206.000 individual residential energy storage units under operation by the end of 2019, with a 44% increase compared with the previous year.

Energy storage technologies include pumped hydro, battery energy storage, flywheel energy storage. Pumped hydro currently accounts for 96% of energy storage capacity due to lower costs. However, in the long term, as battery costs fall, more flexible and cheaper forms of energy storage will be available in the future. Table 12 below illustrates the comparison of different energy storage technologies, including the max rating power, discharging time, response time to the power deviation, and the energy conversion efficiency.

	Max power rating	Discharge	Response	Cost	Efficiency
	(MW)	time	time	(€/kWh)	
Pumped	3.000	4-16h	Few seconds	87-164	70-85%
hydro					
Batteries	100	1min-8h	<seconds< td=""><td>300-1.000</td><td>85%-95%</td></seconds<>	300-1.000	85%-95%
Flywheel	20	Secs-mins	<seconds< td=""><td>600-700</td><td>70%-95%</td></seconds<>	600-700	70%-95%

Table 12 Comparison of different energy storage technologies(Source: The World Energy Council)

#### 2.4.6.1 Pumped hydro

The basic idea behind pumped hydro storage facilities is to store electricity as potential energy and then convert that gravitational potential energy into electricity. When electricity production exceeds demand, water is pumped to a reservoir higher up for storage. At peak demand, water is released higher up through water turbines to generate electricity. Pumped hydro storage is more economical than other forms of energy storage, and its installation cost is about  $1.400-5.400 \in$ /kW. Total project costs range between  $87 \in -164 \in$  /kWh (Jason Deign 2020). Moreover, it has a very high power conversion efficiency between 70%-85%. Furthermore, it can respond to the power system's dispatching demands within seconds and work steadily for hours, so it is commonly used as the primary and secondary response unit in the power grid.

### 2.4.6.2 Batteries

With the promotion of electric vehicle technology, lithium-ion battery technology is becoming more mature, and the cost is also falling. In 2018 it was  $172 \\left kWh$ , and people are positively predicting that it will fall to  $100 \\left kWh$  by 2020. Lithium-ion batteries have high energy density and lightweight advantages, and their efficiency can reach 85% to 95%. According to the Strategic Energy Technologies Information System(SETIS) from the European Commission, current energy costs for lithium-ion battery technology are high, about  $500 \\left -1.000 \\left kWh$ . The target for 2020-30 is to reduce these to  $200 \\left kWh$ (SETIS 2020). Besides, rooftop PV panels plus lithium-ion energy storage microgrid system has been widely received. Families with abundant solar energy resources and equipped with a certain capacity of lithium-ion battery energy storage system can achieve energy self-sufficiency to a certain extent, or even sell electricity to the large power grid, which is also a major trend of the future development of smart power grid. The battery storage facility's response time to the power grid's deviation is less than a second. It can be used as the primary response unit in the power system.

### 2.4.6.3 Flywheel

The motor stores energy by increasing the speed of the flywheel. The motor can then use the stored kinetic energy to generate electricity by reversing it. The flywheel is not adversely affected by temperature changes, can operate over a more comprehensive temperature range, and is not affected by chemically charged batteries' common faults. They are also less potentially damaging to the environment. Another advantage of the flywheel is that the exact amount of energy stored can be known simply by measuring rotation speed. Most modern flywheels are typically sealed devices that require very little maintenance over their entire life. They are, therefore, superior to batteries in terms of overall life and energy storage capacity. The energy cost of flywheel systems is about  $3.500 \in -4.000 \in /kW$ , with power-related costs of between  $600 \in -700 \in /kWh$  (SETIS 2020), which remains higher compared with other energy storage facilities. The response time to the deviation of the flywheel facility is just within milliseconds. Therefore, it can be used as the primary response unit.

# 2.5 Carbon emission

According to the World Nuclear Association(WNA), the carbon emission of each power plant during its entire lifecycle is shown in the following table (WNA 2011).

Power plants	Mean (T e/GWh)	Low (T e/GWh)	High (T e/GWh)
Coal-fired	888	756	1.310
Gas turbine	499	362	891
Solar PV	85	13	731
Biogas	45	10	101
Nuclear	29	2	130
Hydropower	26	2	237
Wind	26	6	124

Table 13 The carbon emission of each power plant during the whole lifecycle

### **2.6 LCOE**

Table 14 shows the LOCE of different power plant technologies based on the data from IEA (IEA 2020).

Power plants	Mean ( $\epsilon$ /MWh)	Low(€/MWh)	High(€/MWh)
Biogas	97	71	123
Wind offshore	72	64	89
Coal-fired	72	64	80
Hydro reservoir	59	39	87
Gas turbine	58	41	73
Nuclear	57	43	62
Hydro run of river	56	44	70
Solar PV	46	35	70
Wind onshore	41	32	53

Table 14 The LCOE of each power plant technology

# 2.7 Summary

# 2.7.1 Startup time

From the previous chapters, we can conclude the average startup time characteristic of different power plants showing as the following Table 15. We can observe that power plants' startup times vary depending on the complexity of the generation process, mostly when all the processes have been stopped and restarted, that is, cold startup.

Power plant	Startup time
Flywheel	Within few milliseconds(ms)
Batteries	3ms-few seconds
Pumped hydro	25-300 seconds
Solar PV	Few seconds
Hydropower	Within 10 minutes
Wind	Tens of seconds/few minutes
Gas engine	1-5 minutes
OCGT	5-6 minutes
CCGT	30-240 minutes
Coal-fired	1-10 hours
Nuclear	3 days-a week
Biogas	Few weeks – few months

*Table 15 The startup time of different power plants* 

Table 15 also shows that energy storage units, including flywheel, batteries, and pumped hydro units, take only a few milliseconds to few seconds to startup, which is the fastest unit than other power plants. Thanks to the solar PV effect and efficient inverters, the solar PV power plants also take few seconds to start from command to full load provided there is the proper temperature, humidity, and appropriate solar radiation. Meanwhile, once the wind speed is sufficient and constant, the WPPs take few minutes to startup. The hydropower plants can run from cold start to full load within few minutes but less than 10 minutes. When it comes to gas engine power plants, which use the combusted natural gas to spin the turbine to produce electricity. It takes roughly between 1-5 minutes to startup. The OCGT, which without the structure of heat recycling, takes less time to a startup than CCGT. 5-11 minutes are enough for OCGT. Most CCGT can reach full operations between one hour to 4 hours, although some can startup within an hour. Conventional steam turbines usually take more time due to steam needs to reach a specific temperature, pressure, and moisture content thresholds before being guided to a turbine that can spin a generator. For example, the coal-fired steam power plants take 1-10 hours to startup. Nuclear power plants also use steam turbines, but it has another time-intensive process involving managing nuclear fuel. Almost all nuclear power plants take more than 12 hours or even three days until a week to be fully operational. If considering the process of anaerobic fermentation of microorganisms, the biogas power plant may take at least a few weeks or even 1-4 months to collect sufficient methane fuel. Only if adequate methane fuel is stored can the biogas power plant get command and startup.

