LEVELIZED COST OF ELECTRICITY OF RENEWABLE ENERGY TECHNOLOGIES AS A CRITERION FOR PROJECT PRIORITIZATION

Lappeenranta–Lahti University of Technology LUT

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Abstract

Lappeenranta–Lahti University of Technology LUT
LUT School of Engineering Science
International Master of Science in Engineering, Entrepreneurship and Resources (MSc. ENTER)

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Levelized Cost of Electricity of Renewable Energy Technologies as a Criterion for Project Prioritization

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Keywords: Renewable energy sources, technology, LCOE, project prioritization

In the recent years, the society is witnessing growing share of renewable energy projects as an effort towards decarbonised economy and more sustainable future. In evaluation of different renewable energy technologies, Levelized Cost Of Electricity (LCOE) is most common measure that investors use a criterion for project prioritization. The aim of this work is to analyse LCOE method as an investment decision criterion on the ground of calculating LCOE for three real life projects in Bosnia and Herzegovina.

There are several studies that investigate theoretical background of LCOE, its weaknesses and strengths, with some of them discussed in this work. How ever, LCOE even it has certain drawbacks, it is still most comprehensive energy cost metric. In the first part of this work, a theoretical background is discussed on hydro, wind, and solar power technologies as selected technologies, with following research on LCOE and other similar energy cost metric. The LCOE calculating method is applied on the collected data for three real renewable energy projects in Bosnia and Herzegovina.

Calculated LCOE for these three projects correspond with global trends for LCOE. In the LCOE calculation investment costs represented the most significant factor that had largest single impact on the resulting numbers of LCOE. According to the calculated LCOE results in the Practical part, wind and solar projects are most economic competitive and desirable from investors perspective, which matches with booming development and enormous cost decrease for these two technologies in the recent decade. As it is indicative on the base of statistical data for solar and wind power technologies, these trends will continue into the future as well.

Renewable energy technologies are investment intensive, and it is understandable that investment costs are impacting LCOE significantly. Future development of renewable energy technologies will contribute to further cost decrease for certain technologies, as it is seen for solar and wind power technologies. More mature technologies like hydropower have reached their technological peak, and significant research and innovations breakthroughs are required to further cost decrease for this these technologies. Significant factor is availability and quality of input data that determines possibilities in the research of LCOE, and in many cases lack of available data represent obstacle in conducting more detailed LCOE calculations.

Thesis assignment

Investment in projects for the construction of power plants on renewable energy sources requires consideration of the techno-economic justification of the projects and their mutual comparison based on different criteria. In addition to criteria such as the Internal Rate of Return, Net Present Value, Benefit-Cost Ratio, the criterion of Levelized Cost of Electricity (LCOE) is also applied.

In the theoretical part of the work, it is necessary to give general descriptions for selected electricity renewable energy technologies (solar, wind power and hydropower), to present the LCOE and the method of LCOE calculation for each of these technologies. In the practical part of the work, it is necessary to give a brief technical description of concrete projects, to collect input data for the calculation and to calculate the LCOE for these projects. Furthermore, a critical review of the results in terms of investment in these projects priorities should be given.

Statement of Originality

I hereby certify that I am the sole author of this thesis and that no part of this thesis has been published or submitted for publication.

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Symbols and abbreviations

List of symbols

E – energy

m – mass

v – velocity

A – surface

ρ – density

t – time

P – power

c_p– power coefficient

ω – angular velocity

C_t – capital expenditure in the year t

O_t – fixed operation cost in the year t

V_t – variable operation cost in the year t

F_t – cost of financing in the year t

E_t – electricity produced in the year t

I_0 – investment cost

k_t – growth factor of operation and maintenance costs in the year t

List of abbreviations

EIA – International Energy Agency

EERE – Office of Energy Efficiency and Renewable Energy

CO_2 – Carbon dioxide

LCOE – Levelized cost of electricity

RES – Renewable energy source

EESI – Environmental and Energy Study Institute

RoR – Run-off River

kW – Kilowatts

MW – Megawatts

GW – Gigawatts

TW – Terawatts

DC – Direct current

p-n – positive – negative

SHC – Solar Heating & Cooling

CSP – Concentrated Solar Power

DCF – Discounted cash flow

WACC – Weighted average capital cost

LCOS – Levelized cost of storage

LACE – Levelized avoided cost of electricity

PV – Photovoltaic

Li-ion – Lithium ion

IRENA – International Renewable Energy Agency

UCOE – Undiscounted cost of energy

DCCOE – Discounted costs cost of energy

TCOE – Total cost of Energy

USD – U.S. dollar

Rpm – rounds per minute

RES – Renewable Energy Source

Table of Contents

1. Introduction

Since the dawn of time, mankind has been using energy for various needs and applications, from food to heating. Revelation on using fire for producing metals and harnessing domestic animals are considered as a first energy transition – this transition raised energy throughput of these societies for more than an order of magnitude. The second energy transition was encouraged several millennials later, with the invention and beginning of usage of waterwheels and windmills, simple inventions that made it possible to convert two common renewable energy forms into useful mechanical energy. Also, wood has been used as the primary source for most needs. The third energy transition, and the most recent, has brought engines, biomass, fossil fuels and electricity with the first electricity generating systems in 1882 as key movers. This transition is known as an industrialization with inventions and technological milestones that improved quality of life. (Smill, V. 1994.)

With the increase of the number of the population around the globe, the task to fulfil increasing energy demand has become a rising issue. This task is a greater struggle with having in mind various ecological and environmental issues caused by using fossil fuels, which still represent the most used form of energy today, participating with 84% in the world total energy consumption. (EIA, 2021)

Environmental issues, like greenhouse effects and increasing CO_2 emissions, are one of the main reasons which made the shift to a more effective and environmentally friendly way of production – using a renewable energy source.

In recent decades, there has been a major uptake in renewable energy sources and mainstream use of them. Some of the reasons are environmental, and others are the development and decreased cost of these technologies that made them more accessible and cost-effective.

There are many definitions of LCOE, and according to Nuclear Energy Agency LCOE is:

> The levelized cost of energy (LCOE) is a measure of a power source that allows the comparison of different methods of electricity generation on a consistent basis. The LCOE can also be regarded as the minimum constant price at which electricity must be sold in order to break even over the lifetime of the project. This can be roughly calculated as the net present value of all costs over the lifetime of the asset divided by

> an appropriately discounted total of the energy output from the asset over that lifetime. (Nuclear Energy Agency/International Energy Agency, 2016).

In this work, the focus will be on explaining LCOE as a concept and calculating LCOE for different methods of electricity generation – hydro power, wind power and solar, with technical description of these technologies.

2. Renewable energy sources

Since the dawn of civilization renewable source have played important role in human history. Renewable energy sources have been for a long time in use since the discovery of fire and later inventions like water mills and windmills which used water and wind for wheat grinding. These energy sources are considered renewable since they cannot be depleted and are naturally replenishing.

One of the definitions of renewable energy according to U.S. Energy Information Administration is:

> Renewable energy is energy from sources that are naturally replenishing but flow-limited; renewable resources are virtually inexhaustible in duration but limited in the amount of energy that is available per unit of time. (EIA, 2021)

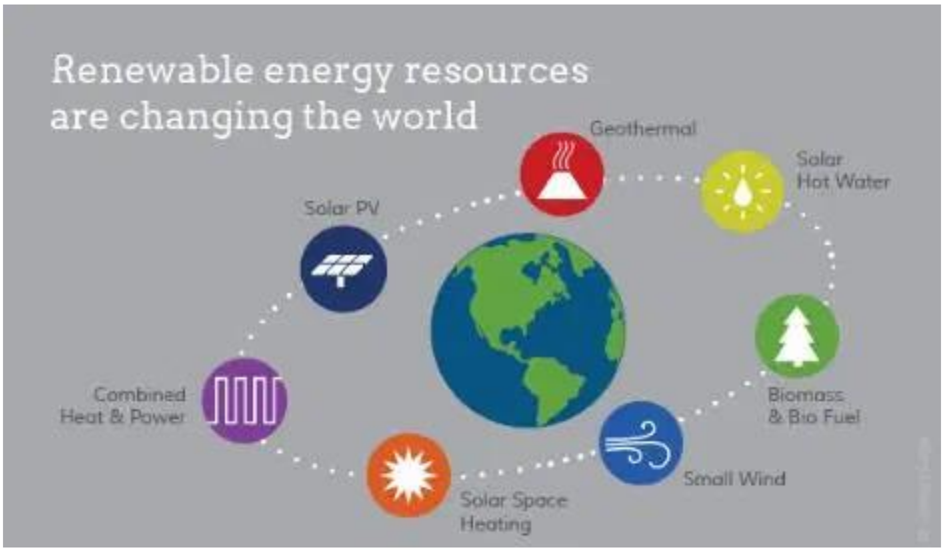

Fig. 1 Types of renewable energy sources by Abdul Majid Qureshi, 2021

Major types of renewable energy resources, as shown on Figure 1 are:

1. Solar
2. Wind
3. Biomass
4. Geothermal
5. Hydropower

2.1.Renewable energy technologies

According to Wikipedia, definition of technology is:

> Technology (“science of craft”, from Greek τέχνη, techne, “art, skill, cunning of hand”; and -λογία, -logia) is the sum of techniques, skills, methods, and processes used in the production of goods or services or in the accomplishment of objectives, such as scientific investigation. Technology can be the knowledge of techniques, processes, and the like, or it can be embedded in machines to allow for operation without detailed knowledge of their workings. (Technology – Wikipedia, 2021)

To put this explanation of technology into the context of this work, technology of renewable energies would represent knowledge of technique and processes embedded in machines used to capture renewable energy flows. These machines are in use for much longer time than most people think, like water mills and windmills, with some of them being in use during Roman and Greek eras. Typical water mill is shown on Fig 2.

Fig. 2 Watermill by Triplet Brown, 2021

Another example of first energy machines is windmill. Windmills were used through the medieval age, for the first time in 9th century in Greater Iran, and in 12th century in Europe. In those days windmills were used for wheat grinding and etc, and they are forerunner of modern wind turbines that are going to appear in late 19th century for the first time.

2.2.Hydropower

Water is covering 71% of the Earth surface. In nature, fresh water can be found in both stock and flowing form. Stock water is stored in lakes, water vapor, ground water and snow while flowing water is in form of streams and rivers According to some estimations made by Gleick in his work, around 69% of fresh water is permanently stored in ice and glaciers, 30 % in underground waters and rest, 1%, in lakes, rivers, atmosphere and biota. (Gleick, P.H. 1993)

Constant moving of water in nature is known as a water cycle – hydrological cycle. It consists of different steps through which water circulates perpetually in nature shown in Figure 3.

1. Evaporation – heated with the solar energy, water evaporates in the form of water vapor - from oceans and other water bodies water is transferred into air.
2. Precipitation – evaporated water condensate and fall to the earth and oceans in form of rain, snow and other.
3. Runoff – water running usually from the land with streams and rivers reaching large water bodies – seas and oceans where it evaporates, and the cycle begin again.

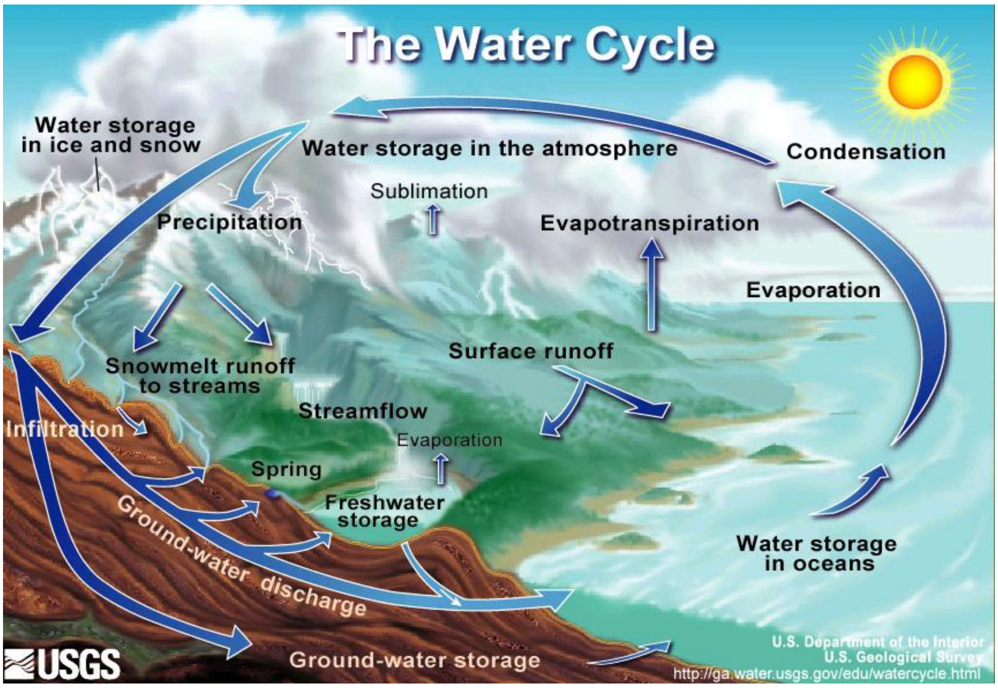

Fig. 3 Water cycle by USGS, 2021

The energy of water cycle, which for a driver has an energy of sun, is possible to use to produce electricity or for mechanical task like wheat grinding. This process is called hydroelectric power production or hydropower and it uses water as a fuel, which is not affected or reduced during this process. Since the water cycle is endless and constantly recharging, hydropower is considered as a renewable energy source. (EERE, 2021)

It is important to understand water cycle in order to understand hydropower. The amount of precipitation plays important role in the hydrological cycle and determines the amount of available hydropower for electricity production. The variation in precipitation like droughts can have big impacts in the availability of producing hydropower. (EIA, 2021)

It can be distinguished few different types of hydroelectric facilities. They all work on the same principal of utilising kinetic and/or potential energy, depending on the type, of the flowing water as it moves downstream. Machines called turbines and generators are used to utilise this kinetic energy and transform it into electricity, which is after that sent to the grid and further to the end user – houses, businesses, industry etc.

There are other types of hydropower technology included, like wave energy which utilise energy of the oceanic waves to generate electricity. In the Fig. 4 are shown different types of wave power plants like point absorber, wave overtopping reservoir etc. These different wave power plants utilise movement of the ocean waves, which by estimation, only in the West Coast of U.S. there is 2,100 TWh of total yearly wave energy. There are some concepts of combining wave and wind technology in a form of offshore energy farms. These types of concepts are still in R&D phase. (EESI, 2021)

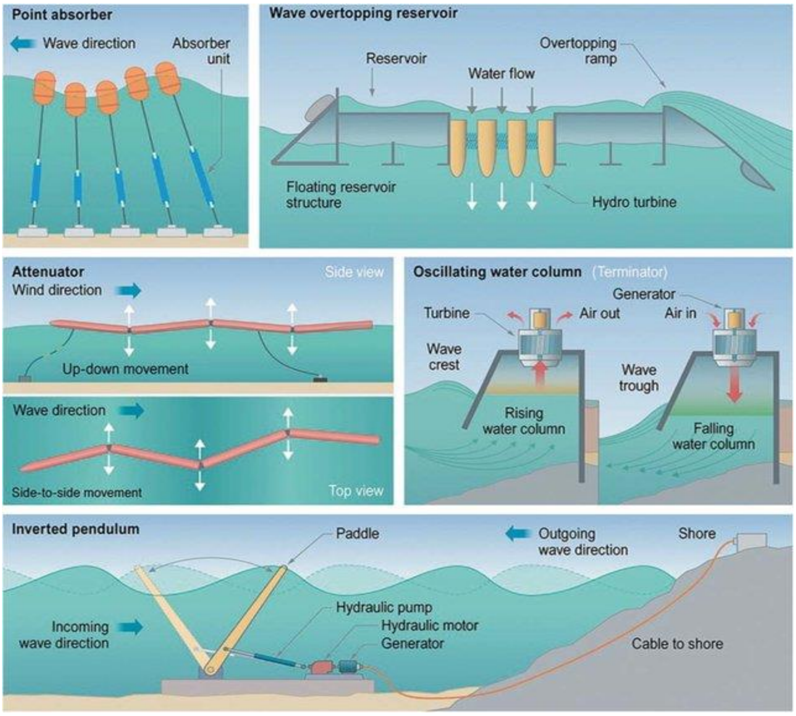

Fig. 4 Wave energy technology by Aydingakko, 2016

2.2.1. Technical description of hydropower technologies

Hydropower has been for a long time in use and the first hydroelectric power plants appeared in the 19th century, when British-American engineer James Francis developed the first modern water turbine. The first hydroelectric power plant was built in the Fox River, America in 1882. (Nunez, 2019)

Since that, hydropower as a technology has developed into a clean, safe, and reliable source of energy and services. In technical sense, hydropower technology is mature, and represents an economically competitive source of electricity under liberalized market conditions. Another important conceptual aspect of hydropower is its position between two important issues, energy and water. It is possible that hydro reservoirs could play waste role in mitigating scarcity of fresh water supply, irrigation during low floods. This enables hydropower technology, to overcome its primary role of producing electricity in the future. (Corà, 2020)

Hydropower provides overall value to the electrical network, since it is fast response source and more flexible than intermittent source – and considering that, it helps to satisfy variable electric demand and provide critical energy. Hydropower is considered as a dispatchable – controlled energy source due to storage capacity and predictability of its production. (Corà, 2020). Today, hydropower corresponds to 7% of total electricity generation in America, 12 % in Europe, and 35.5% in Bosnia and Herzegovina for 2018. (EIA, 2021)

According to Corà, standard hydroelectric power plant, which is shown on Fig. 5, consists of main components:

1. Gates are used to regulate water flow. Exists different form of gates like radial, sliding, fixed and caterpillar gates. Spillway gates are used for flood discharge in case of emergencies.
2. Penstocks represents a pipe or a conduit through which water is supplied from intake to the powerhouse/generator. Construction material that is used for penstocks is usually steel with good strength characteristics due to high water pressure that can cause so called water hammer in case of sudden load increase.
3. In the powerhouse generator is placed. In cases where powerhouse is located far from the water reservoir, the water is transferred to the powerhouse through channels or tunnels. It is important that sufficient amounts of water are going in, since lack of water

causes air to come in into channels and causes vortices, and that can result in problems with the turbine.