In chapter 2, we discussed the peak load and baseload. As we all know, the consumption of electricity changes during the day, week and season. In general, the residential electricity consumption has the lowest load happening in the early morning. The consumption is gradually increasing in the early morning and reaches the peak at that moment of midday. And then the consumption will gradually decrease and reach the lowest point until early of next morning. Therefore, different power plants' requirement to meet the electricity demand at peak load and baseload is a camp up to ensure the power grid's stability. The startup time we discussed in the previous paragraphs reflects the flexibility to react to the peak demand. Since the peak demand always happens within a short time, few seconds, or minutes, it requires a fast compensation to shut down or shut up.

### 2.7.2 The full-load hours

Figure 21 shows the estimated number of hours of German power plants running at full capacity in 2017. As we can see, conventional power plants, such as nuclear and coal-fired power plants have the highest full load hours. And then follows by the bioenergy and offshore WPPs. Onshore WPPs cannot continue to work due to seasonal and unstable changes in wind resources. As offshore wind resources are abundant, the full load hours of offshore WPPs are greater than onshore WPPs. Hydropower plants cannot reach full annual capacity due to seasonal variations in reservoir levels. Due to fluctuations and periodic solar irradiation patterns, the actual operating time of solar PV power plants are less than half of the total 8.760 hours a year. However, when needed, nuclear, coal, and gas plants can operate almost continuously at rated power, 8.760 hours a year(Dr. Harry Wirth 2020).

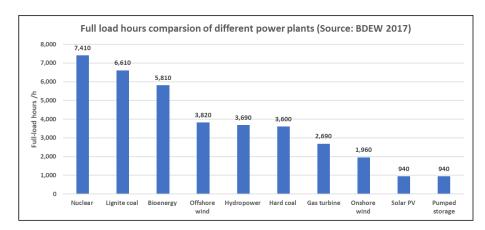


Figure 21 The full load hours of different power plants in Germany

# **Chapter 3 - Simulation**

### 3.1 Mathematic model

Figure 22 shows the blade profile. The leading edge is the front top part of the airfoil, which will first meet the flow; the trailing edge is the airfoil's back tail, which will finally meet the flow. The chord is the middle axis connecting the leading edge and the trailing edge. The upper part is called the suction side, and the opposite side is called the pressure side, which usually has a higher pressure than the suction side when the blades rotate. The upper part of the airfoil is designed to be curved, so the upper part provides a longer path than the lower part. The air particles that reach the leading edge of the airfoil are separated; some flow over the upper part of the airfoil, some flow over the lower part, and to meet at the trailing edge of the airfoil, the air particles in the upper part have to move very fast (Lao Yan 2015). Therefore, according to Bernoulli's law, the greater the speed, the less pressure, and the pressure on the bottom of the airfoil are more significant than the pressure on the top, and when the pressure is big enough, it pushes the airfoil to move up. Then we can see the blades will rotate.

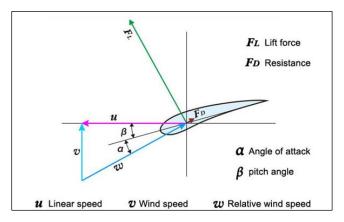


Figure 22 Airfoil pitch angle(Source: Pengky 2020)

The pitch angle represents the fixed angle between the direction you and the forward airfoil direction. The relative wind speed is  $\omega$ , which is the resultant vector between linear speed you and real wind speed v. The angle of attack  $\alpha$  are located between the relative wind speed and chord direction. The purpose of attaching  $\alpha$  is to get the maximum lift force and the lowest resistance.

The blade pitch control has two main purposes: one is to maximize energy extraction from the wind. Another one is to protect the turbine under high wind conditions or extreme weather. Generally, it is called cut-out wind speed, at which condition the pitch angle will rotate to  $90^{\circ}$  in order to avoid the wind flows between the upper and lower blade profile.

0.593 is the Baez limit. This limit tells us that wind turbines' capacity to utilize natural wind energy is limited, ideally up to 59.3%. The power loss is the rotational kinetic energy consumed in the wake. In practical application, the wind energy utilization coefficient of the wind turbine is less than 0.593, which represents the wind energy utilization coefficient,  $C_p$ < 0.593, Based on this, the mechanical power of wind turbine can be obtained as follows:

Where:

 $P_m$  is the mechanical power of the wind turbine;  $\rho$  is the air density; R is the radius of the blade;  $v_w$  is the wind speed;  $C_p$  is the power coefficient;  $\beta$  is the pitch angle;  $\lambda$  is the tip speed ratio;

The tip speed ratio  $\lambda$  is a factor that illustrates the ratio between the speed of the wind turbine blades' tips and the real wind speed. It has the following mathematical relationship:

$$\lambda = \frac{R\omega}{v_w} \qquad \qquad Eq.5$$

Where:  $\omega$  is the rotor speed (rad/s);

From the above equation, when the radius is fixed, the tip speed ratio is dominated by the rotor speed and the wind speed. Assuming that the wind speed at the side of the wind turbine and the air's density flowing through it remain unchanged, it can be obtained from the above equation that the wind energy absorbed by the wind turbine is only related to the rotor speed of the generator. That is to say, at a certain wind speed, the wind turbine can get the maximum wind energy only when it operates at a specific rotor speed. Figure 23 illustrates the relationship between the rotor speed and wind speed. We can see that the power output reached its rated power when it works at the rated wind speed. The power output will keep rising when the wind

speed continues to increase. Therefore, the control system will be required to adjust the pitch angle or the rotor speed to keep the power output at the rated power output.

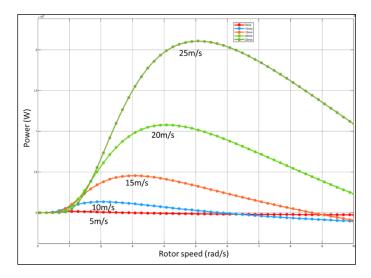


Figure 23 The relation between rotor speed and wind speed

The power coefficient  $C\rho$  satisfies the following mathematical relation:

$$C_{\rho} = 0.5176 \left(\frac{116}{\lambda_{i}} - 0.4\beta - 5\right) e^{\frac{-21}{\lambda_{i}}} + 0.0068\lambda \qquad \qquad Eq.6$$

Where:

$$\frac{1}{\lambda_i} = \frac{1}{\lambda + 0.08\beta} - \frac{0.035}{\beta^3 + 1}$$
 Eq.7

Figure 24 represents the fact that the power coefficient variations with the tip speed ratio change. To some extent, the higher the tip ratio speed, the smaller the power coefficient. Therefore, the tip ratio speed must work at a particular value to get the maximal power coefficient, i.e., must work at rated wind speed or rated rotor speed. Meanwhile, the changing of pitch angle will change the power output. Due to the fast adjustable and startup time, the hydraulic system's pitch angle mechanism participates in the primary frequency control. When the power grid frequency falls, the pitch angle decreases to increase the power output. In reality, the pitch angle control scheme will usually pitch the blades a few degrees to keep the rotor angle optimal and maximize the power extracted from the wind.