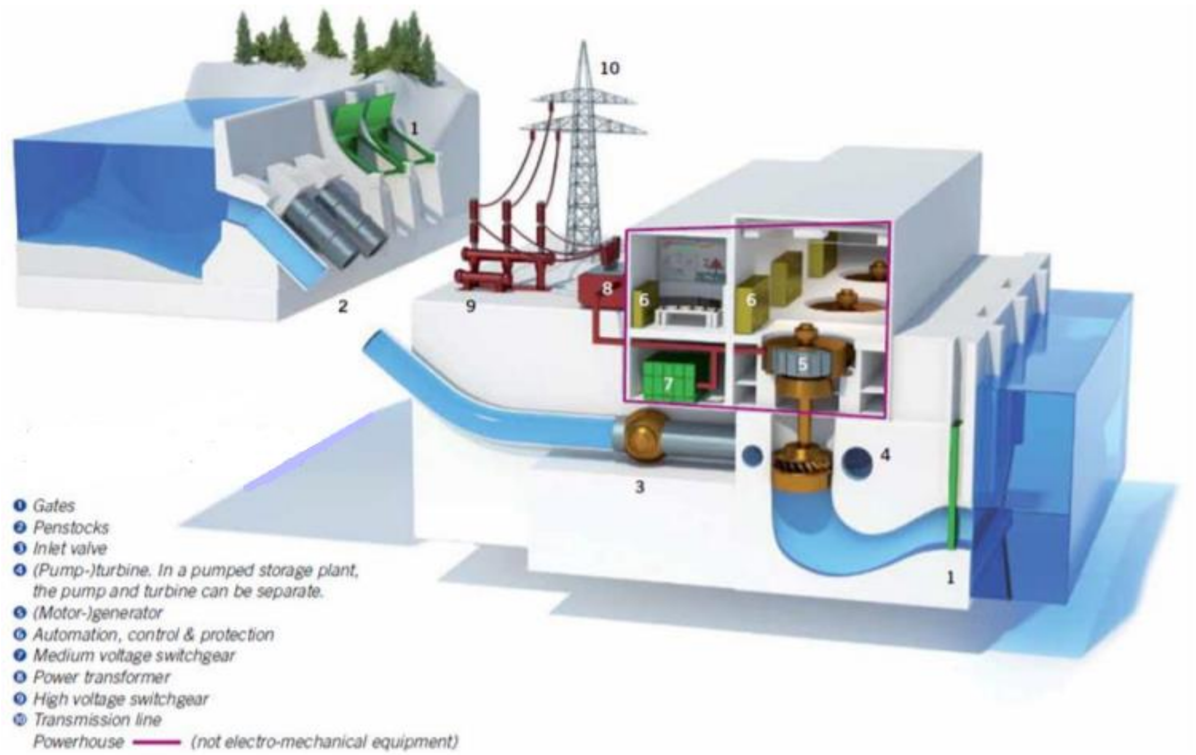

Fig. 5 Hydroelectric power plant with its components by Corà, 2020

4. Surge tank is a tank that is often one of the elements of the hydroelectric facility. Its role is to absorb water surges/impacts due to sudden water impacts.
5. Turbine and generator are two core elements of the hydroelectric power plant, and they produce electricity. Turbine is a rotating element, that is attached to the generator with shaft, and it transforms kinetic/potential energy of the water into mechanical. Generator, which consists of rotor and stator like shown in Fig. 6, transforms this mechanical energy to electricity. This process is happening with spinning large electromagnets - rotor inside a copper wire – stator, and that way electricity is generating.

A major part of the hydroelectric power plant is barrage. Barrage is constructed along side river for water accumulation, and most commonly civil engineering works account for most of the engineering work and costs. Regarding the water accumulation, there are two main types of hydroelectric power plants, hydroelectric power plants with storage and Run-of River power plants. About this will be discussed more in next chapter.

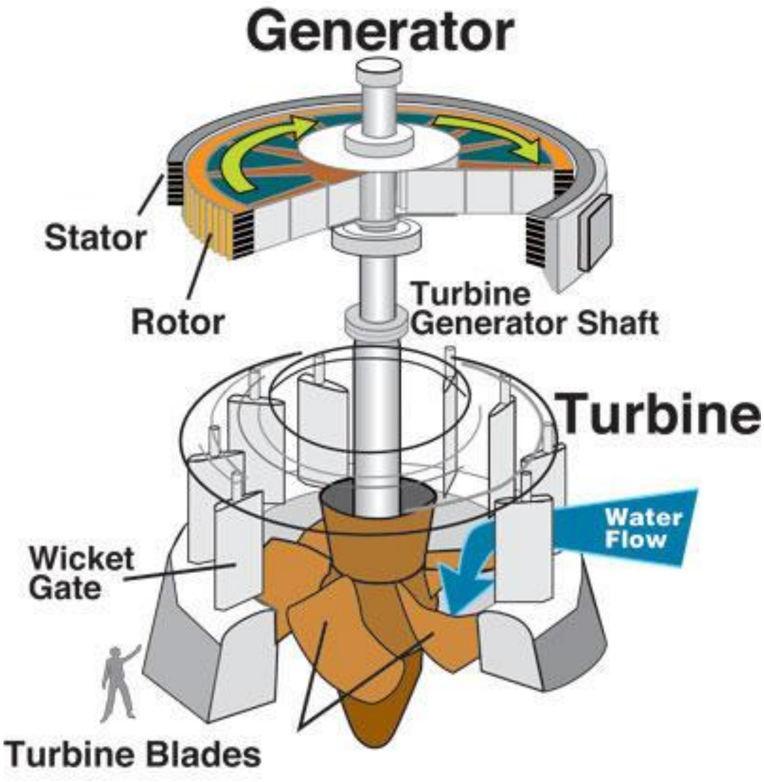

Fig. 6 Generator and Turbine by U.S. Army Corps of Engineers, 2020

There are several different types of turbines with different technical characteristics shown in table 1.

Table 1 Turbine overview by Olek

Type	Slope [m]	Gullet $[\frac{m^3}{s}]$	Power on the shaft [MW]
Pelton turbine	50-1200	0.1-50	to 300
Kaplan turbine	8-80	5-1000	to 200
Pipe Kaplan turbine	1.5-25	5-1200	to 50
Propeller turbine	1.5-25	1.5-100	to 10
Pipe turbine	1.5-25	1.5-100	to 10
Francis turbine	10-600	0.5-1000	to 850

The two most important factors when it comes to hydroelectric power plants, are head and flow. Head and flow of water determine the amount of electricity that is produced. Parameters water head and flow are specific for each location. Head (pressure) represents the vertical distance between the intake point of the water from the outlet. The higher the head is, the more electric power is produced. Typically, storage power plants have higher heads. The flow of the water is flow of the water through turbine, typically expressed in m^3/s or another unit. The greater the flow is, the more electricity is produced. Run-of-river power plants utilise water flow to produce electricity.

2.2.2. Types of hydroelectric power

Hydroelectric power plants are classified in terms of operations and flow. According to the principle of operation, two general types of hydroelectric power plants can be distinguished (EIA, 2021):

- Hydroelectric power plants with reservoir
    - Storage power plants
    - Pumped-storage power plants
- Run-of River power plants

Although there is no universal accepted definition, according to EERE in terms of size of hydroelectric power plants, there are three categories (EERE, 2021):

- Large hydropower – hydroelectric power plants with capacity greater than 30 MW
- Small hydropower – hydroelectric power plants with capacity of up to 10 MW
- Micro hydropower – hydroelectric power plants with capacity of up to 1 MW

Storage power plant

The principle of operating of storage power plants is based on impoundment of the water using dam. These type of power plants are pretty common and represents one of the conventional types of hydroelectric power plants. Water is being impound behind the dam, creating water accumulation. With releasing water through the inlet to the turbine and generator, electricity is created. Storage power plants is shown on Fig. 7. (Corà, 2020)

This type of hydroelectric power plants is not so dependent on the natural flow of the water, since water is being stored in the accumulation. Storage power plants are flexible from this reason, since they can balance variations in precipitations with accumulated water depending on their size. Usually, the larger storage power plants are, the bigger are their possibilities for storage. (Corà, 2020)

Storage power plants may be with diversion or without diversion of water. For storage power plants with diversion, water is commonly transported with diversion channels to the powerhouse which is located away from the dam (Corà, 2020). Powerhouse at storage power plant without diversion is located on or near the dam. In Bosnia and Herzegovina, storage power plant with diversion of water is hydro power plant “Jablanica”, and storage power plant without diversion is “Salakovac”.

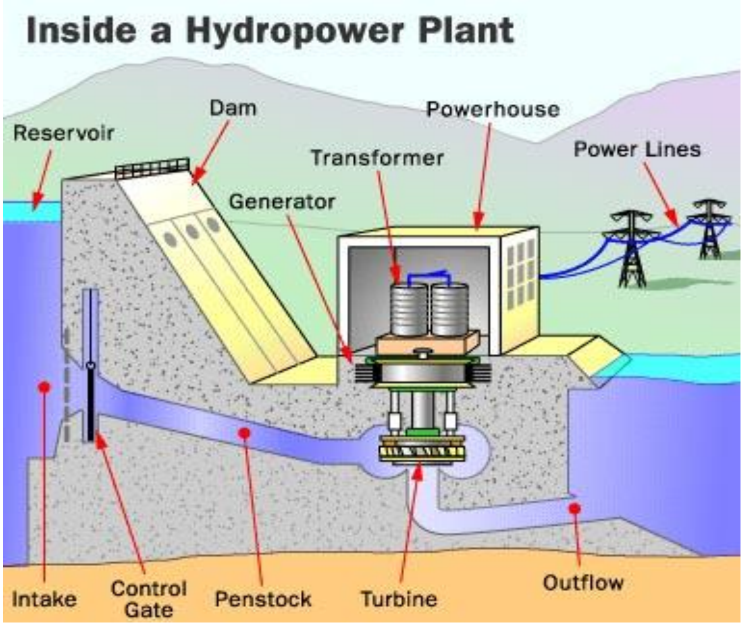

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Fig. 7 Storage power plant by Blerta, 2009

The world´s largest hydroelectric power plant of this type is Three Gorges Dam in China on the Yangtze River shown on Fig 8. It has a installed capacity of 22 500 MW. The height of the dam is 181 m, and it is 2335 m wide. (USGS, 2021)

Fig. 8 Three Gorges Dam by Geoengineer, 2020

Pumped storage power plants

Pumped storage power plants operate on the similar principle like storage power plants, the difference is that there are two reservoirs – lower and higher one as shown on Fig. 9. These two reservoirs are connected with penstock or tunnels. Electricity is generated with releasing water from the higher reservoir to the generator. In the pumping mode, motor/turbine is used to transport water upstream from the lower to the higher reservoir, and this process is happening during low demand periods with surplus of the electricity from the grid. (Corà, 2020)

Due to the mostly large heads, these type of hydroelectric power plants utilizes potential energy of the water.

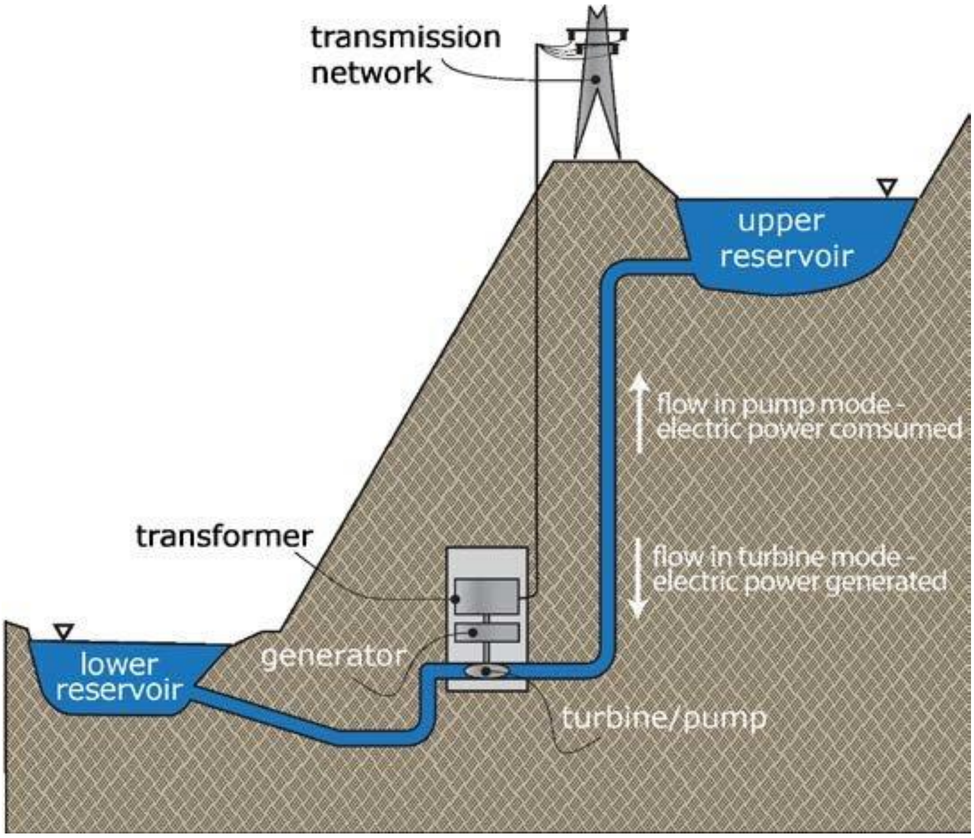


Fig. 9 Pump storage power plant by Viadero, 2017

From the perspective of hydraulic system, there exists two technical variants. One is the reversible pump/turbine where the turbine is in use both for electricity generation and water transport, and another is turbine and pump as two separate elements – ternary systems.

Operation at full capacity of this hydroelectric power plants is defined with capacity of the upper reservoir and with yield from renewable energy sources. Natural lakes are used as a reservoir, or artificial one. In some cases, rivers are used as a lower reservoir or even sea. (Corà, 2020)

In paper, Corà state that storage power plants are most efficient type of hydroelectric power plants with efficiency surpassing 70% to 85%. While this type of hydroelectric power plants produces electricity, it is also a consumer since it consumes electricity when the water is being restored with the pumps back in the upper reservoir. This characteristic – drawback is compensated with high burst of energy that these power plants can provide in the high demand period with fast response. (Corà, 2020)

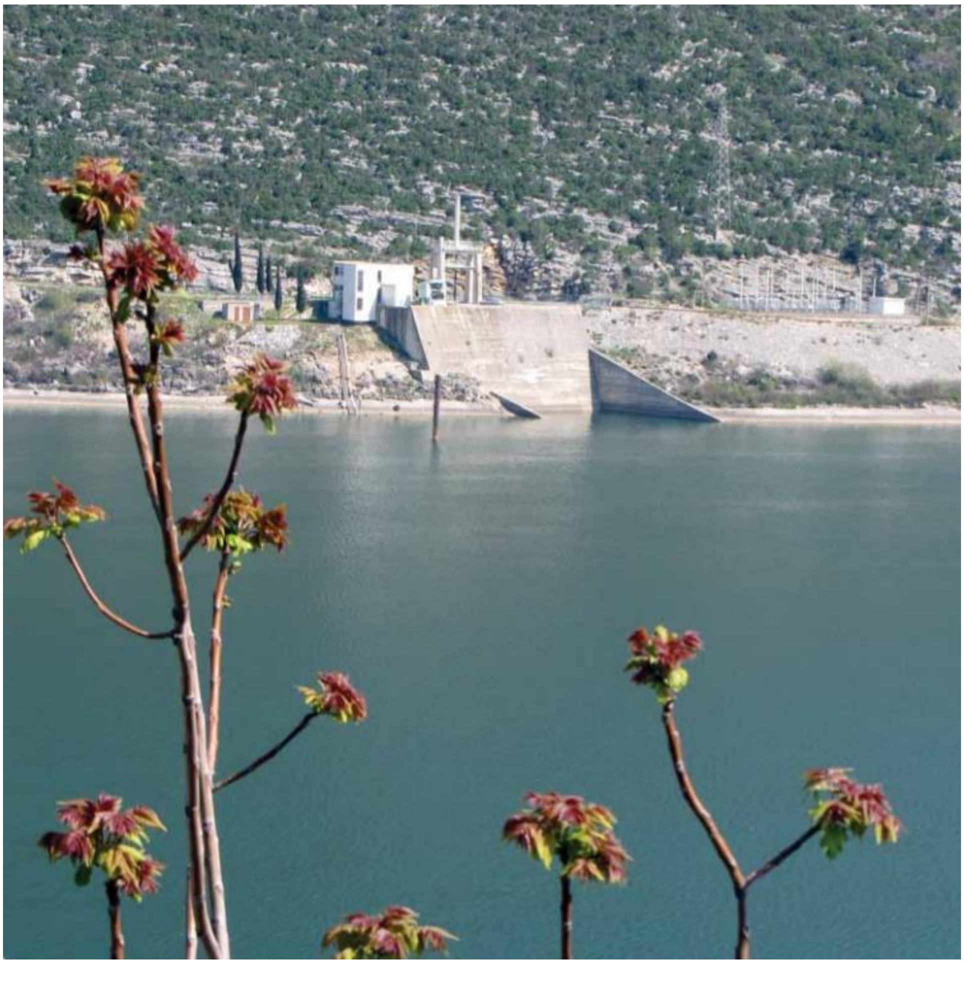


Fig. 10 Hydroelectric power plant Capljina by EP HZ HB, 2009

Largest hydroelectric power plant in Bosnia and Herzegovina by generator capacity, is pumped storage power plant “Capljina”. It has installed generating capacity of 420 MW. The upper reservoir is lake “Vrutak” shown on the Fig 10, and the lower reservoir is the lake in the nature park “Hutovo blato”. Into the upper reservoir flows water from river “Trebisnjica”. It plays important role in electro-energetic system of Bosnia and Herzegovina. (JP Elektroprivreda HZ HB, 2009)

Run-of-river power plant

Run-of River power plants – RoR, are type of hydroelectrical power plants that doesn’t involve any additional impoundment of water. This type of hydroelectrical power plants uses natural flow of the rivers for producing electricity. From that reason, RoR power plants represent less flexible hydroelectrical power plants, and are operating with constrain of maintaining level of water at the inlet with regards to the river flow. (Corà, 2020)

Since RoR power plants use natural river flow for producing electricity, production can vary considerably through year depending on flow. Hydrological forecast which is used in production planning of electricity is considered reliable in terms of todays electric market, and RoR power plants are in use for base-load production. (Corà, 2020)

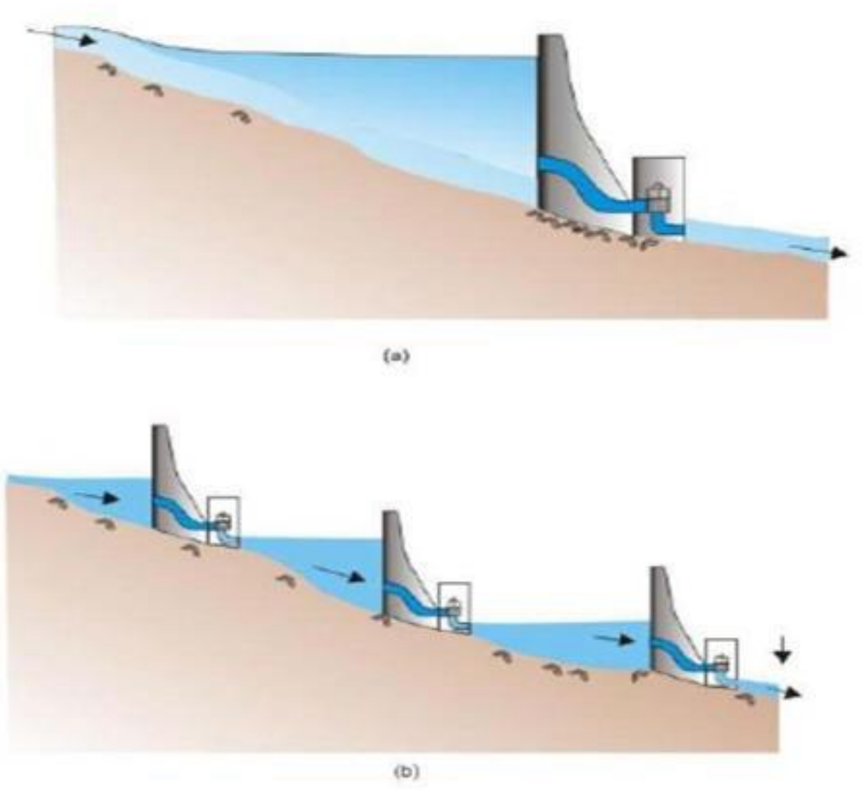


Fig. 11 Single stage and multi cascade by Corà, 2020

There are two possibilities for RoR power plants: single stage and multi cascade power plants as show on Fig. 11. An example of single stage RoR power plant in Bosnia and Herzegovina is Hydroelectric power plant „Vitez-1“. It is located in the central Bosnia on river „Lašva“. It has installed capacity of 1.2 MW. In its regulatoral approval decision, the power plant „Vitez-1“ is classified as a RoR power plant, and it has certain water storage capability for daily balance of the production. Most of the small and micro hydro power plants are single stage RoR power plants.

Cascading RoR power plants are usually made in sequence on the river. That way flow and production of the lower power plant in the sequence is regulated with the upstream RoR power plant. (Corà, 2020). Multi cascade configuration is desirable from the energetic perspective, since all usefull altitude drop/potential energy for certain length of river is used, and hydro potential in that case is used efficently. On the other hand, ecological impacts of multi cascade configuration is not neglible on nature, living animal and herbal life. Enviromental and ecological aspect should be considered carefully when engaging in these kind of projects.

Even though RoR hydroelectric power plants doesn’t have a significant storage capability, Corà in his paper state that RoR power plants can impound water on short term basis for adaptation in demand. (Corà, 2020)

2.3. Wind power

Human civilization has been exploring wind from earlier starts. Wind, even though it is natural phenomena that occurs everyday, when it is thought about it more deeply, most people wouldn’t grasp and define what is wind. In human history, wind has powered boats and ships, decided battles, directed way of history and warfare, transport seeds and provided mechanical energy for work and electricity. Wind plays that important role in human life and nature on Earth since it provides transport to seeds and animals like birds, insects which can travel long journeys on wind currents. Life would be extremely different and hard imaginable without wind. (Wikipedia, 2021)

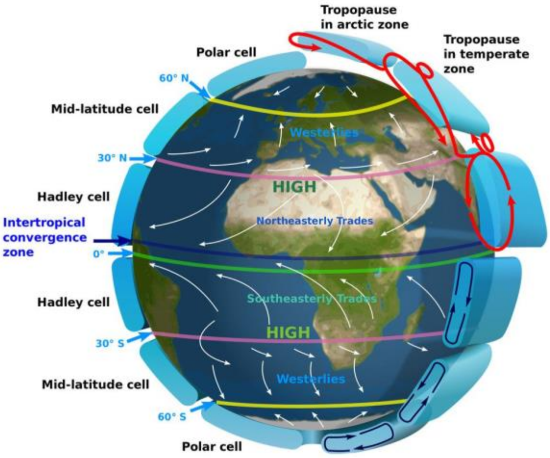


Fig. 12 Wind patterns across the earth by NASA, 2016

Wind is described as a movement of air across the surface of the Earth, with areas of high pressure and low pressure affecting it (Renewable UK, 2011). Wind is vector size with a wind velocity and a wind direction as main characteristics of wind. Categorization of winds is commonly made by spatial scale, regions of occurrence, type of occurring force of winds, velocity and their effects. Wind patterns are shown on Fig 12.

Two main reasons for occurring atmospheric circulations – winds, are difference in heating of the Earths surface and rotation of the Earth. Wind is occurred by difference in pressure, which happens due to temperature gradient – uneven difference in heating of the planet`s surface. When there occurs difference in pressure in atmosphere, air then moves from the area of higher pressure to the area of lower pressure which is then resulting with a wind. (Huang, McElroy, 2015)

One of the scales used for wind measurement is Beaufort scale. This scale describes wind velocity on sea regarding to the observed sea conditions. Enhanced Fujita scale is used in America to describe effects of tornado regarding tornados velocity. Wind rose is graphical chart that represents wind velocity and direction in certain areas. It shows direction and intensity of winds regard to directions like shown on Fig 13.

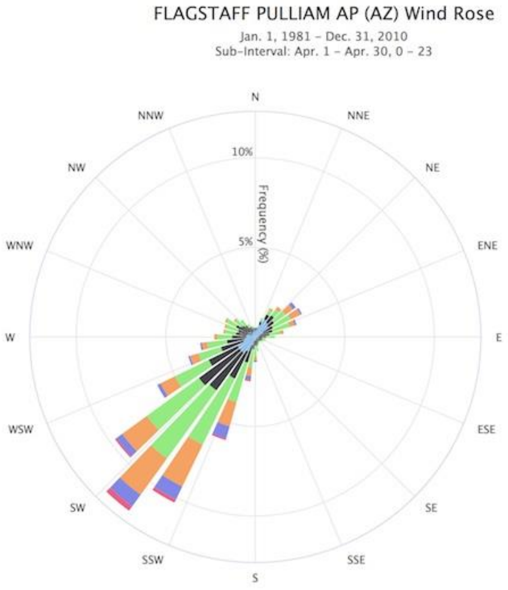


Fig 13. Wind rose by Climate, 2020

Wind is intermittent source of energy and non-dispatchable, which means it cannot be dispatched on demand. It represents a source that consistently intermits energy year to year but can greatly vary on short-term scale. It is mainly used in combination with other energy sources. In 2019, energy of wind produced 1430 TWh of electricity which represents 5.3% of world electricity production. World installed wind power capacity reached up to 651 GW according to Global Wind Report 2019. (GWEC, 2020)

In Bosnia and Herzegovina, wind technology is in its development phase. First large utility scale wind farms are built in the last five years, with wind farm “Mesihovina” being the first large utility scale wind farm in Bosnia and Herzegovina. It has installed capacity of 50.6 MW. Later on, two more wind farms on utility scale have been put into operation.

2.3.1. Technical description of wind power technologies

Wind power represents one of the fastest growing renewable energy technologies today. Even though it is popular opinion that wind power technology is modern technology from 21st century, its beginnings are dating earlier. Windmills were invented in 12th century and are first form of wind power technology that utilise kinetic energy of the wind and transform it into mechanical, for example wheat grinding. Later, appeared wind turbines – wind power structures that use wind for production of electricity.

First wind turbines were put in operation a long time ago, precisely in late 19th century, even though first attempts to utilize wind power for production of electricity date some half century earlier, in 1830s. First modern era vertical-axis wind turbine began its operation in Ohio, America in 1888, shown on Fig 14. (Shahan, 2014)

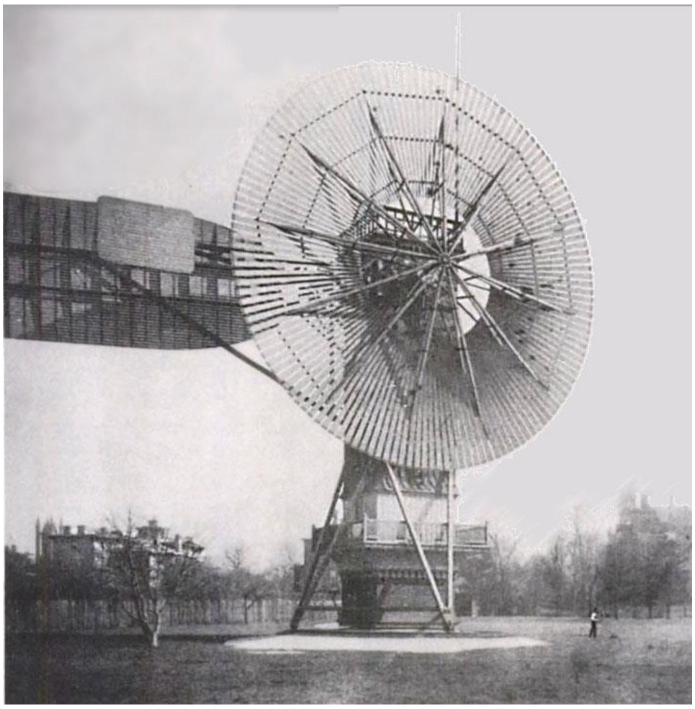


Fig. 14 First modern Wind Turbine in Ohio by DWIA, 2021

Wind turbines work on similar principle like a ventilator, instead of using electricity to produce wind, wind is being used to produce electricity. In other words, kinetic energy of the wind is utilized to produce electricity. The amount of energy that flows through some imaginary area A is defined with equation [1]:

$$E = \frac{1}{2}mv^2 = \frac{1}{2}(Avt\rho)v^2 = \frac{1}{2}At\rho v^3 \text{ [1]}$$

With ρ - density of air v-wind velocity. Avt represents the volume of the air, which is flowing through, and the assumption is that the flow is perpendicular to the surface A . $\frac{1}{2}\rho v^2$ is kinetic energy of flowing air per volume unit. Finally, since the power is energy during time, the equation for wind power [2] through surface A (for example, equal to the area of wind rotor) is:

$$P = \frac{E}{t} = \frac{1}{2}A\rho v^3 \text{ [2]}$$

Available power is increasing in eightfold with wind velocity doubling, since in the equation [2], the wind velocity is on the power of third. Since at lower wind velocities there is not that much available energy to harvest, efficiency is not that relevant, while at higher wind speeds wind turbine must rid off any excess energy then it is designed for. According to this, efficiency is more relevant and important in the region of wind velocities where the most of energy is found. (Van Bussel, 2008)

Efficiency of the wind turbines is described with the power coefficient C_p. Simply, output of electricity is divided with wind energy output. Power coefficient says how efficient is the wind turbine, how much wind energy is transferred into electricity.

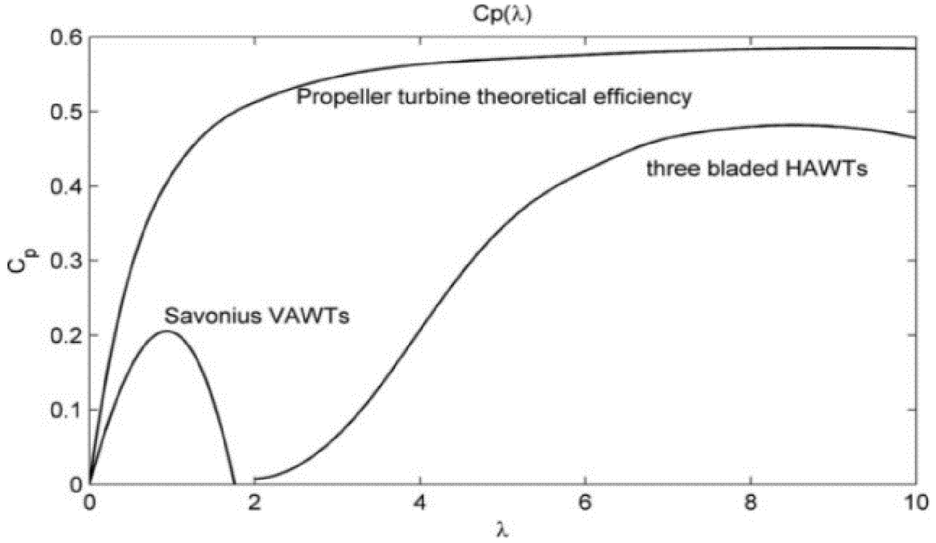


Fig. 15 C_p - λ curve graph by Ricci, 2014

Tip velocity ratio λ is the ratio of the velocity of the tips of the blades – angular velocity ω of the blades, and wind velocity. The power coefficient – aerodynamic conditions have to be determined for each wind velocity. These data are then plot on the graph which is called Cp - λ curve. The graph is shown on Fig. 15.

It is important to mention Betz law. The Betz law says, that as moving air - wind flow through certain area, and with wind velocity decrease due to energy transfer to the turbine, the flowing air is distributed to larger area. This for results has geometrical limit that limits the maximum efficiency of wind turbines to 59.3 % - not all wind energy can be captured. (Wikipedia, 2021)

There were numerous studies for assessment of the global wind capacities. The researchers Miller and Kledion from the Max Planck institute have come to the number of 18 to 68 TW of extractable wind energy (Miller, Gans and Kleidon, 2011). Studies from Harvard suggest that there is 1700 TW of available energy, with 72 to 170 TW that could be practically extracted at a economic price. (Jacobson and Archer, 2012)

Wind velocity varies, and average wind velocity for some locations doesn't tell us the amount of energy that could be produced with wind turbines. The other important factor is wind occurrence – wind distribution. The probability distribution is fit to the wind velocities data. The distribution that describes the best wind speed in hourly/ten minutes periods is Weibull distribution on Fig. 16. Another distribution that is in use is Rayleigh distribution, which is more simple and less accurate. (DWIA, 2021)

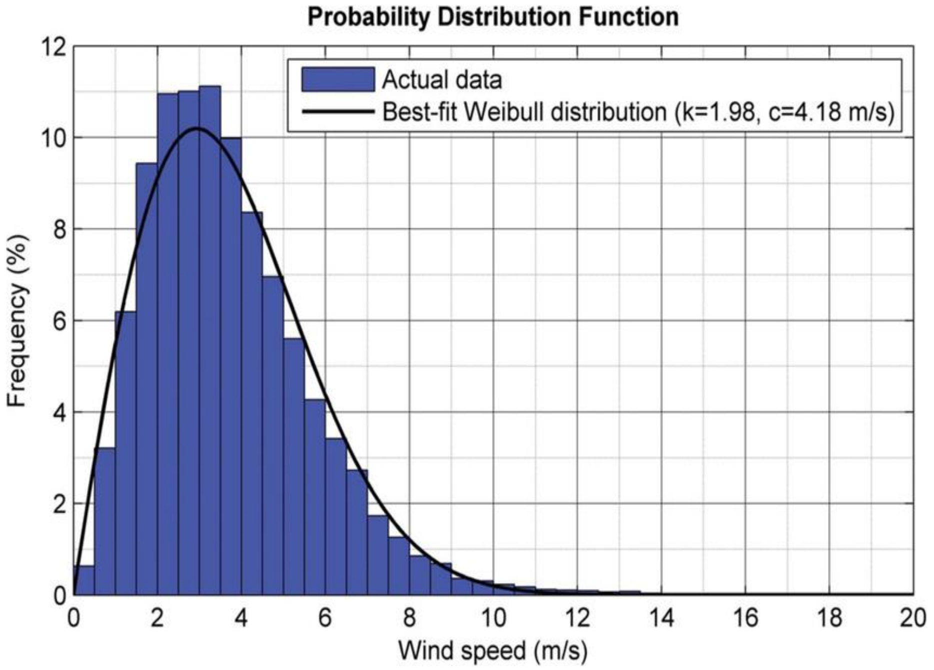


Fig. 16 Weibull distribution of wind velocity by Ricci, 2014

2.3.2. Types of wind power technologies

There are two types of wind turbines:

- Vertical axis wind turbines
- Horizontal axis wind turbines

Wind turbines can also be distinguished according to size. Smaller wind turbines have smaller blades and typically power of up to 10 kW. This is enough to power a single house (EERE, 2021). Larger wind turbines have larger diameter of blades that can range of up to 70-80 meters and power of up to 10 MW (largest one). (EERE, 2021)

Larger wind turbines are commonly grouped together in wind farms or wind power plants shown on Fig. 17, which produce electricity for the grid. (EERE, 2021)

Fig. 17 Wind farm by Warren, 2021

Horizontal axis wind turbines

This type of wind turbine is the most common one. The axis of the shaft of the propeller is parallel to the ground. Propellers typically consist of three blades and look like airplane propellers. Horizontal axis wind turbines or HAWTs operate at high speeds. HAWTs can face direction of wind in two ways: upwind and downwind. Upwind rotors require jaw and/or a motor to position them in the direction of the wind, while downwind rotors have coned blades that positions them, shown on Fig. 18.