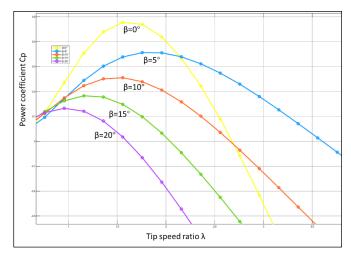


Figure 24 The power coefficient variations with tip speed ratio

# 3.2 Control loop

Figure 25 the open-loop control system of a wind turbine:



Figure 25 The open-loop control block diagram

Figure 26 shows the closed-loop control block diagram:

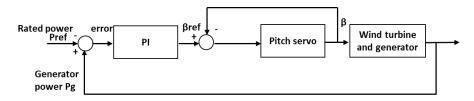
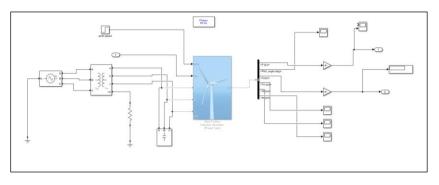
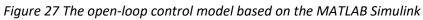


Figure 26 The closed-loop control block diagram

# **3.3 Simulation result**





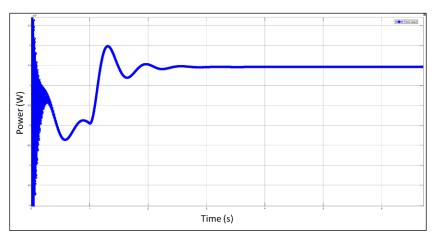


Figure 28 Turbine active power output curve

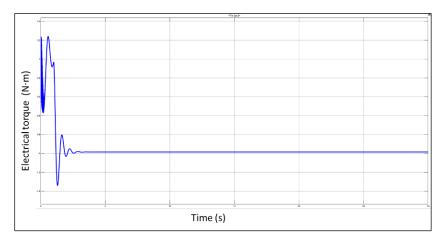


Figure 29 Turbine electrical torque output curve

# Chapter 4 – Conclusion and discussion

# 4.1 Conclusion

# 4.1.1 Base load and peak load

From chapter 2 we know that the base load is a load line that remains almost constant over 24 hours. The power plant responsible for the base-load electricity needs to operate continuously and steadily without shutting down. They are usually large coal-fired and nuclear power plants but can also be powered by hydropower plants, biogas power plants, and CCGT power plants. Although these plants take a long time to start up, this is hardly a problem because they rarely shut down. Fuel costs per kilowatt generated tend to be lower.

The peak load generally does not require a continuous round-the-clock operation. Notably, peak load is managed by smaller, more responsive plants whose power output can be increased, decreased, or switched on and off quickly. Because demand is high, time is shorter, and peak prices are much higher than the prices at base load. Ideally, peak load can be handled by hydropower plants as a result of their high share in the power system and fast ramp rate. Renewable energies, such as solar PV and wind, also have the potential to eliminate the need for peaks, effectively lowering the electricity price at peak load and reducing emissions, especially when they become more reliable and widely available.

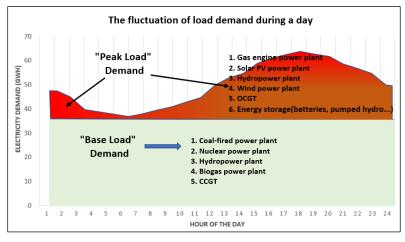


Figure 30 The suppliers of based load demand and peak load demand

The daily process of electricity demand depicts a fluctuating curve showing as above Figure 30. The upper part of the curve, daytime, corresponds to the additional power output required compared to the night level. In the past, this extra demand has been supported by conventional coal-fired and gas turbine power plants in response to demand. Nowadays. much of the extra peak load needed today could be covered by solar and wind power. Since solar PV power plants are concentrated in the daytime and fully follow high load demand for electricity.

#### 4.1.2 The classification of power plants

#### 4.1.2.1 Minimum load and ramp rate

The reaction time of each power plant depends on ramp rate attributes and the power system's requirement. From the above chapters, we can conclude the following chart showing as the Table 16. We can observe that the energy storages, such as batteries, pumped hydro and flywheel units; all have the highest flexibility. They have the attribute to be operated at zero loads of their full load and have the fastest reaction speed, the ramp rate are all approximately 100%/minute, i.e., they can reach their full load within or even less than one minute. As a result of the technology effect and expensive costs, they are generally small, operating as backup units.

A wide operating range is the characteristic of a low minimum load in a power plant. Such plants can operate on a fraction of their maximum load. We can see that REPPs like wind and solar PV power plants are not required to operate at minimum load currently. One reason may be the remaining high fixed costs, which leads to the power suppliers operating the REPPs as much as possible, instead of working at a minimum load. Another reason may be no minimum load requirement in the power system. The ramp rate of solar PV power plants is between 8.3%/minute to 100%/minute based on the latest data from different regions, which is even significantly faster than the hydropower power plant. The wind power plant has a 10%/minute - 100%/minute ramp rate. Besides, the hydropower plant is also relatively flexible. It has a 5% minimum load and a 15%/minute ramp rate.

When it comes to conventional power plants, the gas engine power plant is considered the most flexible. It has the fastest startup time and lowest minimum load. Meanwhile, modularity further increases the flexibility of the operating range. It can reach 100% load within less than one minute. OCGT has a relatively lower minimum load and higher ramp rate than CCGT due to the lack of a

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heat recycling system. Even though CCGT has higher efficiency, OCGT has higher flexibility. The coal-fired have the minimum load attribute of 30% of its full load. Finally, it is worth noting that the nuclear power plant has the lowest flexibility of any other power plant. It has the 50% of its minimum load, and the ramp rate is relevant lower, around 2%/minute.

Power plants	Minimum load (% full load)	Ramp rate (%full load/minute)
Batteries	0	100%
Pumped hydro	0	100%
Flywheel	0	100%
Gas engine	10%	60%-100%
Solar PV	-	8.3%-100%
Wind	-	10%-100%
Hydropower	5%	15%
OCGT	15%	20%
CCGT	20%	8%
Biogas	20%	6%
Coal-fired	30%	6%
Nuclear	50%	2%

Table 16 The minimum load and ramp rate of different power plants

In chapter 2, different power plants are divided into three categories based on their response time to the power system—the primary response power plant, secondary response power plant, and tertiary response power plant. The primary frequency response is fundamental and autonomous to support the power system. It will continue to function without any external power input, forcing the necessary relationship between speed and power. The secondary control is used to compensate for the frequency deviation caused by the central control. The tertiary control is used to optimize operation in two operating modes and power flow control in grid-connected mode.