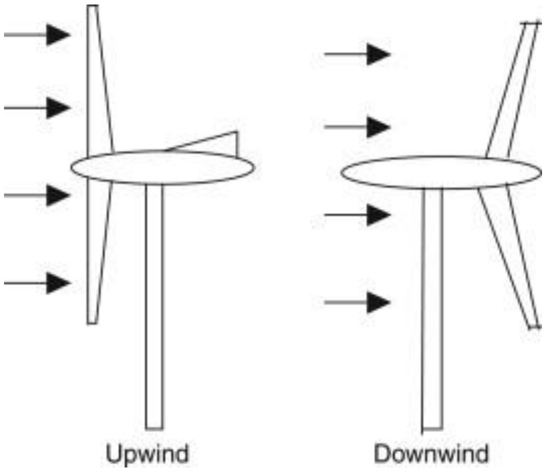


Fig. 18 Representation of upwind and downwind turbine by Mathew, Philip, 2012

Nacelle with rotor blade, as shown on Fig. 19, are being mount on the tower, which can have very large height regarding the diameter of the blades, the larger the diameter of the blade is, the larger the height of tower is.

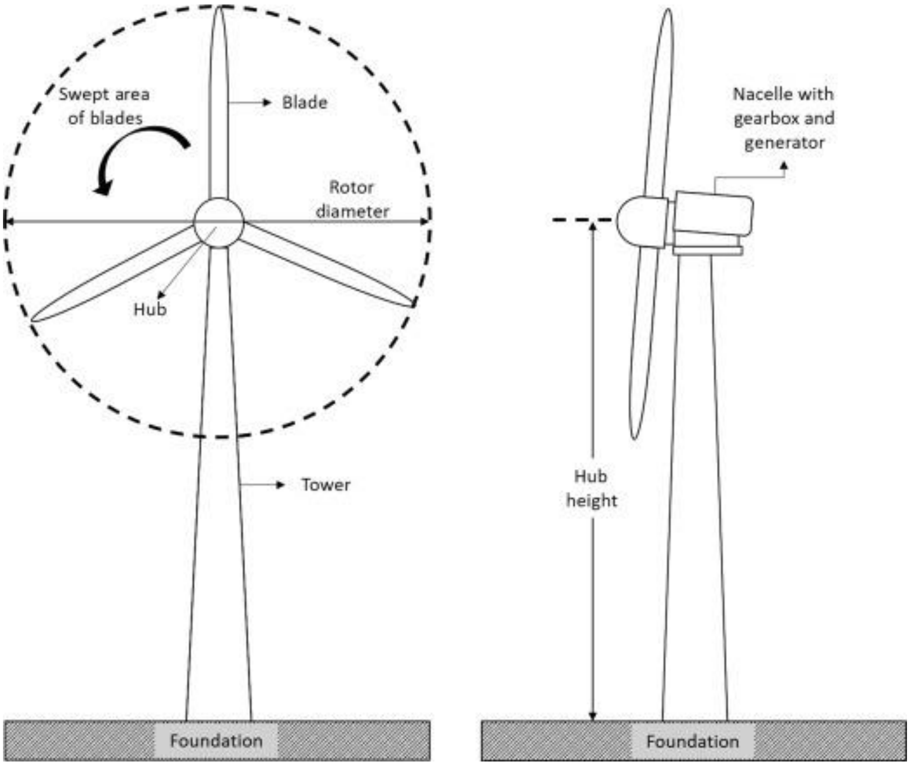


Fig. 19 Basic elements of wind turbine by Montoya, 2020

Nacelle represents the housing of the turbine.

Inside nacelle, the generator with a gearbox and other equipment is mounted. Gearbox is connection between rotors with the blade and generator. It transforms lower rotation velocity of rotor into higher velocities suitable to the generator for electricity production. There was research and development of direct-drive generators that can operate at lower speed, with that eliminating need for gearbox. Gearbox is heavy and one of the most expensive elements of the wind turbine. (EERE, 2021)

Controller, anemometer, brake, yaw, yaw motors are measuring devices and equipment that are being stored in nacelle.

Vertical axis wind turbines

Vertical axis wind turbines or VAWTs are type of wind turbines with axis of blade rotation being vertical to the ground and perpendicular to the wind direction like. Typical look of VAWTs is shown on Fig. 18. This type of wind turbine is not so widespread since it is less efficient and reliable than HWATs. (Luvside, 2020)

Fig. 20 Vertical wind turbine by ChristianT, 2010

VWATs typically have less capacity with 55 kW wind turbine being one of the largest one. (Ryse Energy, 2021)

Onshore and Offshore wind turbine

Regarding the locations of wind turbine, wind turbines can be categorized as onshore or offshore. Onshore wind turbines are placed on land and having capacity of 100 kW to several MW. Offshore turbines are placed in seas and oceans like shown on Fig. 21, and harvest wind energy to produce electricity. Comparing to the onshore wind, offshore wind velocities are in average higher, therefore is available more wind power electricity generation per capacity. Offshore wind turbine projects are usually more costly than onshore ones, since sea is more hostile environment than the land. Offshore wind turbines usually have shorter life cycle, stronger materials are required, and maintenance costs are much higher compared to the onshore ones. Maintenance of offshore wind turbines requires more resources, time, and infrastructure (AGI, 2021). Another factor that can result in potentially larger costs and differs offshore wind projects from the onshore ones is connection these offshore wind turbines to the grid with the power cable under the seafloor. (BOEM, 2021)

Fig. 21 Offshore wind turbine by SteKrueBe, 2009

Offshore wind capacity accounted in 2020 for 1% of world electricity generation. (Reed, 2020)

2.4. Solar Technologies

The Sun is the central star in the Solar system in which is placed our planet, planet Earth. Sun is a sphere of hot plasma, heated to incandescence with nuclear fusion – reaction that is occurring in the core of the Sun (NASA, 2008). Outer temperature of the sun is around 6000 K, with temperature of the core reaching of up to 15 million K. Distance of Sun from the Earth is 150 million of km. Its mass is 333 000 times of the Earth, and it accounts for about 99% of the Solar system. Sun emits solar radiation - sunlight which supports and is basis of almost all life on earth with photosynthesis, impacts on atmosphere and weather. (Wikipedia, 2021)

The sun is the brightest object in the sky from the Earth and largest source of energy. At an average, it needs 8 min and 19 seconds for sunlight to reach the Earth. The amount of power that sun emits to directly exposed surface on earth every second is called the solar constant – it is equal to approx. $1368 \frac{W}{m^2}$. The amount of energy that reach Earth surface, due to atmosphere, is less than that value and amount to approx. $1000 \ \frac{W}{m^2}$ in good weather conditions. The quantity of suns energy that hits earth in an hour and half is enough to supply world energy consumption for an entire year. (EERE, 2021)

The solar energy technology made available this energy to be captured and transformed into electricity or thermal energy. The first use of solar energy was way before, dating from 7 century B.C., with using glass for starting fire. Romans have used light in famous Roman bathhouses, which are still popular today. (Austin, 2019)

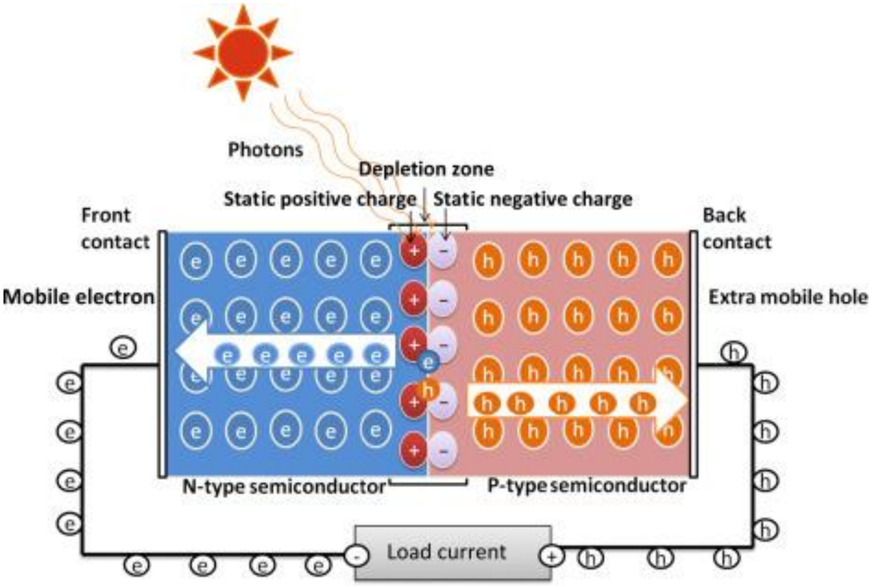


Fig. 22 Photovoltaic cell by Simya, 2018

The big discovery in solar technology was discovery of photovoltaic effect in 1839. Physicist Edmond Becquerel discovered that metal cells in electrolyte were producing electricity when exposed to sunlight. Photovoltaic effect is shown on Fig. 22. This discovery represents the base for modern solar technology as we know it today. The first practical solar photovoltaic cell was made in 1954 in America, by three scientists. Since then, the solar technology has improved and been in development. (Aps, 2009)

2.4.1. Technical description of solar technology

The sun is emitting solar radiation or sunlight to the Earth. This energy can be captured with solar technology and transformed into useful forms heating and electricity. The amounts of energy that can be transformed depends on availability of sunlight on certain location. Since every part of the Earth gets some sunlight during the year, according to EERE, the amount of sunlight on certain location varies in accordance with (EERE, 2021):

- Location
- Landscape
- Weather
- Climate
- Time of the day

Significant factor is the angle of sunlight falling on the earth, which depends on the time of the day, location. When the angle of the sunlight is closer to 0 – near the horizon, the less sunlight hits the earth since sunlight travels longer in that case through the atmosphere, and with that it is being more scattered and diffuse. This happens on earths north and south pole, where because of earth tilted axis of rotation, these areas doesn't receive sunlight for the part of year.

The amount of sunlight or solar radiation that reaches earth is called direct solar radiation. The part of solar radiation that gets absorbed, scattered, or diffuse is called diffuse solar radiation. The sum of these two radiations is called global solar radiation. Atmospheric conditions have large impact on direct solar radiation, and they can reduce it for 10% on sunny, dry days or 100% on cloudy days. (EERE, 2021)

The solar radiation is captured and transformed into electricity or heating with solar technology. There are two types of solar technology: solar photovoltaic and concentrated solar-thermal power. As mentioned, the first practical solar cell was invented in 1954 in America, and it made foundation for modern solar technology. The solar cell is electronic device which transforms sunlight into electricity with photovoltaic effect. The solar cells have certain characteristics like voltage, current and resistance which vary when exposed to the sunlight. The production of electricity in solar cell happens in three steps.

First, when sunlight reaches surface of the solar cell, the energy from the sunlight – photons are being absorbed by the semiconducting material of the cell. Most common cells today are made of silicon.

Electrons in the cell are being excited from with the received energy and start their journey across cell. On this journey, electrons can dissipate this energy in the form of heat and return to their positions, or travel through the cell until they reach an electrode.

Flow of the current cancel potential and electricity is generated. In this process of electricity production, chemical bonds of the material represent essential factors. The material of cell, usually silicon, is used in two layers. These layers have different electrochemical charges and direct the current of electrons – electricity. An array of solar cells – module transforms sunlight into DC, which is then transformed into alternate current with inverter. (EERE, 2021)

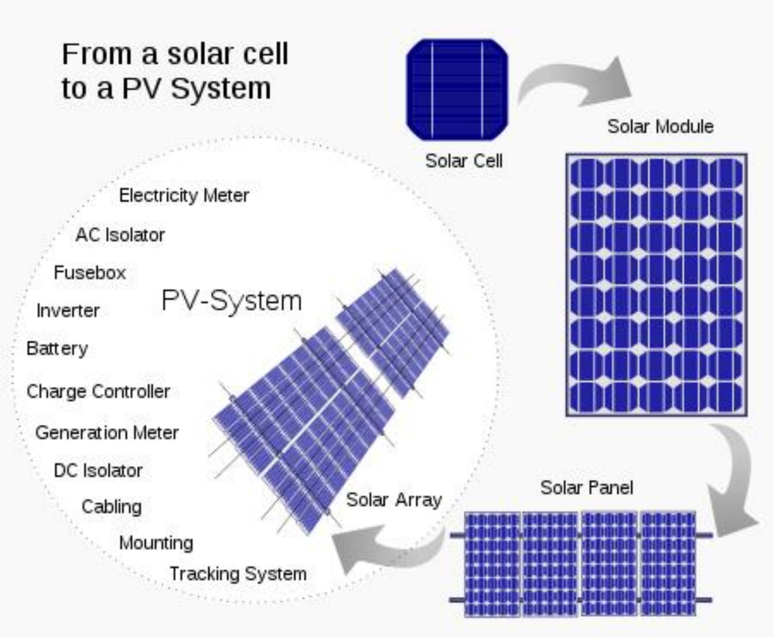


Fig. 23 Structure of solar panel by Rfassbind, 2014

Most common solar cell is configured as p-n junction, which is made of silicon layers with different charges. On Fig. 23 is shown integration of solar cells and panels into PV system.

The maximum theoretical efficiency for a single p-n junction solar cell is 33.7%. This value for silicon solar cells is around 32%. Some solar cells, those with multiple layers outperform this limit and solar thermal technology. Typical efficiency of modern silicon solar cell is about 24%. (Wikipedia, 2021)

The solar technology has seen a booming in development and production in the past two decades. This made available dropping prices and development of solar technology. China, Taiwan, Germany, Japan, and America are the largest producers of solar cells in the world with accounting for 94% of world`s manufactured solar cells. (Su, 2013)

China is also the world largest producer of solar energy, with having more than 250 GW of installed capacity in 2020 with trend of growing shown on Fig. 24. In 2019, installed solar capacity in China was 204 TW. (Wikipedia, 2021)

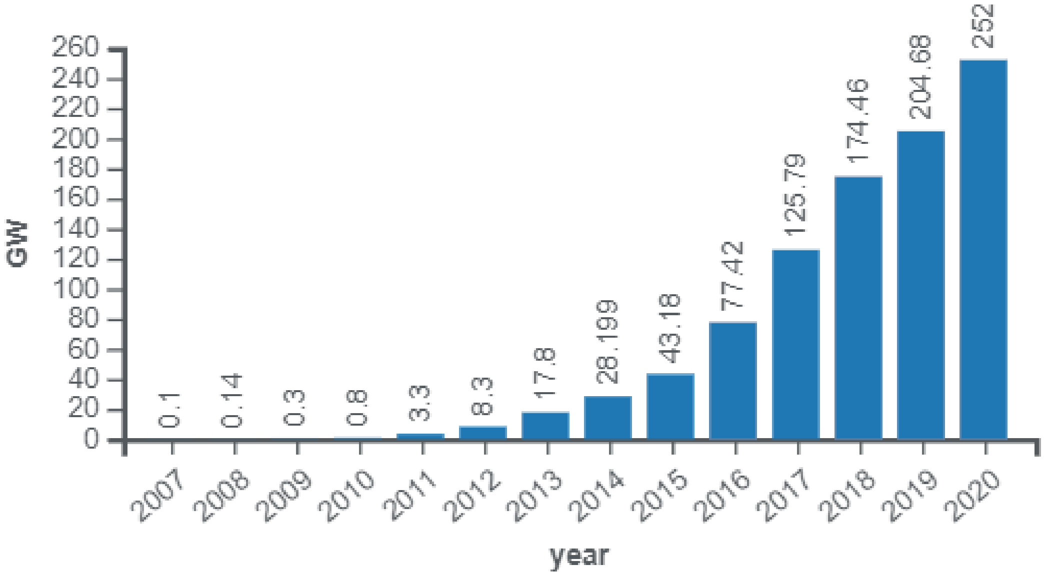


Fig. 24 Solar capacity in China by Wikipedia, 2021

2.4.2. Types of solar technology

There are three primary solar technologies:

- Solar photovoltaics
- Concentrating solar power
- Solar heating and cooling

All of these technologies use solar radiation – sunlight and transform it into useful form of energy, electricity and heating. Solar photovoltaics converts sunlight into electricity, concentrating solar power can produce both electricity and heating energy, while third technology SHC is used for heating and cooling. (SEIA, 2021)

Solar Photovoltaics

Solar photovoltaics technology is the type of solar technology that transforms sunlight directly to electricity with solar cells that utilise photovoltaic effect. Photovoltaic devices are photovoltaic cell that are combined into solar panels. Photons from sunlight falls to the solar panel and ionize the semiconducting material of the panel. Ionized electrons from the material travel to the electrode and then to the external load. This way an electric current is generated. This process is shown on Fig. 25.