### 4.1.2.2 Classification

### --Theoretically

In theoretically, gas engine, hydropower, and OCGT power plants are considered highly flexible power plants, which are defined as the primary response units. Besides, biogas and OCGT power

plants are flexible generation technologies. Moreover, due to the relatively higher minimum load and lower ramp rate, the coal-fired and nuclear power plants take a longer time to respond to the frequency deviation, which is considered as the inflexible power plants. Table 17 shows the theoretical classification of different response power plants.

	retieur clussification of utfferent re	sponse power planes
Primary response	Secondary response	Tertiary response
Gas engine	Biogas	Nuclear
Hydropower	CCGT	Coal-fired
OCGT		

Table 17 The theoretical classification of different response power plants

### -- In reality

In reality, depending on the size of the load set point, the load deviation, and the type of control, the flow turbine may be faster in response. Meanwhile, due to the high share in the power system worldwide, with the advanced control strategies, large and flexible coal-fired power plants can also provide excellent frequency response. Table 18 shows the current classification of different response power plants. Although the REPPs and power storages like batteries all have the higher flexibility to react to the power system deviation, they are not extensively involved in the frequency modulation of electricity supply as a result of the low share and expensive fixed costs.

Primary response	Secondary response	Tertiary response
Gas engine	Biogas	Nuclear
Hydropower	CCGT	Coal-fired
OCGT	Large coal-fired	
Large coal-fired		

*Table 18 The current classification of different response power plants* 

# -- In the future

With the high penetration of wind and solar PV power plants in the power system, as well as the decline costs of energy storages. Besides, more and more countries are phasing out coal-fired and nuclear power plants, which leads to a lower and lower share of the electricity system, but they will not be phased out completely in the short term, they will be retained to a certain capacity to continue to provide base load stability. Table 19 shows the future classification of different response power plants.

Primary response	Secondary response	Tertiary response
Batteries	Pumped hydro	Nuclear
Pumped hydro	Biogas	Coal-fired
Flywheel	Solar PV	OCGT
Hydropower	Wind power	CCGT
Solar PV		
Wind power		

Table 19 The future classification of different response power plants

## 4.2 Discussion

### 4.2.1 Uncertainties

Different countries have different requirements of power plants for frequency response, which highly depends on the electricity sources and the local policies. In this thesis, some typical countries have been studies, such as Europe, Germany, China, Russia, the USA, and India. The conclusion is based on the situation in most countries, it does not represent the situation of every country.

The startup time differs from various producers depending on the size, technology. The larger size, the bigger the ramp rate. In this thesis, the average figures have been used, but it does not represent every device offered by a different producer. In some special situations, the coal-fired power plant might have a higher ramp rate than a gas turbine power plant.

# 4.2.2 The conventional power plants will still dominate the power system in short term view

Solar PV and wind power are currently capable to reduce fossil fuel consumption and carbon dioxide emission to some extent. However, they will not completely replace conventional power plants until a significant hydroelectric or energy storage plant is on the grid. Especially in the winter, when there is no wind or sun when electricity consumption is at its maximum, and there is no solar or wind available, conventional power plants must run at a high load capacity to fulfill the demand.

In the absence of commercial and cost-effective large-scale storage capacity, the impact of the growing popularity of solar and wind power in some countries has forced fossil fuel power plants to provide highly variable output to meet the load from moment to moment. As a result, thermal power plants initially designed for the base load will increasingly need to operate under load or

cycle. That means they need to ramp up and down the hill more often, faster, and more costeffectively to reach some of the load. A study indicated that the hydropower plant would largely provide the primary response in Germany and the EU when the REPPs have a high penetration rate in the power system(Appendix C).

#### 4.2.3 The dispatching of the power system is a combination of flexibility

Schedulable power plants, demand-side, and energy storage facilities need to provide different types of flexibility. There is no single flexibility option that effectively provides all flexibility requirements; it combines different options. At the same time, all sources of flexibility complement and compete with each other. It is impossible to predict which combination will be in the future, but providing a level playing field is necessary for finding the best combination. Transparent market rules, regulations, and environmental policies promote competition among all flexible options. The bidding mechanism of the European grid is sufficient for the flexible dispatch of the power system.

# 4.2.4 The share of REPPs will gradually increase and provide frequency response in the future

Developments over the past few decades have brought the cost of renewables such as solar PV and wind power down rapidly, and in some areas are now lower than the cost of coal-fired power plants. Renewable energy is expected to grow rapidly in the coming years, with most countries planning to cut carbon emissions.

The countries withholding a high share of REPPs have required the solar PV and wind power plants to provide the frequency response, such as Denmark, Germany, China. Meanwhile, incentives must be offered by the national policies, otherwise, it will lead the economic loss.

# Chapter 5 – Future work & Outlook

# 5.1 Future work

### 5.1.1 The economic assessment of operation costs of each power plant

The operating costs of power plants include fuel, labor, and maintenance costs. The total operating costs of a plant depend on how much electricity the plant produces. Fuel costs dominate the total operating costs of thermal power plants like gas and coal. For renewable energy, the fuel is usually free except for biomass power plants, which have to buy different feedstock, and in fact, the fuel cost for nuclear power plants is meager.

In general, the dispatch center must consider capital and operating costs. Those with higher capital costs tend to have lower operating costs. For example, the capital cost of a solar PV power plant is around 3.600  $\in$  /kW, but its operating cost is 0.01  $\in$  /kWh(Seth Blumsack 2020)(Appendix A).

### 5.1.2 The solutions to improve the ramp rate of conventional power plants

Besides, the inevitable effect of increasing wind and solar PV power plants capacity in the power system will lead to the decline of the capacity factor of base-load plants, and there will be an increasing demand to regulate and track the load left by wind and solar PV power plants as their output energy changes. To some extent, thermal power plants, such as coal-fired and gas turbine power plants must although operate to supply the base load, are also supposed to react more flexibly. To reduce the minimum load, increasing the ramp rate parameters as well as advanced control strategies will bring them more possibilities to participate in the power system deviation.

### 5.1.3 The solutions to improve the inertia response

A large number of REPPs connected to the power system will replace the traditional power plants, which will lead to a reduced inertia response of the power system. When inertia is low, frequency fluctuations become faster, so the system will likely enter an emergency state before the secondary control is activated. The primary control of conventional power plants may not be sufficient or fast enough to control the frequency. The inertia response from wind turbines and hydropower plants would be a research topic in the future.

### 5.2 Outlook

#### 5.2.1 More efficient and flexible conventional power plants

The intermittency of RES will increase the number of times conventional power plants start and stop, requiring greater flexibility. It is necessary to upgrade traditional power plants' technology, making them have a smaller minimum load to allow for a broader range of dispatching capabilities. Reducing startup time and increase their ramp rate to improve response time. For instance, Gas turbine efficiency and ramp rate will be improved by compressed air injection; after upgrading the control system of a particular coal-fired power plant in Germany, the software was optimized. These upgrades reduced the minimum load by 170 MW and increased the slope rate by 10 MW/min in one unit, which brings in millions of euros in extra income before interest and taxes.

#### 5.2.2 Wind and solar PV will participate in a large scale the power system response

It is foreseeable that the installation of wind and solar PV power plants will continue to grow at a high rate as a result of many countries have set clear targets to reach the peak of carbon emissions. Technically, wind turbines can provide all three types of reserve capacity. The output can be adjusted by changing the pitch angle. Solar PV power plants can quickly disconnect and link inverters to respond to grid demands. Wind and solar PV power plants will be required to provide frequency response in the regions where have high penetration. Large-scale involvement of renewable energies in the dispatch and frequency modulation in power systems can effectively reduce the dependence of conventional power plants, thereby reducing fossil fuel emissions.