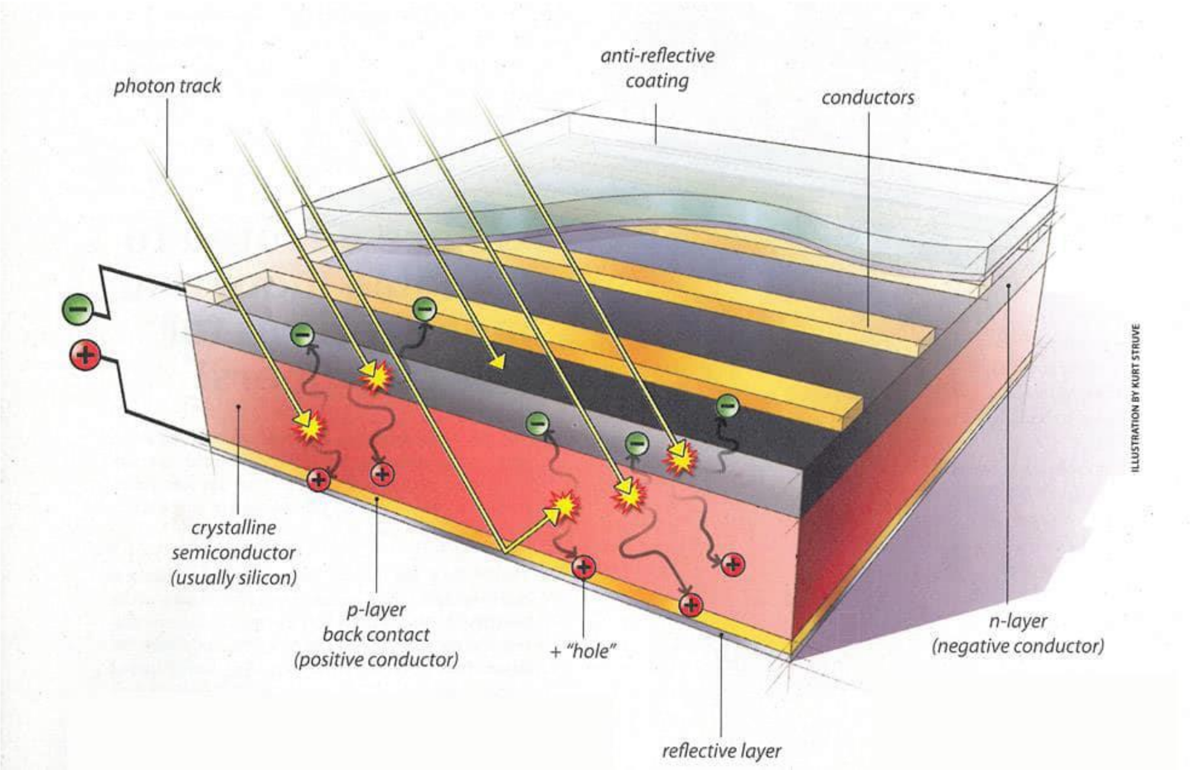


Fig. 25 Solar cell under sunlight producing electricity by SEIA, 2021

Solar photovoltaic panels can be installed in houses for domestic demand, in commercial purpose, and in solar farms where electricity is generated on utility scale. Drop in prices for solar photovoltaic have made possible for this technology to be most distributed.

Concentrated solar power

Concentrating solar power plants use mirrors for focusing sunlight that drives turbines for electricity production. Typically, this type of power plants is made in dessert areas with high sun irradiance. Electricity is generated by the generator connected to the typically steam turbine. Turbine is powered with fluid heated with sunlight and transformed into steam. Additional thermal storage is incorporable in concentrated solar power plants, enabling CSP plants to provide electricity day and night. This make CSP dispatchable source of energy. (Deign, 2015)

Concentrated power plants can have large electricity output, with largest CSP plants having capacity of 400 MW like Ivanpah Solar Power plant on Fig. 26.

Fig. 26 Ivanapah solar power plant by Butz, 2014

This type of CSP power plant is with power tower as a generating unit. The sunlight is focused on power towers where fluid, water or molten salt is heated. Working temperatures in CSP with power tower is 500-1000 °C This fluid is then used as a power source for electricity production. This type of CSP plants offers high efficiency and energy storing capacity. (Silva-Perez, 2017)

Another type of CSP plants is parabolic through. A parabolic through consists of reflectors with a tube in a focal point which contains liquid. This liquid is heated and used as a power source in electricity generating systems. Working fluid operates on temperature of 350-550 °C. (Müller-Steinhagen, Freng and Trieb, 2004)

Installed CSP capacities in the world in 2019 was 6500 MW (Reve, 2020). Efficiency of concentrated solar power technology is approx. 23-25%.

Solar heating and cooling

Solar heating and cooling technologies collect solar thermal energy and uses it for providing hot water, heating to houses, cooling for residential, commercial and industrial application.

The main operation principle of solar heating and cooling technology is heating work fluid, most commonly water or air, with sunlight using adsorbent material. (EPA, 2021)

There are more type of solar heating and cooling technologies like (EPA, 2021):

- Unglazed solar collectors
- Transpired solar air collectors
- Flat-plate solar collectors
- Evacuated tube solar collectors

Solar heating and cooling technologies are mainly used in residential appliances. They can be used for buildings like hotels and similar in locations where is mostly sunny. A more detailed discussion of solar heating and cooling technologies will not be conducted in this work, since they are not in primary focus of this work.

3. LCOE

The World has witnessed almost exponential increase of the population in the 20th century with figures increasing from 1.6 billion in the 1900, to 6 billion in the year 1999 (Worldometer, 2021). Current estimation of the human population is 7.8 billion in the 2020, with projection of United Nations that human population will reach the number of 10.7 billion (United Nations, 2021). Along with the increase in worlds population, there is an increase in energy needs with arising demand that needs to be fulfilled. Considering emerging public concern and climate changes, mission to effectively satisfy energy needs of human population across the globe is becoming one of the most important tasks of humankind. Technology progress in the recent century has made this task a bit easier, since the number of available electricity generation technologies that are in use is bigger than ever before. Considering mentioned and also taking into account ever present and most important aspect for today`s investors, economical aspect of the energy projects and their profitability, making the best decision is becoming a challenge for today energy project investors and policy makers. To overcome these challenges, energy cost metrics are being used in the investment decision making process as a tool to get better overall understanding and comparison of cost structure and economic competitiveness between different energy production technologies, since for electrical industry participants it is of much interest to evaluate competitiveness of different energy technologies. Economic competitiveness of energy production technologies is very interesting topic to electrical industry participants, where energy cost metrics, as suggested by Mai, Movers and Eurek in 2021, is used as an indicator of whether certain technology is viable from the economic aspect, how far is technology from the economic viability and the relative ranking between options (Mai, Movers, Eurek, 2021).

Levelized cost of electricity represents, in simple words, average revenue per unit of electricity that is required to come to breakeven point – cost recovery during life cycle of the electricity power plant. The costs that are included during financial life and duty cycle of electricity power plant are cost of building the plant, and costs of operating and maintaining. LCOE method is having base in discounted cash flow method – DCF, with discounting cash flows to common base with respect to the time value of the money in order to calculate costs of renewable energy technologies. (EIA, 2021)

Considering that most renewable energy technologies have low or zero fuel cost with the fact that they are capital intensive, the weighted average cost of capital WACC commonly have most critical impact on LCOE.

In evaluation of different renewable energy projects LCOE is most used method for calculating cost and revenue ratios and understanding economic competitiveness for different technology projects. There are also similar metrics, LCOS and LACE that can be used with LCOE in evaluating projects for better overall understanding of all factors in investment decision making (EIA, 2021).

While hydro energy is considered dispatchable energy technology, which means that is possible to dispatch/produce electricity when there is need for it, this cannot be also said for wind and solar energy technologies. Wind and solar energy are not dispatchable due to their fluctuation nature. From the reason of intermittent nature of these sources, wind and solar electrical power plants commonly have to be planned into the grid with other sources of energy and ways needs to be found to compensate for this intermittency in electrical production.

One of the greatest challenges for solar power technologies is matching it with electricity demand profile, since solar power technology produce electricity only during the day while the demand ramps when the sun sets, and it is most intensive in the evening hours shown on Fig. 27. With increasing use of PV systems, there also appears possibility of overgeneration of electricity during the day, which also have negative impact on the grid. (Jones-Albertus, 2017). To overcome these challenges in demand and improve grid safety from overproduction, it is of essential importance to find the way to overcome the gap between periods of max electricity production and period of highest demand. Energy storage technologies are the key element to integrate renewables into the electrical grid.

There were few projects launched in 2016 that should help utility companies to better estimate and rely on solar resources. This should make easier for utility companies to meet needs of their customers and maximize their solar resources. (Jones-Albertus, 2017)

Other efforts are made in to make possible to easier predict when, where and how much solar power will be produced, and with that maximize solar resources. Advanced computer technology like machine-learning technology is used for forecasts, and projects like those of IBM made improvement in prediction accuracy of 30%. How ever, with the increasing trend in installed solar capacity further improvements in prediction accuracy are required. (Jones-Albertus, 2017)

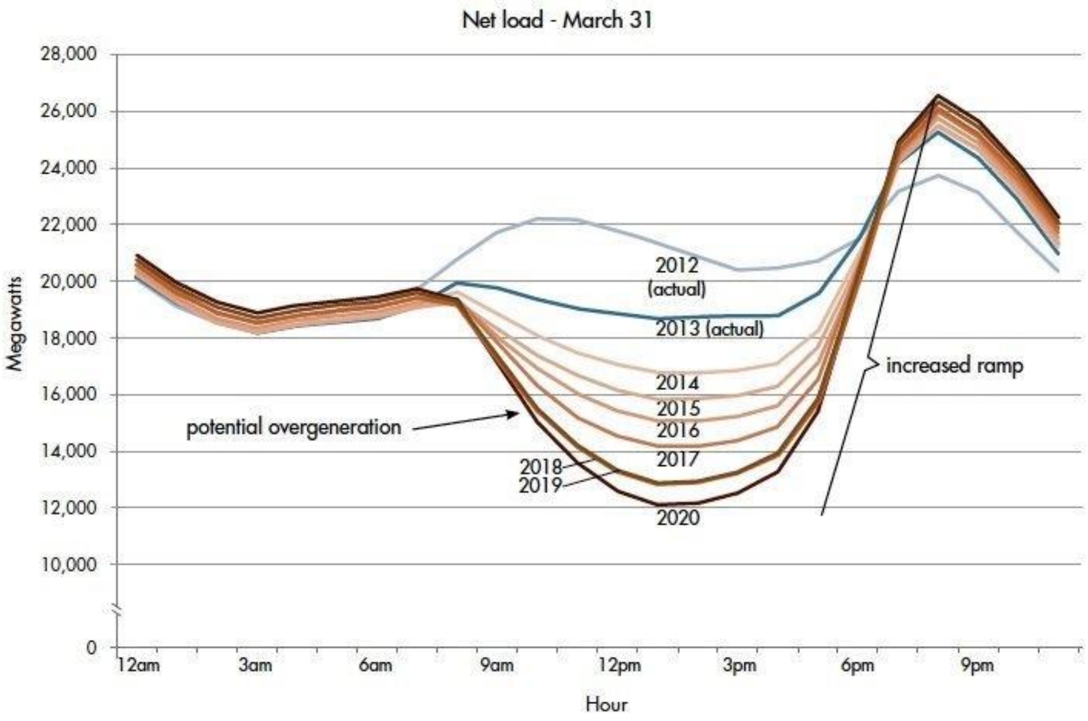


Fig. 27 Electricity demand profile by Albertus-Jones, 2017

For the past decade, engineers and policy makers are turning their efforts and attention towards energy storage technologies. Energy storage technologies can help to address the issue of intermittency of solar and wind technologies and in many cases, respond rapidly to fluctuating demand and increase over all flexibility and stability of the electric grid (Zablocki, 2019). There are 4 main categories of energy storage technologies shown on Fig. 28, according to Buchroithner *et al* (Buchroithner *et al*, 2019):

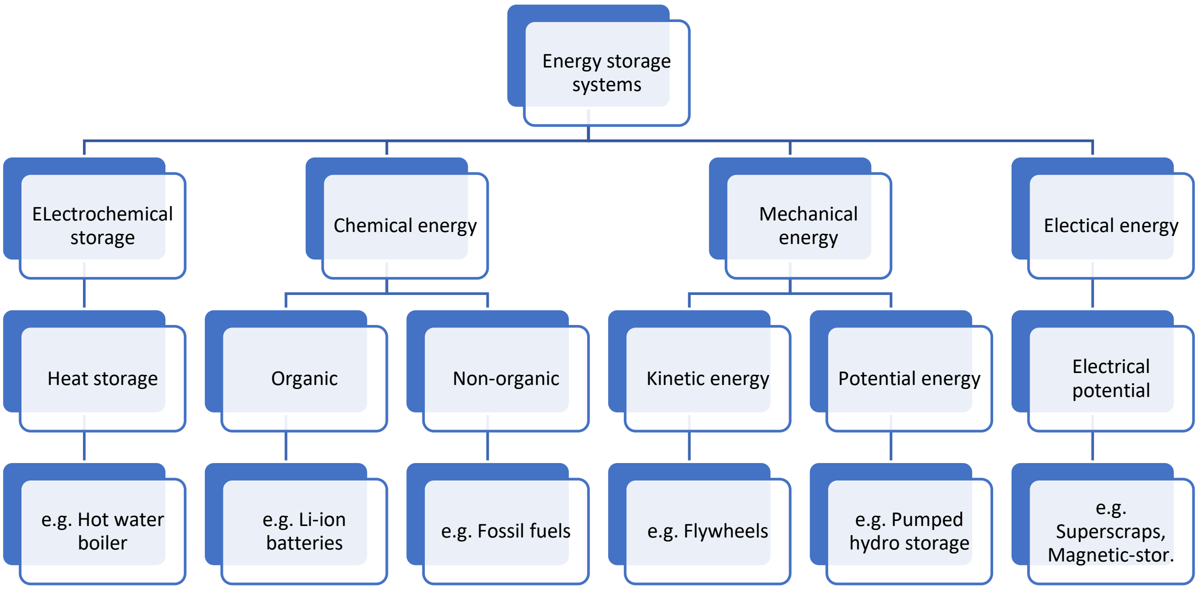


Fig. 28 Classification of energy storage systems by Buchroithner, 2019

Pumped storage hydro power plants represent one of the simplest and used form of energy storage, and these contribute to 95% of electric storage in 2017 (IRENA, 2017). In the rest of 5%, are technologies like Li-ion batteries system, a technology that has seen significant development in past years and cost reduction. Improvements and optimisation in manufacturing, combined with more efficient and reduced use of materials are some of the key drivers for this technology in the upcoming years. It is expected that installation costs reduce between 50% to 60%, and battery cells cost even more, until 2030. (IRENA, 2017). The worlds installed energy storage capacity in 2017 was 176.5 GWh (Zablocki, 2019). In assessment of energy storage technologies LCOS is used.

LCOS stands for Levelized Cost of Storage, and it is defined as a total lifetime cost of investment into electricity storage technology divided with its cumulative delivered electricity (Pawel, 2014). **LCOE** is used to evaluate and compare techno-economical aspect when deciding among different energy storage technologies. According to Cascone and Sonti in 2019 (Cascone, Sonti, 2019), LCOS is calculated as shown in formula [3]:

$$LCOS = \frac{sum\ of\ costs\ over\ lifetime}{sum\ of\ discharged\ electricity\ over\ lifetime} \frac{\sum_{t=1}^{i} \frac{Capital_t + O\&M_t + Fuel_t}{(1+r)^t}}{\sum_{t=1}^{i} \frac{MWh_t}{(1+r)^t}} \qquad [3]$$

Where in LCOS equation [3] are:

$Capital_t$	Investment expenditures in year t
$O\&M_t$	Fixed operation and maintenance costs in year t
$Fuel_t$	Charging cost in year t
MWh_t	The amount of discharged electricity in year t in MWh (measure for capacity factor)
i	lifetime of the energy storage
r	discount factor

When comparing different energy storage technologies, LCOS is preferred unit of measure. LCOS is analogue to LCOE – Levelized cost of electricity, the difference is that in LCOS equation, for input parameter fuel costs is meant charging cost of energy storage, and discharged electricity is taken instead of produced electricity (Cascone, Sonti, 2019). In the last year, a combination of these metrics emerged for solar PV. It is called levelized cost of solar plus storage, and it basically combines these two metrics, LCOE and LCOS for solar PV technology.

There are more detail equations for calculating LCOS, with input variables being taken in more thoroughly and precise manner. Since LCOS is not primary focus of this work, the mentioned equation represent concept in a convenient and adequate manner.

LACE stands for levelized avoided cost of energy. LACE is method which tell us the about value of the plant in serving the electric grid. It is a measure used for evaluating and assessment of potential new energy projects through consideration of avoided costs. It answers the question of what would cost the grid to produce electricity that is otherwise produced with new generation project as well it`s levelized costs.

LACE is calculated with dividing avoided costs with average annual output. The LACE is compared with LCOE as indication if project values exceed it`s cost or not. This is done to evaluate which project has the best net economical value (EIA, 2014). Avoided costs are commonly complex to calculate, since there is not always available required data.

These methods are framework for observing different renewable energy projects, understanding their competitiveness, and their assessment in decision making of investing into a project.

Even though these three metrics, LCOE, LCOS and LACE, with accent to LCOE, are most used energy cost metric now days, there are alternative energy cost metrics from the same cost metric family. They also take total costs and divide it with total energy produced. (Aldersey-Williams, Rubert, 2018)

UCOE or undiscounted cost of energy is simple metric that is equal to total capital and operations costs divided with the energy produced as shown in equation [4]:

$$UCOE = \frac{\sum_{t=1}^{i} C_t + O_t + V_t}{\sum_{t=1}^{i} E_t} \qquad [4]$$

UCOE might be informative in comparing projects that use the same technology, while it is not useful in comparing between technology types. It offers no insight into the impact value of the timing energy production or cashflows, since it doesn`t consider time value of money (Aldersey-Williams, Rubert, 2018).

DCCOE or discounted costs cost of energy is defined with diving the discounted sum of all costs, capital and operational, with the sum of energy produced. It is defined with the equation [5] (Alderey-Williams, Rubert, 2018):

$$DCCOE = \frac{\frac{\sum_{t=1}^{i} C_t + O_t + V_t}{(1+r)^t}}{\sum_{t=1}^{i} E_t} \quad [5]$$

Unlike the LCOE, which results in an unambiguous number that is clearly defined as a minimum constant energy price required to deliver the return with taking into account applied discount rate, DCCOE return`s a figure that doesn’t have clear meaning. This lack of apparent meaning makes it less useful metric. (Aldersey-Williams, Rubert, 2018)

TCOE or total cost of energy is also one of the alternative energy metrics from the family of metrics that is calculated with dividing total costs with energy produced. It is defined, according to Aldersey-Williams and Rubert (Aldersey-Williams, Rubert, 2018), with formula [6]:

$$TCOE = \frac{\sum_{t=1}^{i} C_t + O_t + V_t + F_T}{\sum_{t=1}^{i} E_t} \quad [6]$$

One parameter is added, F_t – the costs of financing during each year, which is calculated on the base of annuity formula. (Alderey-Williams, Rubert, 2018)

3.1.Key concept: LCOE

Various researchers wrote on the topic of LCOE and there are multiple definitions. According to Sing and McCulloh, LCOE or levelized cost of electricity is defined as:

> The **levelized cost of energy** (**LCOE**), or **levelized cost of electricity**, is a measure of the average net present cost of electricity generation for a generating plant over its lifetime. It is used for investment planning and to compare different methods of electricity generation on a consistent basis. (Sing, McCulloh, 2017)

Different methods of electricity production can produce significantly different costs at different time. These costs can include investment capital, costs of operation and maintenance, cost of fuel, and costs of de-commissioning or remediating. Calculation of these costs expressed as a cost per unit of energy may or may not include cost of connection to the grid – transmission cost. (EIA, 2021)

To evaluate different electricity production projects, it is useful to compare cost per unit of energy, and they are typically expressed per kilowatt or megawatt. In this context the LCOE method is used as a tool and a framework for estimating the financial and technical aspects of project. LCOE is useful for policymakers, investors, and others as a guideline in assessing new energy policies or in decision making.

One perspective of LCOE is a minimum constant price at which electricity is sold in order to project break even during its lifetime, which is usually twenty to forty years.

This is calculated as the net present value of all costs during lifetime of the plant divided with discounted value of total energy production during facility lifetime. LCOE according to EERE is calculated as shown in [7] (EERE, 2021):

$$LCOE = \frac{sum\ of\ costs\ over\ lifetime}{sum\ of\ electricity\ produced\ over\ lifetime} = \frac{\sum_{t=1}^{i} \frac{I_t + M_t + F_t}{(1+r)^t}}{\sum_{t=1}^{i} \frac{E_t}{(1+r)^t}} \quad [7]$$

In LCOE equation [7]:

I_t investment expenditures in the year t

M_t maintenance and operation expenditures in the year t

F_t fuel expenditures in the year t

E_t electricity produced in the year t

i lifetime of the power plant

r discount rate

In comparing different LCOE calculations for different technologies, attention should be taken, since LCOE is dependent on made assumptions, financial terms and technological development. For example, capacity factor has significant impact on LCOE, caution should be taken that parameters taken into calculations correspond to real terms.

Similar concepts to LCOE are LACE and LCOS and are commonly used together when evaluating different energy technologies and projects in order to get a better understanding of their economic competitiveness.

LACE represents the levelized avoided cost of electricity, and it represent the value that power plant provide to the grid. (EIA, 2021)

At high share of variable energy source – VRE, non-dispatchable energy source like wind and solar with regarding their fluctuating nature opposite to hydropower, LCOE isn’t the methodology that fits the best to calculate costs that occur. Since that, term of system LCOE is introduced.

System LCOE take into account cost of integration of variable renewable energy - VRE into the grid among with cost of electricity production.

Compared to simple LCOE which is considering power plant on the plant level without considering wider costs and impact on the grid or ecological impact, system LCOE is considering power plant level cost and implications on the grid and costs that could occur.

System LCOE is better overall framework an for grid designers in building more efficient power system, and represent more comprehensive energy cost metric in general from the mentioned reasons (Ueckerdt *et al*, 2013). Due to lack of data, calculation of system LCOE will not be considered in this work.

3.2.Parameters

In the LCOE calculation, according to Visser and Held (Visser, Held, 2014) following parameters are included as the minimum:

Cost parameters:

- Equipment costs
- Other investment and planning costs
- Land
- Administrative costs
- Capital cost
- Operation and maintenance costs
- Fuel costs
- Decommission costs
- Common costs for grid connection
- Network related costs

Electricity production parameters

- Calculation in advance
- Adjustments made ex post
- Technology specific load

3.3.LCOE calculation for hydropower

Hydropower as an electricity production technology is in use for more than a century. It represents often a most affordable way to produce electricity where unexploited hydro resource exists. Hydropower as a technology has matured, and according to IRENA, cost reduction of hydropower technology is usually limited to improvements in civil engineering part of construction of hydroelectric power plants (IRENA, 2021). Example of structure of the costs is shown on Fig. 29.

For large hydropower projects the weighted average LCOE of new projects added over the past decade in China and Brazil was USD 0.040/kWh, around USD 0.080/kWh in North America and USD 0.120/kWh in Europe. For small hydropower projects (1-10 MW) the weighted average LCOE for new projects ranged between USD 0.040/kWh in China, 0.060/kWh in India and Brazil and USD 0.130/kWh in Europe. (IRENA, 2021)

The installation costs for most of hydropower projects that were put in use from 2010 to 2019, range from 600$/kW to high as a 4500$/kW. Most of installation cost is associated with site works, where for example, installing hydropower on already existing dam can amount 450$/kW. (IRENA, 2021)

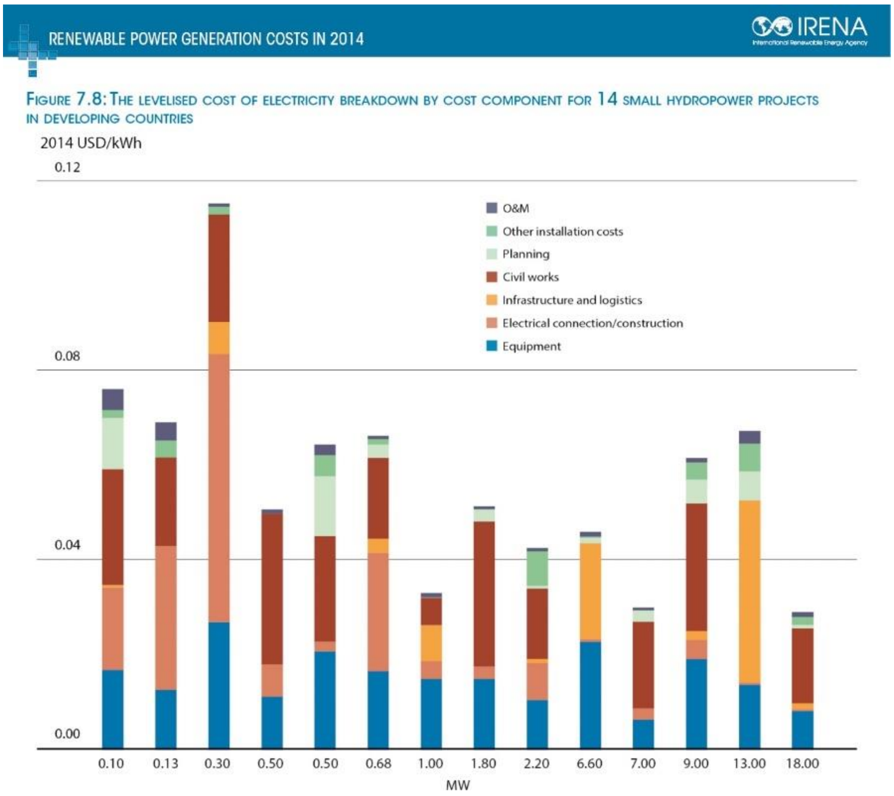


Fig. 29 Structure of LCOE costs for RES in 2014 by IRENA, 2014

3.4.LCOE calculation for wind power

Wind power technology has been in development in recent decade and the cost of electricity from this source continuous to drop. This is caused with decrease of price of wind turbines of 44% to 78% in 2007 to 2010, where they were at maximum. Improvement in technology, rotors and overall efficiency results in larger wind turbine capacity being produced.

When calculating LCOE for wind power technologies, significant impact has capacity factor and investment costs. Resulting LCOE for different average wind speed is shown on Fig. 30.

The global weighted-average cost of electricity of new onshore wind farms in 2019 was USD 0.053/kWh with region values of between USD 0.051 and USD 0.099/kWh depending on the region. Costs for the most competitive projects are now as low USD 0.030/kWh, without financial support. Costs are set to continue to decline, with no significant slowing in wind turbine price declines, and continuing advancements in wind turbine technology which for result have higher energy yields and with that higher capacity factor. (IRENA, 2021)

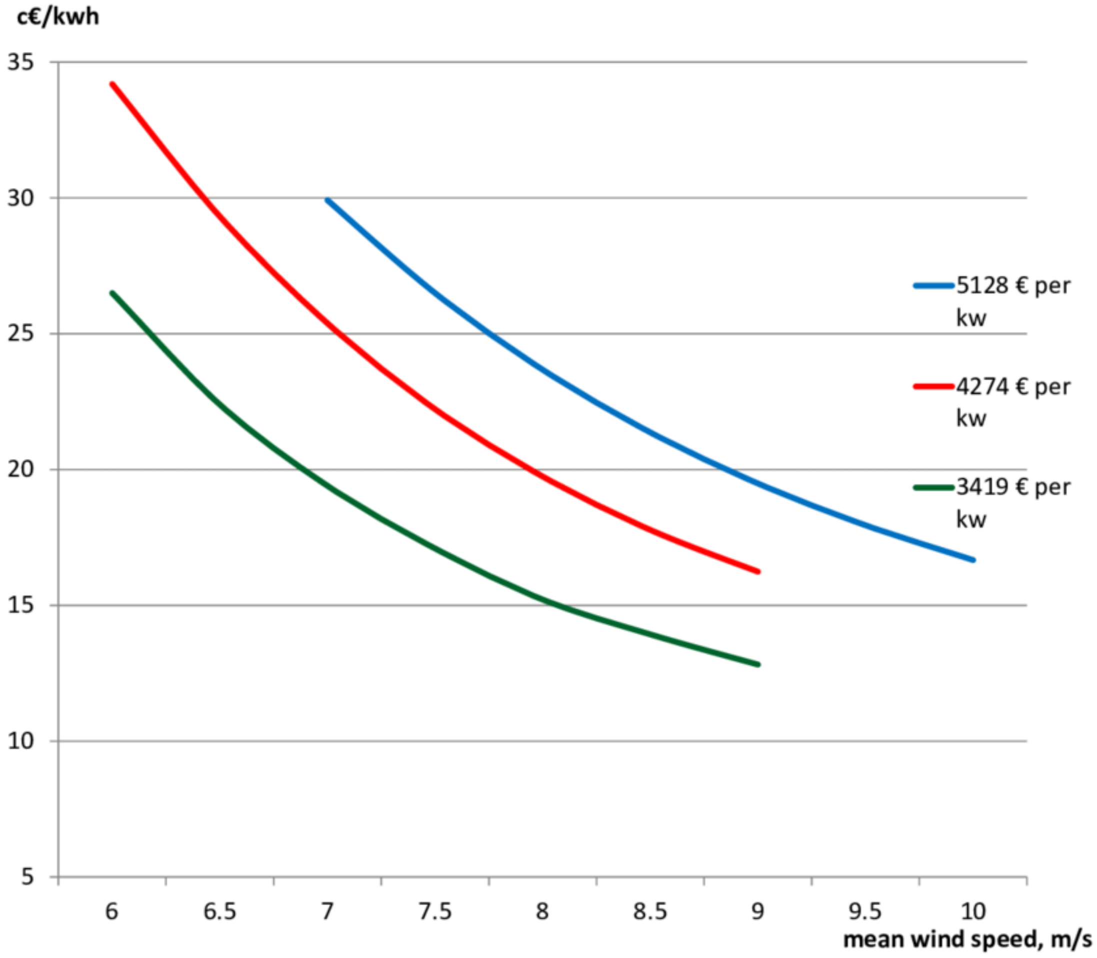


Fig. 30 LCOE for different average wind velocity by Jacobsen, 2019

3.5.LCOE calculation for solar power

Availability of solar resource in every place make solar power technology highly competitive. Solar photovoltaic - PV and concentrating solar power – CSP are technologies that are in use to produce electricity from solar radiation, sunlight. Solar power technology has experienced development in recent years, mostly due to drop in price of solar modules and inverters and other parts.

Between 2010 and 2019, the dramatic fall in solar PV module prices, along with continuing reductions in balance of system costs and the increase in capacity factors where reasons for the global weighted- average LCOE of newly commissioned utility-scale solar PV fall 82%, to USD 0.068/kWh in 2019. (IRENA, 2021)

Deployment of the utility-scale solar and costs in the America is shown on Fig. 31.

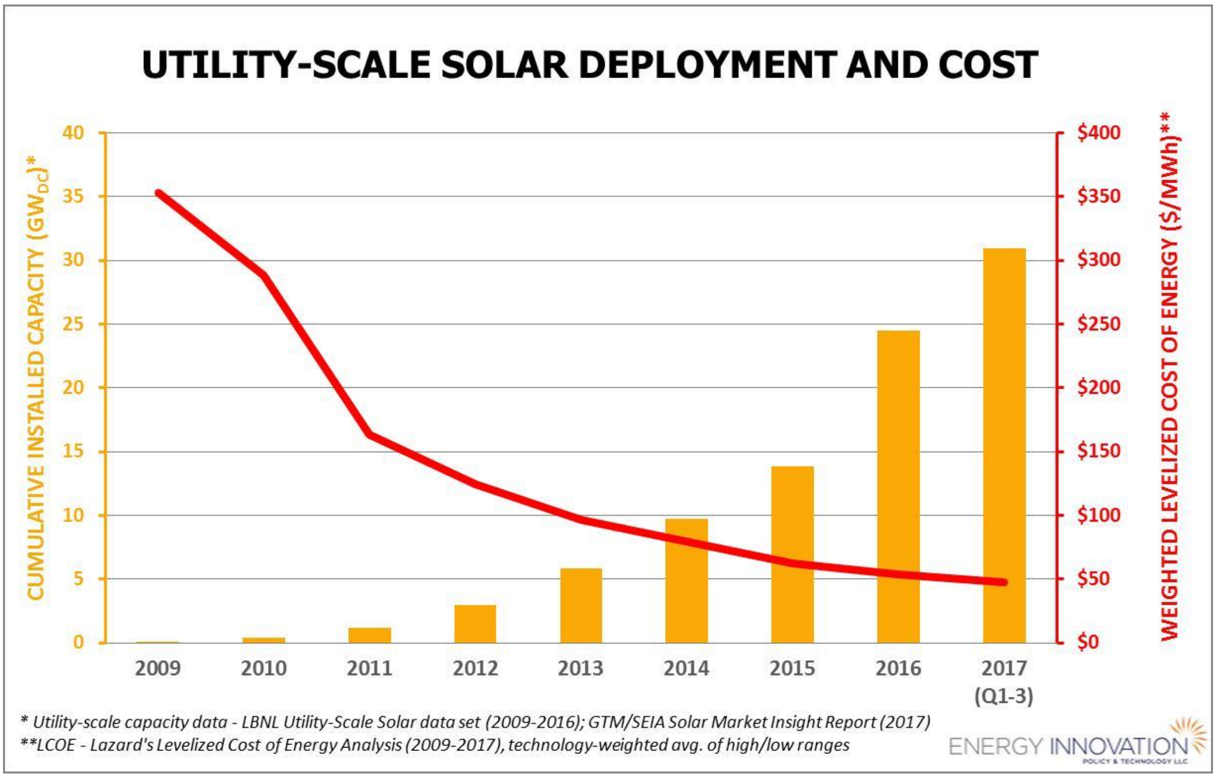


Fig. 31 LCOE for solar photovoltaic by Energy Inovation, 2018

4. Practical part

In the practical part of this work, the LCOE calculation is calculating for three electric power plants located in Bosnia and Herzegovina. The selection of the electric power plants was made so to encompass renewable energy of technologies which are subject of research of this work, hydro power technology, wind power technology and solar power technology.

Note: Data that are used in the practical part of this work are data for three real projects. Public electric utility company A and private electric company B, that are both from Bosnia and Herzegovina and are owners of projects, have approved access and use of data in this work. For the confidentiality reasons, the names of projects and companies is coded. Decision on free access to information and data can be found in Appendix.

4.1.Technical description of real projects

Power plant 1

Power plant 1 is classified as RoR hydroelectric power plant like on Fig. 32. As already stated, RoR power plants doesn't commonly have water storage, even though the Power plant 1 has certain water accumulation. The water accumulation is created with the dam which is 27.5 m height and 143 m wide. Installed water flow is 130 $\frac{m^3}{s}$ and net head for this flow is approximately 10.20 m. Electricity is generated in two generating units, each with installed capacity of 6.1 MW. Total installed capacity of Power plant 1 equals to 12.2 MW, and possible yearly production is 58.53 GWh.

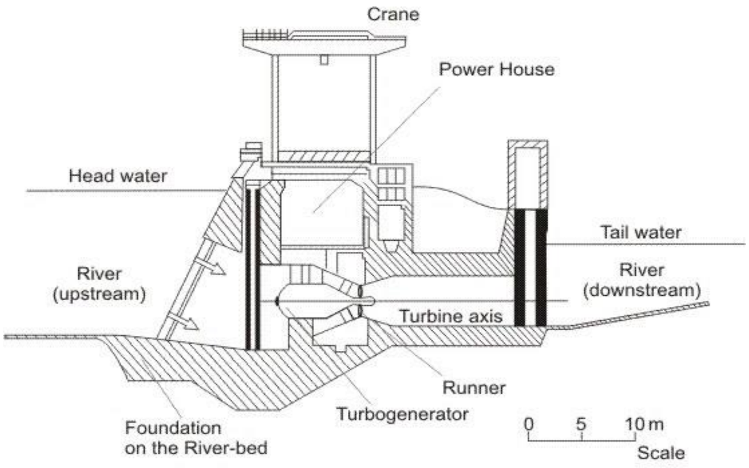


Fig. 32 Run-of River power plant by EDCLGroup, 2021

Regarding the water head, Power plant 1 is close in classification to storage power plants, and from energy aspect it is Run-off River power plant which utilise flow of the water.