#### 5.2.3 Energy storage will play a big role

In the long term, the development of energy storage technology and reducing costs will effectively solve the intermittent of wind and solar PV. Large utility battery storage units have proven to be economically and technically feasible in Australia and China. With the increase of marketization and the decrease of battery cost, more and more solar PV and wind power plants will be equipped with specific energy storage devices, which will enable them to provide power output and participate in scheduling more stably. For example, in some regions in China, energy storage facilities are mandatory for new solar PV and wind power plants. The energy storage capacity is considered as 20% of the project installed capacity, and the energy storage time is 2 hours.

#### 5.2.4 Power to gas, the power to liquid

Power to gas(PTG), the power to liquid(PTL), new and additional electricity consumers, make it possible to provide renewable energy for all applications. Only through the use of PTG and PTL in industries that are still highly dependent on fossil fuels, including transportation, aerospace, and shipping, will it be possible to achieve energy supply based entirely on renewable resources in the long term, without the use of artificial biomass.

Among them, electrolytic hydrogen production technology by many countries attention. Offshore wind power is considered to have a geographical advantage, providing excess energy for electrolytic hydrogen production and storing it. Hydrogen is clean energy, which will replace natural gas as the fuel source of gas turbines.

#### 5.2.5 Energy network makes the dispatch of power system more intelligent

Energy networks, artificial intelligence, and other digital technologies can make the dispatching of the power grid more accurate and intelligent. For example, the analysis of big data can accurately predict the demand load and determine the generation capacity of REPPs through the forecast analysis of weather data to make scheduling arrangements in advance.

In power stations, a large amount of process data is permanently recorded, which provides information about the system's state. This data can be used to optimize the entire process or even individual components. The aim is always to improve efficiency, make operational methods more flexible, and better predict operations. For example, by evaluating process data, the energy requirements of components can be minimized, or the startup efficiency of plant modules can be improved, thus saving resources.

# **Publication bibliography**

50Hertz Transmission GmbH (2020): Balancing energy. Cooperating for Grid Control. Available online at https://www.50hertz.com/en/Market/Balancingenergy, checked on 11/3/2020.

Agora Energiewende (2015): The European Power System in 2030: Flexibility Challenges and Integration Benefits, checked on 1/3/2021.

Alejandro Hoese (2016): What is the typical MW/minute ramping capability for each type of reserve? Available online at

https://www.researchgate.net/post/What\_is\_the\_typical\_MW\_minute\_ramping\_capability\_for\_ each\_type\_of\_reserve, checked on 2/13/2021.

Amprion GmbH (2020): Balancing capacity in Germany. Amprion GmbH. Available online at https://www.amprion.net/Energy-Market/Market-Platform/Control-Energy/, checked on 11/2/2020.

Asko Vuorinen (2020): Frequency control and regulating reserves, 2020, checked on 2/16/2021.

Bernhard Drosg (2013): Process monitorng in biogas plants, checked on 1/14/2021.

Carlos Perez Linkenheil; Isabelle Küchle; Tobias kurth; Fabian Huneke (2017): Flexibility Needs and Options for Europe's Future Electricity System - an Evaluation, checked on 12/27/2020.

Christia Roselund (2019): Inertia, frequency regulation and the grid. PV Magazine. Available online at https://pv-magazine-usa.com/2019/03/01/inertia-frequency-regulation-and-the-grid/, checked on 1/22/2021.

Dawei Zhao; Jin Ma; Huimin Qian; Wancheng Wang (2019): Photovoltaic power station participates in the control gain study of primary frequency modulation of large power grid. Available online at http://www.doc88.com/p-0048453930746.html, checked on 12/12/2020.

Deloitte (2019): Assessing the flexibility of coal-fired power plants for the integration of renewable energy in Germany. Available online at https://www2.deloitte.com/content/dam/Deloitte/fr/Documents/financial-

advisory/economicadvisory/deloitte\_assessing-flexibility-coal-fired-power-plants.pdf, checked on 2/13/2021.

Dennis Normile (2020): Can China, the world's biggest coal consumer, become carbon neutral by 2060? Asia/Pacific, Climate, Enviroment. Available online at https://www.sciencemag.org/news/2020/09/can-china-worlds-bigger-coal-consumer-become-carbon-neutral-2060, checked on 10/23/2020.

Dr. Andreas Feldüller (2017): Flexibility of coal and gas fired power plants. Available online at https://www.cleanenergyministerial.org/sites/default/files/2018-01/Andreas%20Feldmueller%20Siemens.pdf, checked on 2/19/2021.

Dr. Harry Wirth (2020): Recent Facts about Photovoltaics in Germany, checked on 1/21/2021.

Dr. Robert Peltier (2019): Flexible Operation of Nuclear Power Plants Ramps Up. Available online at https://www.powermag.com/flexible-operation-of-nuclear-power-plants-ramps-up/, checked on 12/17/2020.

Ela Erik; Tuohy Aidan; Milligan Michael; Kirby Brendan; Brooks Daniel (2012): Alternative Approaches for Incentivizing the Frequency Responsive Reserve Ancillary Service. In *The Electricity Journal* 25 (4), pp. 88–102. DOI: 10.1016/j.tej.2012.04.015.

EnergiMine (2019): Understanding peak and base load. Available online at https://medium.com/energimine-news/what-is-peak-and-base-load-7dffd707fb71#\_msocom\_1.

Fabian Huneke (2016): Climate Action Plan 2050 - Germany's long-term emission development strategy. Goal and content. Available online at https://www.bmu.de/en/topics/climate-energy/climate/national-climate-policy/greenhouse-gas-neutral-germany-2050/#c12744, checked on 10/23/2020.

Federal Ministry for Economic Affairs and Energy (2020): Development-of-renewable-energysources-in-germany-2019, checked on 1/6/2021.

George Dickeson; Lachlan McLeod; Anthony Dobb; Lyndon Frearson; Bert Herteleer; Dione Scheltus (2017): ramp-rate-control-for-pv-plant-integration-experience-from-karratha-airportshybrid-power-station. Available online at https://arena.gov.au/assets/2017/02/ramp-ratecontrol-for-pv-plant-integration-experience-from-karratha-airports-hybrid-power-station.pdf, checked on 2/13/2021.

Gonzalez-Salazar Miguel Angel; Kirsten Trevor; Prchlik Lubos (2018): Review of the operational flexibility and emissions of gas- and coal-fired power plants in a future with growing renewables. In *Renewable and Sustainable Energy Reviews* 82 (Nr. 024022), pp. 1497–1513. DOI: 10.1016/j.rser.2017.05.278.

Haihua Song; Wuping Liu; Fuping Liu (2015): The influence of the primary frequency resonse of coal-fired power plant to the power system. Available online at https://www.ixueshu.com/document/6880d4cbb106d1b50dc4a1db7e82f151318947a18e7f9386 .html#, checked on 2/20/2021.

Homebiogas (2020): What is Biogas? A Beginners Guide. Available online at https://www.homebiogas.com/Blog/142/What\_is\_Biogas%7Cfq%7C\_A\_Beginners\_Guide, checked on 1/12/2021.

IAEA (2018): Non-baseload Operation in Nuclear Power Plants: Load Following and Frequency Control Modes of Flexible Operation. Available online at https://wwwpub.iaea.org/MTCD/Publications/PDF/Pub1542\_web.pdf.

Ibrahim Nassar; Salaheddin Alali; Harald Weber (2014): Effects of Increasing Intermittent Generation ‎ on the Frequency Control of the ‎ European Power System, checked on 1/31/2021.

IEA (2020): Projected costs of generating electricity 2020. With assistance of International Energy Agency. Available online at https://www.iea.org/reports/projected-costs-of-generating-electricity-2020, checked on 2/24/2021.

Illian Howard F. (2010): Frequency Control Performance Measurement and Requirements, checked on 12/5/2020.

International Energy Agency (2020): Electricity Information: Overview. Available online at https://www.iea.org/reports/electricity-information-overview, checked on 10/23/2020.

International renewable energy agency (2016): Measuring Small-scale Biogas Capacity and Production, checked on 1/12/2021.

International renewable energy agency (2019): Innovation landscape brief: Flexibility in conventional power plants, checked on 1/3/2021.

Jason Deign (2020): Pumped Hydro Moves to Retain Storage Market Leadership. Available online at https://www.greentechmedia.com/articles/read/pumped-hydro-moves-to-retain-storage-market-leadership, checked on 2/12/2021.

John A Dutton (2018): Introduction to Electricity Markets. The Dispatch of Power Plants by an Electric Utility. PennState College of Earth and Minernal Sciences. Available online at https://www.e-education.psu.edu/ebf483/node/534, checked on 11/1/2020.

John Undrill, L. L.C. (2018): Primary Frequency Response and Control of Power System Frequency. Energy Analysis and Environmental Impacts Division. Lawrence Berkeley National Laboratory, 1 Cyclotron Road, MS 90R4000 Berkeley CA 94720-8136. Ernest Orlando Lawrence Berkeley National Laboratory, checked on 06,06,2020.

Joseph Ferrari (2014): Power System Optimization by Increased Flexibility. Agile gas-based power plants for affordable, reliable and sustainable power, checked on 1/14/2021.

Julian Spector (2020): Australia Picks Massive Tesla-Supplied Battery to Ease Transmission Constraint. Available online at https://www.greentechmedia.com/articles/read/australia-picksmassive-tesla-battery-to-ease-transmission-constraint, checked on 1/15/2020.

Kamal Abudu; Uyioghosa Igie; Orlando Minervino (2020): Gas turbine efficiency and ramp rate improvement through compressed air injection. Available online at https://journals.sagepub.com/doi/full/10.1177/0957650920932083, checked on 1/31/2021.

Karsten Capion (2019): Why German coal power is falling fast in 2019? . Available online at https://www.carbonbrief.org/guest-post-why-german-coal-power-is-falling-fast-in-2019, checked on 2/18/2021.

Kerstine Appunn; Yannick Haas; Julian Wettengel (2020): Germany's energy consumption and power mix in charts. Clean Energy Wire. Available online at https://www.cleanenergywire.org/factsheets/germanys-energy-consumption-and-power-mixcharts, checked on 10/23/2020.

Kirsten Trevor; Gonzalez-Salazar Miguel Angel; Prchlik Lubos (2018): Review of the operational flexibility and emissions of gas- and coal-fired power plants in a future with growing renewables. In *Renewable and Sustainable Energy Reviews* 82 (Nr. 024022), pp. 1497–1513. DOI: 10.1016/j.rser.2017.05.278.

M J. E Alam; K M. Muttaqi; and D Sutanto (2014): A novel approach for ramp-rate control of solar PV using energy storage to mitigate output fluctuations caused by cloud passing. Available online at https://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.686.6808&rep=rep1&type=pdf, checked on 2/13/2021.

Mahmood Reaz Sunny; Nabid Faiem (2015): Output Power Ramp-Rate Control of a Grid-Connected PV Generator using Energy Storage System. Available online at https://www.ijireeice.com/upload/2015/july-15/IJIREEICE%201.pdf, checked on 2/13/2021.

National Energy Administration (2020): Detailed Rules for the Implementation of auxiliary Service Management for grid-connected power plants. Available online at https://www.sohu.com/a/417816749\_440908, checked on 12/12/2020.

Nguyen Ha Thi (2018): Frequency Characterization and Control for Future Low Inertia Systems, checked on 1/27/2021.

Paris Agreement (2015): The Paris Agreement. Energy, Climate change, Enviroment. European Commission. Paris. Available online at https://ec.europa.eu/clima/policies/international/negotiations/paris\_en, checked on 10/23/2020.

Pietro Tumino (2020): Frequency control in a power system. Learn about the primary, secondary and tertiary frequency control in a power system. Available online at

https://eepower.com/technical-articles/frequency-control-in-a-power-system/#, checked on 12/6/2020.

Powerline (2019): The report to assesses the ramping capability of coal-based units. Available online at https://powerline.net.in/2019/07/01/reality-check/, checked on 2/13/2021.

Rebello Eldrich; Watson David; Rodgers Marianne (2018): Developing, implementing and testing up and down regulation to provide AGC from a 10 MW wind farm during varying wind conditions. In *J. Phys.: Conf. Ser.* 1102, p. 12032. DOI: 10.1088/1742-6596/1102/1/012032.

Saracevic Ervin; Frühauf Susanne; Miltner Angela; Karnpakdee Kwankao; Munk Bernhard; Lebuhn Michael et al. (2019): Utilization of Food and Agricultural Residues for a Flexible Biogas Production: Process Stability and Effects on Needed Biogas Storage Capacities. In *Energies* 12 (14), p. 2678. DOI: 10.3390/en12142678.

Schill Wolf-Peter; Michael Pahle; Christian Gambardella (2016): On start-up costs of thermal power plants in markets with increasing shares of fluctuating renewables, checked on 1/5/2020.

Schill Wolf-Peter; Pahle Michael; Gambardella Christian (2017a): Start-up costs of thermal power plants in markets with increasing shares of variable renewable generation. In *Nat Energy* 2 (6), p. 65. DOI: 10.1038/nenergy.2017.50.

Schill Wolf-Peter; Pahle Michael; Gambardella Christian (2017b): Start-up costs of thermal power plants in markets with increasing shares of variable renewable generation. In *Nat Energy* 2 (6), p. 65. DOI: 10.1038/nenergy.2017.50.

Sebastian Just (2015): The German market for system reserve capacity and balancing energy, checked on 2/9/2021.

Seth Blumsack (2020): Basic economics of power generation, transmission and distribution. Available online at https://www.e-education.psu.edu/eme801/node/530.