Two horizontal bulb Kaplan turbines connected to the generator shown on Fig. 33, are used for electricity production. The horizontal bulb Kaplan turbines with double sided regulation were selected regarding the installed water flow 130 $\frac{m^3}{s}$ and belonging net head. Installed flow per turbine is 65 $\frac{m^3}{s}$, with min. technical flow of 13 $\frac{m^3}{s}$. Nominal rotation velocity of turbines is 166 rpm, and maximal 420 rpm.

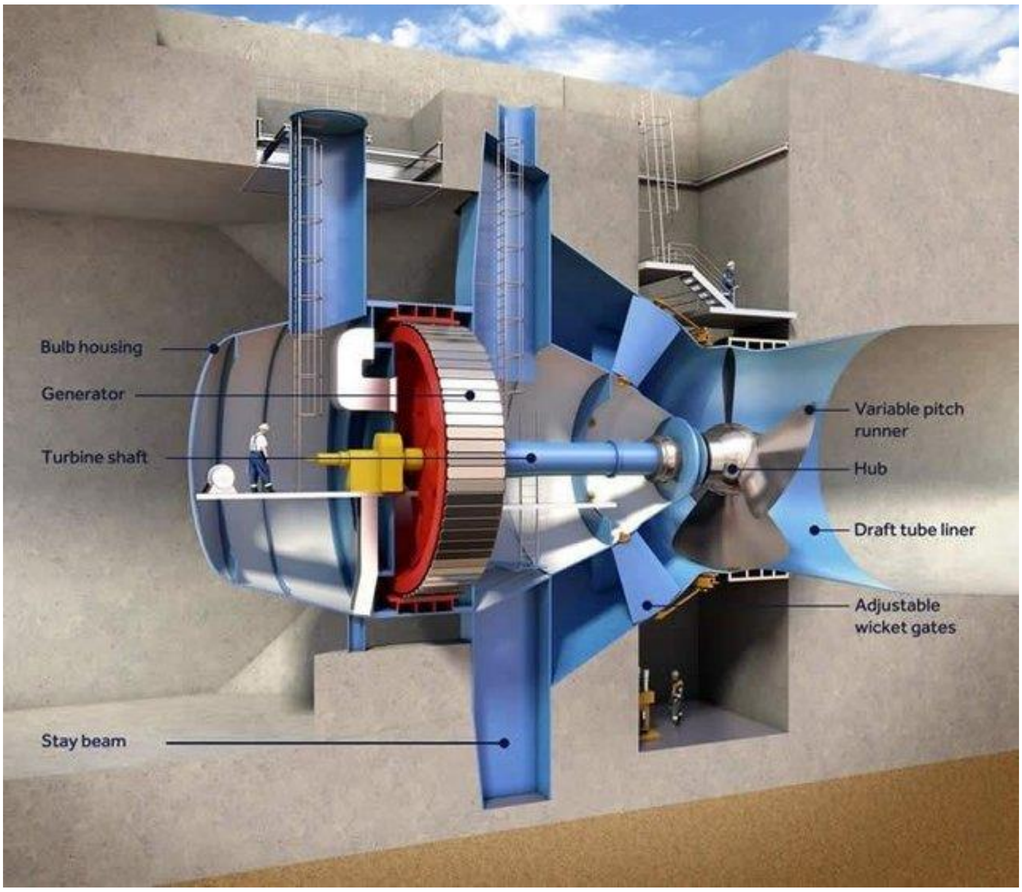


Fig. 33 Bulb Kaplan Turbine with double sided regulation by Yates, 2017

The turbines with generator are placed in powerhouse. The powerhouse is located on the left side of the dam.

For the intake of the water, slide gates are used. Upstream intake is placed 12 m below minimum operating level of the water. For maintenance and regulation of water in the accumulation, four spillway bays are used. The spillway bays are mounted with radial gates. In case of high water, spillway bays with radial gates are used to evacuate excess water. The radial gates are opened and closed with two hydraulic cylinders.

For the purpose of connecting Power plant 1 to the electrical grid, 110 kV transmission line needs to be built.

Power plant 2

Power plant 2 is an onshore wind farm, that is made of 15 wind turbines. The production capacity of individual turbine varies in range from 3.0 – 3.2 MW, and total installed production capacity of Power plant 2 is up to 48 MW. Wind turbines installed in Power Plant 2 are Siemens SWT – 3.2 – 113 IIA, shown on Fig. 34.

The manufacturer of this wind turbine is Siemens Wind Power, later known as Siemens Gamesa Renewable Energy. The SWT`s – 3-2 – 113 cut-in wind velocity, wind velocity at which it starts to work, is 3 m/s, and the cut-out velocity is 25 m/s. The cut-out velocity is velocity of the wind at which wind turbine shut down its operation, due to safety. Modern wind turbines have advanced regulation systems that gradually decrease power output and rotor movement at high wind velocities, and with that extend the operational range of wind turbine at higher wind velocities and enable stabile electricity production. For the most wind turbines, cut-out velocity is 25 m/s.

Fig. 34 SWT – 3.2 – 113 by Matsyik, 2016

SWT -3.2 -113 is mounted with direct drive generator, without gearbox. Direct drive systems don’t have a lot of moving parts, and with that doesn’t require a lot of maintenance. Gearbox commonly represent one of the most expensive pieces of equipment in the wind turbine, which direct drive systems doesn’t have. On the other hand, direct drive systems commonly require heavier generators than those systems with gearbox, which increases weight and cost of tower and foundation, and use of expensive and rare earth materials (EERE, 2019).

This wind turbine is upwind wind turbine, which use yaw system. The yaw system is powered with electric gear motors to position the turbine in the direction of wind. The wind turbine rotor is made of 3 rotor blades, and the rotor diameter is 113 m. The rotor swept area is 10 000 m^2.

The height of tower on which nacelle with rotor is mounted is 92.5 m, with manufacturer standard for tower height range from 79.5 m up to 142 m. For the construction of the tower, steel tube/bolted steel shell tube is used. On the steel tube, corrosion protection is applied in the form of anti corrosive paint.

The weight of tower is approx. 75 tons, nacelle 78 tons and rotor 67 tons.

The annual planed electricity production of Power plant 2 is 130 GWh. For the construction of the power plant and its operation, access road was built. The road connection between wind turbines was made, so each individual wind turbine is accessible. The electric power transformation station is built as a part of the wind farm which enables connection to the grid. The Power plant 2 is in the terrain that is 600 m - 900 m height above sea level.

Power plant 3

Power Plant 3 is solar electric power plant. It is solar power plant that use solar PV technology. The Power Plant 3 is made of 2460 LONGI MONO solar panels with power output of 440 W. LONGI MONO solar panels with P-V curve are shown on Fig. 35. Total installed generation capacity is 1080 kW. In the P-V curve it shown power output of solar panel depending on the amount of the sun`s irraditon. The amount of direct sun irradiation on the location of Power plant 3 is between 3.0 kWh/m^2 to 3.2 kWh/m^2 (Solargis, 2021). The solar panels are mounted on the aluminium frame construction.

The solar panels do not possess tracker systems. Power plant 3 includes electric power transformation station 10(20)/0.4 kV, which regulate voltage, transform direct current DC produced with solar panels to alternating current AC, which most electronic device use. It provides connection to the grid. For building the electric power transformation station and mounting of holders for solar panels, certain civil engineering works needed to be conducted at first.

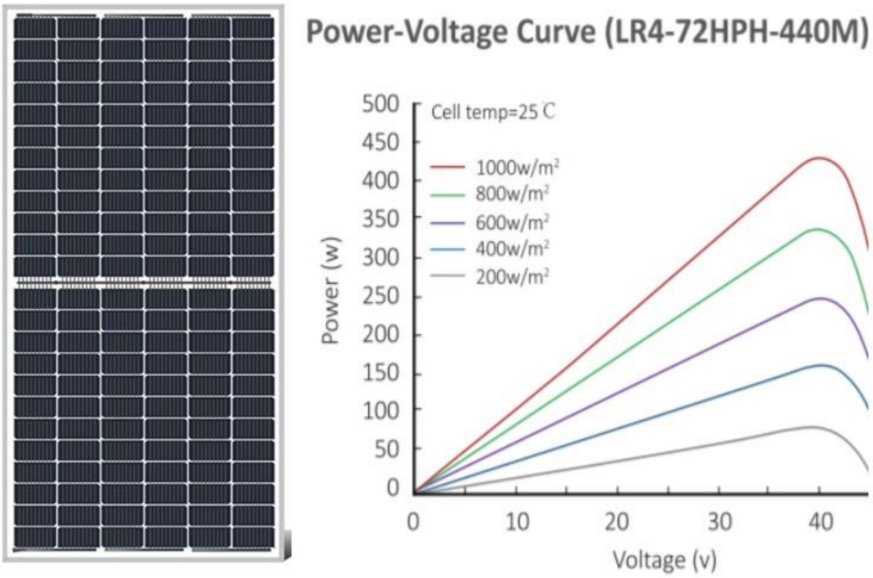


Fig. 35 LONGI MONO Solar panel with P-V curve by Solaris, 2021

It is important to note one characteristic of solar PV technology, and that is degradation of solar panels. This is natural phenomena that happens in solar panels during time because of oxidation of bor – silicium, elements of which solar cell is made of. This doesn`t represent a problem, since most solar panels manufacturers give warranty for linear degradation of solar panels, in which is defined percentage of power solar panels lose each year. How ever, unexperienced handling, mounting and operating of solar panels can cause increase degradation rate and care needs to be taken. The degradation rate typically amounts for 0.5 % yearly. On the Fig. 36 is shown linear degradation rate for LONGI MONO solar panel.

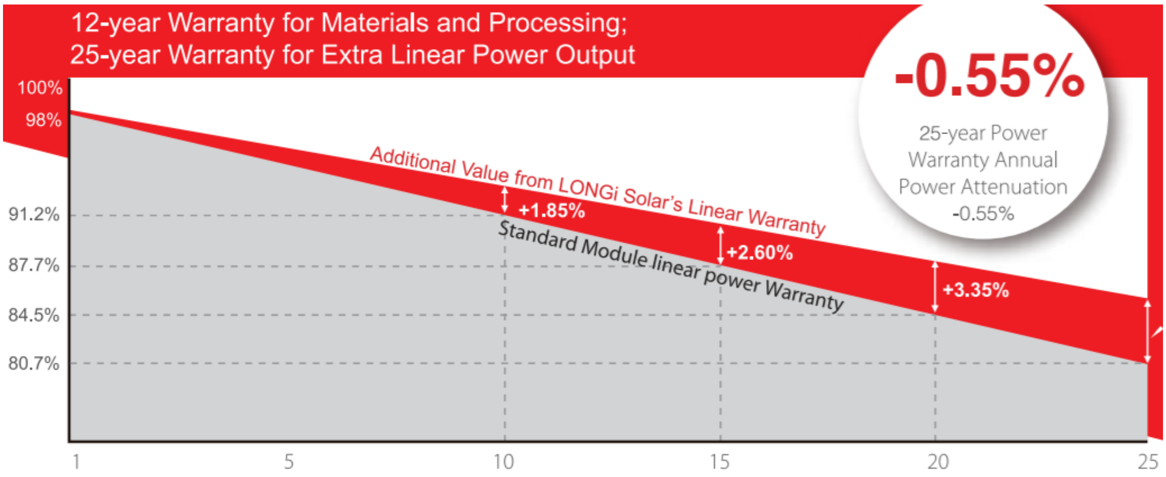


Fig. 36 LONGI Solar linear warranty by Solaris, 2021

This loses are typically taken into account and calculated into yearly production capacity of solar power plants.

In the table 2, insolation – the amount of sunny hours during the year is presented together with annual electricity production. The data for number of sunny hours during the year are collected with series of measurement from the Federal Hydrometeorological Institute for the time 2001 – 2010. Data is presented in Table 2. These data serve as the base for electricity production projection.

Table 2 by Company B

Month	Insolation (h)	Electricity (kWh)
January	83.1	62 106
February	96.3	71 971
March	137.2	102 538
April	155.8	116 439
May	197	147 230
June	226.4	169 202
July	253.3	189 306
August	233.5	174 509
September	163.4	122 119
October	152	113 599
November	102	76 231
December	55	41 105
TOTAL	1 858.5	1 386 355

4.2. Overview of the input data for LCOE

Brief overview of the input data for levelized cost of electricity has already been shortly discussed in section **3.2.** Main categories of costs and electricity production have been mentioned.

Input data for costs

Table 3 by Company A&B

	Power plant 1	Power plant 2	Power plant 3
Investment capital	89 166 055.30	122 043 792.00	1 722 300.00
Discount rate	5 %	5%	5%

In the Table 3, the investment capital in Bosnian Marks - BAM with discount rate is shown. Financial costs of projects aren`t taken into account for LCOE calculation. **Note**: All costs are expressed in Bosnian Marks – **BAM**, 1 **€** = 1.95583 **BAM** (fixed exchange rate).

In the case of Power plant 1, the financing of investment is done with 40% of own funds in the amount of 35 666 422.12 BAM, and the rest 60 %, in the amount of 53 499 633.18 BAM from credit funds.

In the case of Power plant 2, the financing of investment is done entirely from credit funds.

In the case of Power plant 3, the financing of investment is done 20% of own funds in the amount of 344 460.00 BAM, and the the 80%, in the amount of 1 377 840.00 BAM from credit funds.

Operation & Maintenance costs

Under operation and maintenance costs are considered all costs over its lifetime, necessary for a project to operate and function. These costs can include costs like cost of workforce, insurance fees, maintenance fees etc. Different type of costs can occur for different energy technologies.

In Table 4, the yearly operation and maintenance costs are displayed for each Power plant.

Table 4 by Company A&B

	Power plant 1	Power plant 2	Power plant 3
Operation and maintenance costs	1 420 127	2 885 592.43	12 345.28
Growth of O&M costs	*	0.5 %	0.5%

The amounts include all costs necessary to Power plant operate and function. * Note: For Power plant 1, the growth of O&M costs is not expressed in the yearly percentage of growth, rather in pre-determined operation and maintenance plan.

In the case of Power plant 1, in the first 5 years of operation, maintenance cost amounts for 71 844.00 BAM. In the period of operation 5 – 10 years, maintenance costs amount for 107 765.00 BAM. In the following 10 years period, 10 – 20 years of operation, maintenance costs amount for 215 531.00 BAM. In the period of 20 – 30 years of operations, maintenance costs amount for 239 478.00 BAM.

Other cost under operation & maintenance costs can include costs like labour costs, cost of land fees, insurance etc.

In the case of Power plant 1, annual fee is paid in the amount of 853 323.00 BAM for using the natural resources. Also, insurance fee is paid on yearly base in the amount of 100 000.00 BAM during the Power plant 1 lifetime. Cost of work force for Power plant 1 is 394 960.00 BAM yearly. These costs are calculated into the O&M costs.

In the case of Power plant 2, cost of work force 367 816.00 BAM yearly, and in the case of Power plant 3, the yearly cost of work force is 7 178.28 BAM.

These costs are calculated into the O&M costs that are shown in Table 4. Lifetime of Power plant 1 according to project is 30 years, with possibility of reconstruction after 30 years to extend the operation for 20 years more. Lifetime of Power plant 2 and Power Plant 3 is 20 years.

Fuel costs

For Power plant 1, Power plant 2, Power plant 3 there are no fuel costs since selected technologies doesn’t require fuel for its operation.

Electricity production

According to installed capacity, in the table is shown overview of the yearly electricity production for Power plant 1, Power plant 2, Power plant 3.

Table 5 by Company A&B

	Power plant 1	Power plant 2	Power plant 3
Installed generating capacity	12.2 MW	48 MW	1.08 MW
Electricity production	58 530 MWh	130 000 MWh	1 386.36 MWh

Important note needs to be taken for the Power plant 3. Due to linear degradation of solar panels, care is taken in calculating yearly electricity production. The linear degradation rate for Power plant 3 is 2 % in first year, and 0.5 % in period 2-20 years of operation.

4.3.LCOE Calculation

Levelized cost of electricity is, as already mentioned, energy cost metric. It represents a value that is equal to the minimum constant price of electricity that is required for a project to achieve a target return (Alderey-Williams, Rubert, 2018). LCOE is calculated according to equation [8], which represent slightly modified [7]:

$$LCOE = \frac{sum\ of\ costs\ over\ lifetime}{sum\ of\ electricity\ produced\ over\ lifetime} = \frac{I_0 + \sum_{t=1}^{i} \frac{I_t + M_t * k_t + F_t}{(1+r)^t}}{\sum_{t=1}^{i} \frac{E_t}{(1+r)^t}} \quad [8]$$

The essence of modified equation [7] remains the same, with two additional factors added in the equation to capture more precise certain variables. Two factors are added in equation [8] compared to [7]:

I_0 – investment cost necessary for project to start its operation

k_t– growth factor of operation & maintenance costs in the year t

Power plant 1

For Power plant 1, input variables are:

$I_0 = 89\ 166\ 055\ BAM$

$$I_0 + \sum_{t=1}^{30} \frac{I_t}{(1+0.05)^t} = 89\ 166\ 055\ BAM$$

$$\sum_{t=1}^{30} \frac{M_t * k^t}{(1+0.05)^t} = 23\ 121\ 686.05\ BAM$$

$$\sum_{t=1}^{30} \frac{F_t}{(1+0.05)^t} = 0.00\ BAM$$

$$\sum_{t=1}^{30} \frac{E_t}{(1+0.05)^t} = 899\ 749.56\ MWh$$

$LCOE = 124.80\ BAM/MWh$

The installation costs for Power plant 1 are 7309 BAM/kW.