SETIS (2020): Electricity storage in the power sector. Available online at https://setis.ec.europa.eu/system/files/Technology\_Information\_Sheet\_Electricity\_Storage\_in\_t he\_Power\_Sector.pdf, checked on 2/12/2021. Shao Shuai; Ming Li; Hongfei Cai; Xianghui Meng (2014): Reviews of Frequency Dynamic Process in Electric Power System, pp. 1–2, checked on 11/1/2020.

Sören Amelang; Benjamin Wehrmann (2020): German onshore wind power – output, business and perspectives. Available online at https://www.cleanenergywire.org/factsheets/germanonshore-wind-power-output-business-and-perspectives, checked on 1/19/2021.

Southern Regional Power Committee (2016): Sub-Regulation 6.3B of Central Electricity Regulatory Commission (Indian Electricity Grid Code) (Fourth Amendment) Regulations, 2016. Available online at http://www.srpc.kar.nic.in/website/2016/meetings/special/4IEGC17-06-16a.pdf, checked on 2/19/2021.

Statista (2020): Weighted average cost for installed onshore wind energy worldwide from 2010 to 2019\* (in U.S. dollars per kilowatt). Available online at https://www.statista.com/statistics/1027721/weighted-average-lcoe-of-offshore-wind-worldwide/, checked on 2/21/2021.

Statista (2021): Countries with largest installed capacity of coal power plants worldwide as of January 2021. Available online at https://www.statista.com/statistics/530569/installed-capacity-of-coal-power-plants-in-selected-countries/, checked on 2/19/2021.

Vivint solar (2019): History of solar energy: Who Invented solar panels? Available online at https://www.vivintsolar.com/learning-center/history-of-solar-energy, checked on 1/20/2021.

WindPrimControl (2020): Grid Operation and Coordination with Wind. Available online at http://home.engineering.iastate.edu/~jdm/wind/WindPrimControl.doc, checked on 2/13/2021.

WNA (2011): Comaparison of lifecycle greenhouse gas emissions of various electricity generation sources. Available online at http://www.world-

nuclear.org/uploadedFiles/org/WNA/Publications/Working\_Group\_Reports/comparison\_of\_lifec ycle.pdf, checked on 2/24/2021.

Yang Weijia; Yang Jiandong; Guo Wencheng; Norrlund Per (2016): Response time for primary frequency control of hydroelectric generating unit. In *International Journal of Electrical Power & Energy Systems* 74, pp. 16–24. DOI: 10.1016/j.ijepes.2015.07.003.

Yolanda (Ed.) (2010): Three stage frequency control. Available online at http://blog.sina.com.cn/s/blog\_6a844a780100l2s7.html, checked on 11/29/2020.

Yu Chen (2012): How can the frequency of hydropower station generators remain stable? Available online at https://www.zhihu.com/question/20046443/answer/133355386, checked on 12/15/2020.

# Appendix A: Additional data

## A.1 The capital and operating cost

Table 20 Typical capital costs and operating costs of different power plants (Source: Seth Blumsack2020)

Power plants	Capital cost(€/kW)	Operating cost(€/kWh)	
Coal-fired power plant	413-827	0.02-0.03	
Gas engine power plant	330-661	0.03-0.08	
CCGT	500-1.000	0.03-0.08	
Wind power plant(on&offshore)	1.000-4.000	> 0.01	
Nuclear power plant	1.000-4.000	0.02-0.04	
Solar PV power plant	< 3.700	>0.01	
Hydropower plant	1.000-4.000	> 0.01	

### A.2 the startup number and cost prediction from 2020-2030

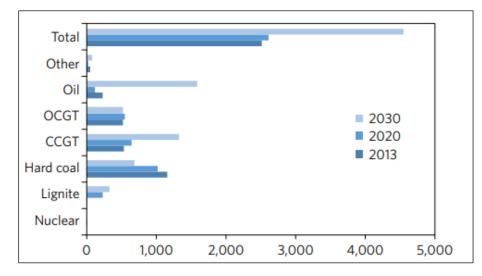


Figure 31 Number prediction of start-ups in the German power system (Source: Schill Wolf-Peter et al. 2017a)

From 2013-2020, the hard coal power plant had the maximal number to be a startup. From 2020 until 2030, with the increasing renewable energy, the CCGT and oil engine power plant will play the central role to provide a fast response to the power system.

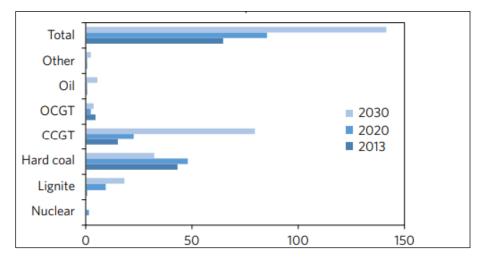


Figure 32 Start-up costs prediction in the German power system(million  $\in$  ) (Source: Schill Wolf-Peter et al. 2017a)

From 2013-2020, the hard coal power plant had the maximal startup costs due to many startup times. From 2020 until 2030, with the increasing renewable energy, the CCGT will play the leading role in providing a fast response to the power system. Therefore, it has a dramatic increase to be the top.

# Appendix B: Turbine power output curves

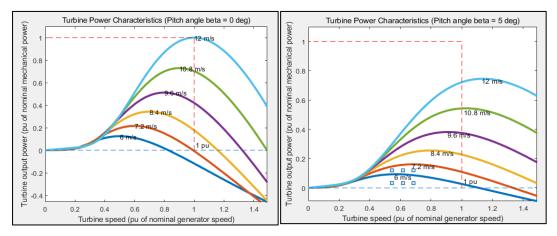


Figure 33 The power curve when the pitch angle is 0  $^{\circ}$  or 5  $^{\circ}$ 

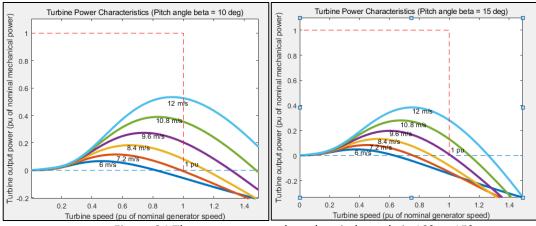


Figure 34 The power curve when the pitch angle is 10° or 15°

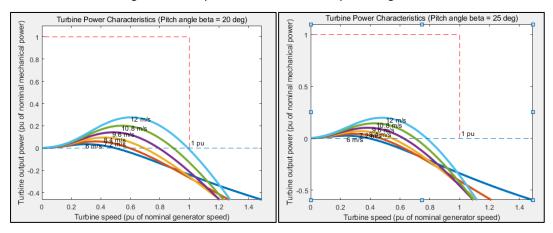
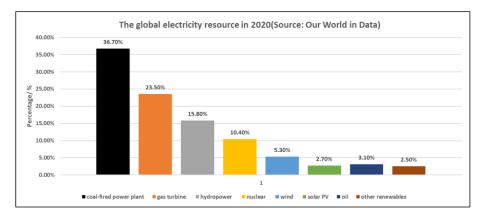


Figure 35The power curve when the pitch angle is 20° or 25°

# Appendix C: Primary response plants in Germany and EU



C.1 The electricity resource in global, Germany, and EU

Figure 36 The global electricity resource in 2020

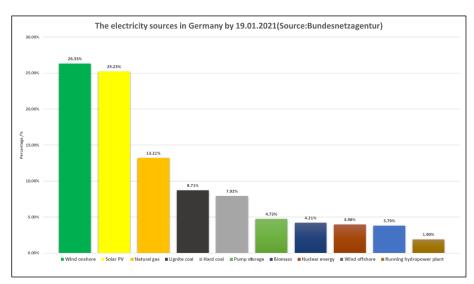


Figure 37 The electricity sources in Germany by 19.01.2021

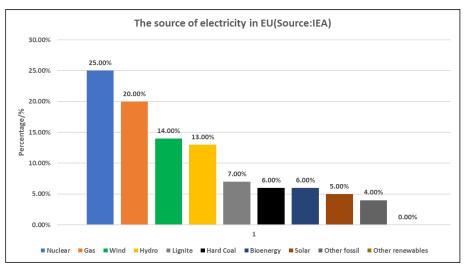


Figure 38 The electricity sources in the EU in 2020

### C.2 The primary response plants in Germany and EU (Ibrahim Nassar et al. 2014).

 Scenario one: in winter 2011, with 0% renewable energy in operation in both Germany and the EU power system

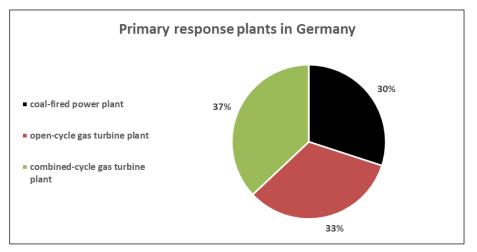


Figure 39 The primary response plants in Germany under scenario one

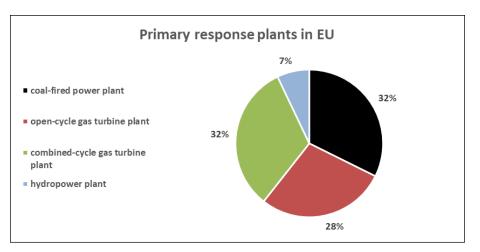


Figure 40 The primary response plants in EU under scenario one

Scenario two: in winter 2020, with 60% renewable energy in operation in Germany and 25% in the EU power system

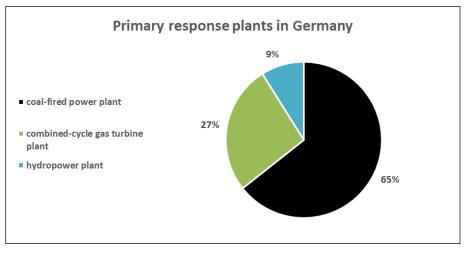


Figure 41 The primary response plants in Germany under scenario two

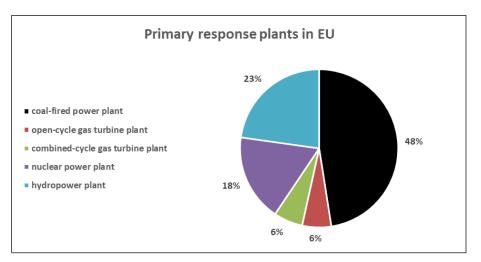


Figure 42 The primary response plants in EU under scenario two

Scenario three: in winter 2020, with 77% renewable energy in operation in Germany and 47% in the EU power system

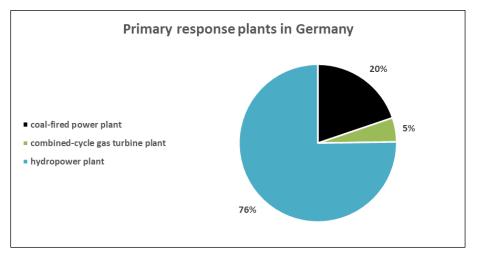


Figure 43 The primary response plants in Germany under scenario three

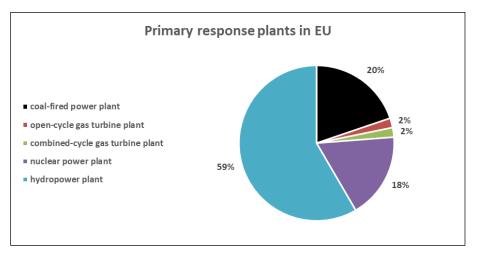
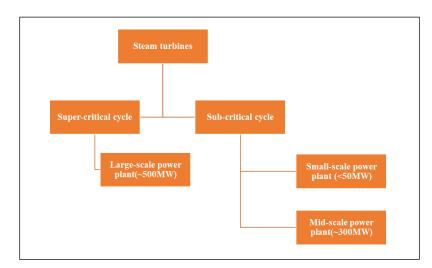


Figure 44 The primary response plants in EU under scenario three

# Appendix D: The steam turbine power plants

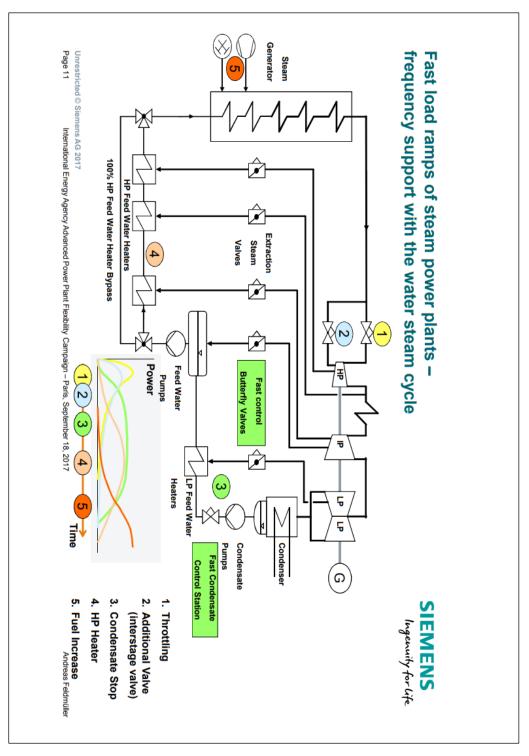


D.1 The representative examples of steam turbine power plants

*Figure 45 The representative examples of steam turbine power plants (Source: Kirsten Trevor et al. 2018)* 

Characteristic	Subcritical(<50MW)		Subcritical(300MW)		Supercritical(500MW)	
	Minimum	Maximum	Minimum	Maximum	Minimum	Maximum
Minimum load (%FL)	10%	60%	10%	60%	20%	50%
Efficiency(%)	25.2	28.2	32.5	35.5	37.1	40.1
Ramp rate (MW/min)	0.2	2.8	1.6	22.0	3.3	40.0
Ramp rate (%FL/min)	0.6%	8.0%	0.6%	8.0%	0.6%	8.0%

Table 21 The representative values of the flexibility of coal-fired power plants (Source: Kirsten Trevor et al. 2018)



**D.2** The methods of fast load ramps of steam power plants(Source: Siemens)

Figure 46 The methods of fast load ramps of steam power plants(Source: Siemens)