Power plant 2

For Power plant 2, input variables are:

$$I_0 = \ 122\ 043\ 792\ BAM$$

$$I_0 + \sum_{t=1}^{20} \frac{I_t}{(1+0.05)^{20}} = 122\ 043\ 792\ BAM$$

$$\sum_{t=1}^{20} \frac{M_t * k^t}{(1+0.05)^{20}} = 64\ 021\ 588.72\ BAM$$

$$\sum_{t=1}^{20} \frac{F_t}{(1+0.05)^{20}} = 0.00\ BAM$$

$$\sum_{t=1}^{20} \frac{E_t}{(1+0.05)^{20}} = 1\ 620\ 087.34 MWh$$

$$LCOE = \ 114.85\ BAM/MWh$$

Installation costs for Power plant 2 are 2543 BAM/kW.

Power plant 3

For Power plant 3, input variables are:

$$I_0 = \ 1\ 722\ 300\ BAM$$

$$I_0 + \sum_{t=1}^{20} \frac{I_t}{(1+0.05)^{t}} = 1\ 722\ 300\ BAM$$

$$\sum_{t=1}^{20} \frac{M_t * k^t}{(1+0.05)^{t}} = 154\ 613\ BAM$$

$$\sum_{t=1}^{20} \frac{F_t}{(1+0.05)^{t}} = 0.0\ BAM$$

$$\sum_{t=1}^{20} \frac{E_t}{(1+0.05)^{t}} = 16\ 180.54\ MWh$$

$$LCOE = \ 116.00\ BAM/MWh$$

Installation costs for Power plant 3 are 1595 BAM/kW.

4.4.Overview of the results

The results of LCOE calculation are presented in following table 6.

Table 6 by Company A&B

	Power plant 1	Power plant 2	Power plant 3
LCOE (BAM/MWh)	124.80	114.85	116.00
Installation costs (BAM/kW)	7309.00	2543.00	1595.00

On the base of results shown in table 6, it can be seen that different decisions would be made in case of decision making based on the installation costs, than decision making based on LCOE. In case of prioritizing based on installation cost criteria, the most competitive is solar technology – Power plant 3, then wind technology – Power plant 2, and hydro technology – Power plant 3 placed as third. On the other hand, in case of prioritizing of projects is done on the base of LCOE, the order is different. Based on LCOE, most competitive project is Power plant 2 – wind technology, then as second is Power plant 3 – solar technology, and at third place is Power plant 1 – hydro technology. It needs to be mentioned that LCOE is more sophisticated method of evaluating potential costs and production of different energy projects than one done with simple metrics like installation costs per unit. Comprehensiveness of LCOE is giving more reliability in deciding among different energy technologies compared to simple metrics.

Table 7 by Naydenova

	2 – 23 kW	23– 150 kW	150kW – 1 MW	1 – 10 MW	>10 MW
Solar power	0.49705	0.30696	0.25971	-	-
Wind power	0.37124	0.22140	0.18917	0.16033	0.14766
Hydropower	0.29036	0.18192	0.13751	0.12373	-

As it is presented in table 7, these are the amounts of feed-in tariffs in Federation of Bosnia and Herzegovina for 2018. The feed-in tariffs prices are expressed in BAM/kWh for selected technologies. Feed-in tariffs represent guaranteed prices of electricity that RES Operator pays to the plant owner after they have concluded power purchase agreement. Even though the first thought may be that easiest way to evaluate certain energy project is to compare LCOE with prices of electricity on the market, that is not correct way of using it. LCOE`s primarily use is to compare between different energy technologies, and not to directly evaluate if certain energy project is profitable or not. How ever, this is not discouragement to not in detail inform on feed-in tariffs when making investment decision in energy project.

As it is shown with the results, the lowest LCOE is for wind technology, following solar and hydro technology. This coresponds more or less with trends in the world, and with current situation in the electric industry that produce energy using renewable technologies. In the last decade, 2010 – 2020, the world witnessed a remarkable cost reduction for solar and wind technologies (IRENA, 2021).

In this period, global LCOE for solar PV reduced for 85%, from 0.385 USD/kWh to 0.057 USD/kWh shown on Fig. 37. Installation costs seen reduction from 4 731 USD/kWh to 883 USD/kWh for the period 2010 – 2020.

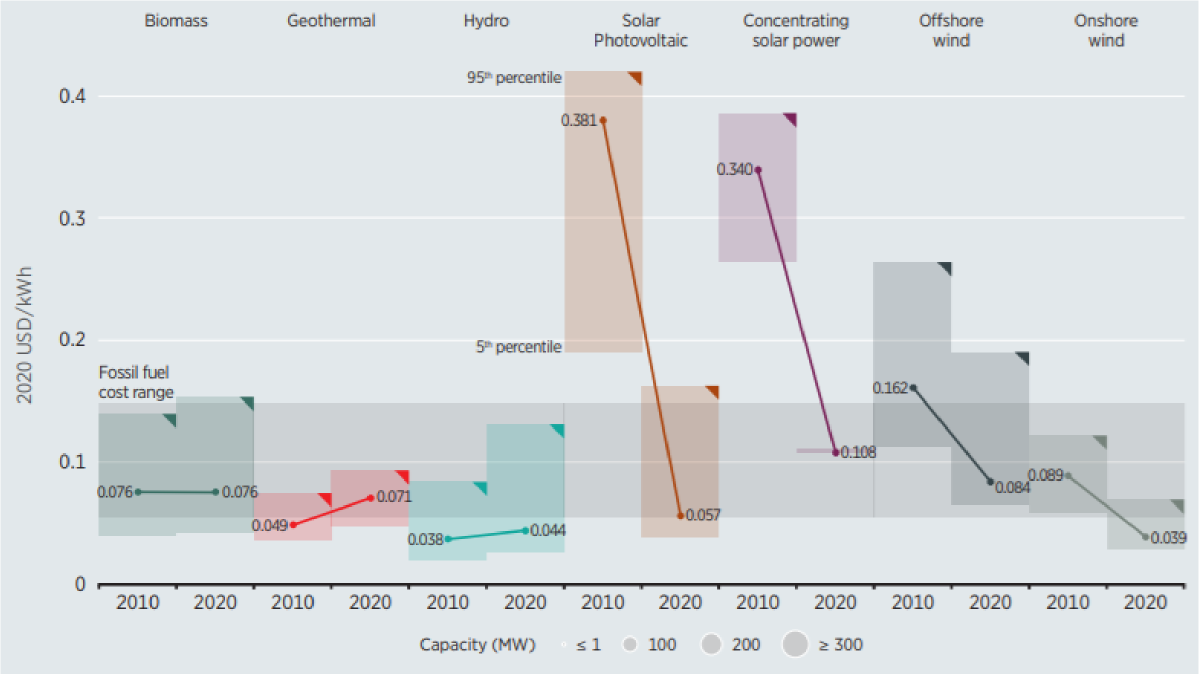


Fig. 37 Installation cost and average LCOE for 2010 – 2019 by IRENA, 2021

LCOE for onshore wind projects declined for 56% in period 2010 – 2020, from 0.089 USD/kWh to 0.039 USD/kWh. Installation costs are reduced from 1971 USD/kWh to 1335 USD/kWh

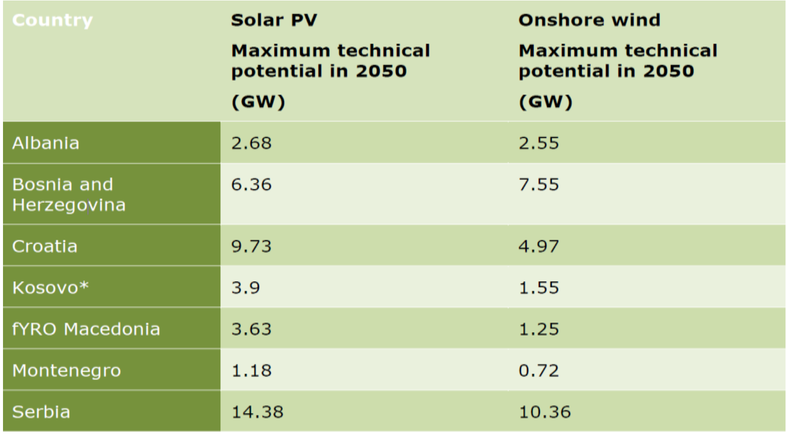
In 2020, the average LCOE for new capacity installments of onshore wind technology declined for 13% and for solar technology 7%, compared to 2019 (IRENA, 2021).

The technological development of these technologies and energy polices that aim to decarbonise electricity generation were some of the key drivers. Solar and wind power technologies are probably going to remain most attractive renewable energy technologies in the future, and main drivers towards low carbon economies and electricity production.

The LCOE for power plants in Bosnia and Herzegovina, fits global LCOE, with hydropower technology having slightly increase LCOE compared to global one. The potential reason for this is that hydropower technology is used in Bosnia and Herzegovina for more than a half century, and economically most competitive locations are already in operation. In the recent years, interest of public and investors is on use of small hydro power, even though there is a lot of public discussion and disagreement because of environmental and ecological issues that these projects could potentially cause. Hydropower technology is highly intensive from investment aspect, and in 2016 average installation cost were 5312 USD/kWh, with difference of over 2000 USD/kWh to the nearest other renewable energy technology. (EIA, 2018)

On the example of Power plant 1, it is seen impact of high investment costs in hydropower projects. In this LCOE calculation method financial costs weren`t considered. The resulting LCOE values would be higher in the case of taking into account financial costs as well. In that case financial terms on investment like interest rate, loan repayment time and belonging fees would have significant impact on the LCOE. Investment costs are having large impact on LCOE as it can be seen on the case of hydropower projects.

LCOE for wind and solar projects are lower, and this is possible to contribute to relatively unexploited potential of solar and wind potential in Bosnia and Herzegovina, with these two technologies still being in early phase of its operations and start of exploitation. In Bosnia and Herzegovina and region, solar and wind potential is shown on Fig. 38.



Country	**Solar PV** **Maximum technical potential in 2050** **(GW)**	**Onshore wind** **Maximum technical potential in 2050** **(GW)**
Albania	2.68	2.55
Bosnia and Herzegovina	6.36	7.55
Croatia	9.73	4.97
Kosovo*	3.9	1.55
fYRO Macedonia	3.63	1.25
Montenegro	1.18	0.72
Serbia	14.38	10.36

Fig. 38 Technical potential for solar and wind potential in SEE by Costis, 2016

Global trends of cost reduction in equipment for and installation costs for these technologies are also reflected on the condition of solar and wind projects in Bosnia and Herzegovina. Regarding this, future solar and wind projects are potentially attractive renewable energy technologies.

5. Conclusion

In the 21st century, the world has seen a booming development and use of renewable energy technologies. In early 2000s, new installed capacities from renewable energy sources amounted only for 10% of yearly commissioned new production capacities, while in 2107, the share of new electricity production capacity from renewable energy sources was 84% (IRENA, 2019).

Society is becoming aware of importance of producing electricity using renewable energy sources, which mostly doesn’t have any larger environmental consequence and CO_2 emissions, as one of the foundations towards toward safer, healthier, and sustainable future for humankind on planet Earth.

Even though renewable energy projects have their role in achieving these goals, they are also becoming more attractive from the investor`s perspective. For the countries in development, like Bosnia and Herzegovina is, along with environmental and ecological benefits that producing electricity using renewable energy technologies provides, the financial aspect represent factor that doesn’t lack in importance as well.

Energy cost metrics are used as tool for investors in energy projects, in order to better understand and compare financial aspect and economic competitiveness when deciding among different energy technologies. Even though there are more energy cost metric going through literature, levelized cost of electricity – LCOE is most used energy cost metric now days. (EIA, 2021)

Levelized cost of electricity provides framework for investors to consider all potential costs of certain energy project and electricity production over its lifetime, in order to make best investment decision. The advantage of LCOE is that it replaces a big number of often complicated input data, which are required to be considered when the investment decision is being made, with one unambiguous number that has clear meaning. LCOE is providing number of average real price required for project to achieve rate of return during its lifetime.

Alternative energy cost metrics mentioned in this work and found in literature, are having this issue with a lack of apparent meaning, and this is the largest single advantage of LCOE.

Along side with LCOE, levelized cost of storage – LCOS and levelized avoided cost of electricity – LACE can commonly be used, in order to comprehensively evaluate energetic projects. In this work LCOE and LACE weren`t calculated, since more detailed data are required for that.

Solar, wind and hydro technology are renewable energy technologies that are in main research focus of this work. In discussion of LCOE for these technologies, LCOE is figuring lowest for wind and solar, with trends of cost decrease (IRENA, 2021). The technology development of these technologies in the recent decade contributed for this. Costs for solar PV have decreased for 80% in the past 10 years, from 2 USD/W to 0.2 USD/W (Sun, 2019). The costs for solar PV reduce in 28.5 % for every doubling in total installed capacity. (Fickling, 2020)

The onshore wind has seen declines in cost for 40 % in the recent decade. Wind projects are becoming more attractive to investors, with cost reduction and increasing capacity factor of wind projects in the world (IRENA, 2020). On the other hand, wind projects have not neglectable ecological impact, since there isn`t yet efficient solution for recycling used wind blades. (Pinna, 2021)

LCOE calculation that is done for the real projects in Bosnia and Herzegovina, confirms trends in the world. The lowest LCOE is for Power plant 2 that is wind farm, following with Power plant 3 – solar. Numbers of LCOE for Power plant 1 is above these two, which is contributed with high investment cost for this project. Further cost reduction for hydropower technology is mainly possible in improvements techniques of civil engineering (IRENA, 2021).

LCOE as an energy cost metric, even it has certain drawbacks, is most popular metric that is in use now days. Its main limitation is that costs and production is considered on the level of a power plant, without considering wider impacts on the system. Its strength is reflected in reduction of several complex factors into one single unambiguous number, that is easier to interpret and understand.

There has been proposals and research on topic to look for metric that would better describe costs and benefits of energy projects. System LCOE is a metric that is more comprehensive and adding system level factors into account among with electric power plant level. Due to limitation in collected data for this work, System LCOE was not considered in this work.

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Table 3. Data Company A&B

Table 4. Data Company A&B

Table 5. Data Company A&B

Table 6. Data Company A&B

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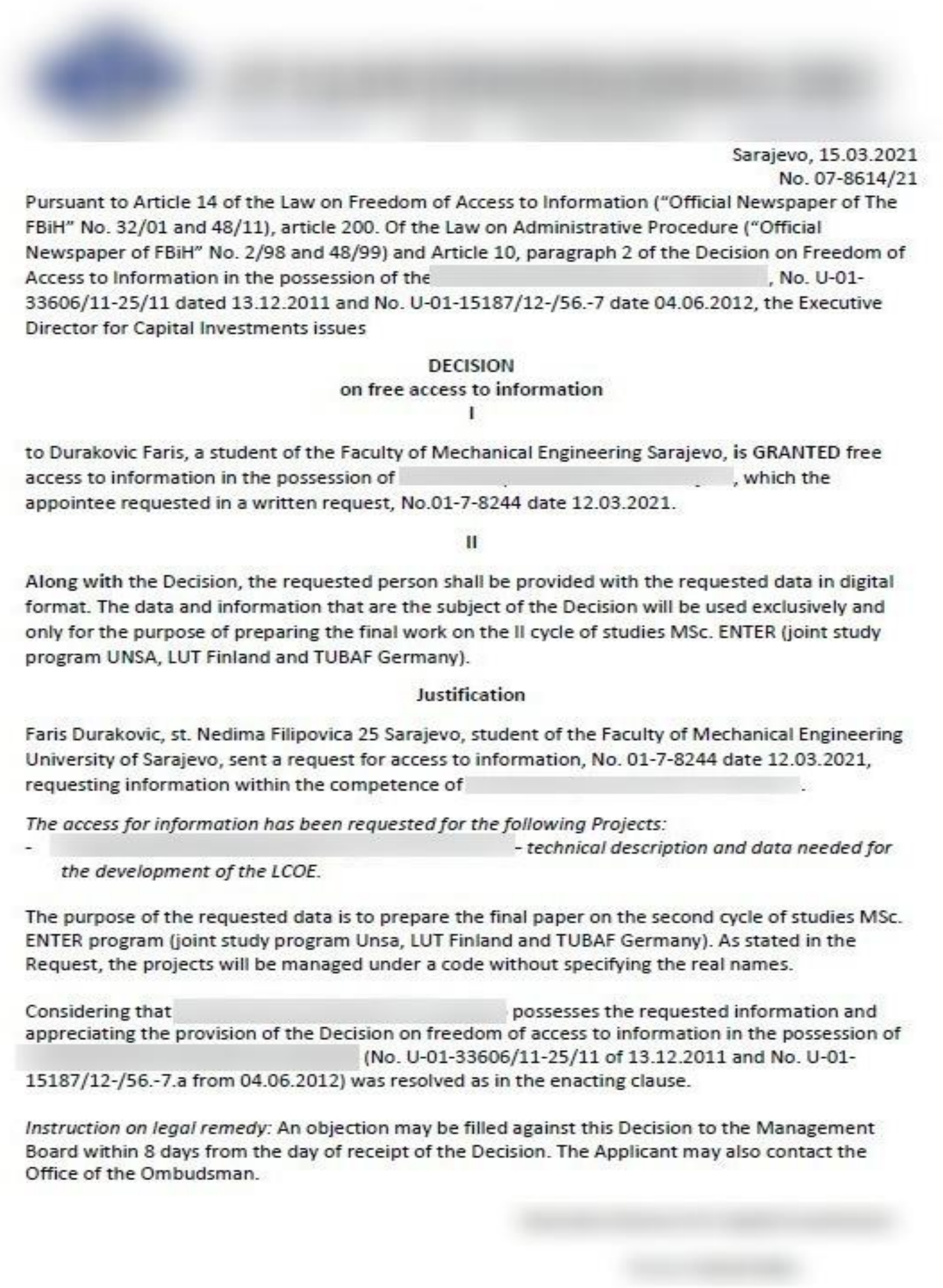
6.4.Decisions on free data access

- Decision on free access to data of Company A



[redacted]

Sarajevo, 15.03.2021
No. 07-8614/21

Pursuant to Article 14 of the Law on Freedom of Access to Information ("Official Newspaper of The FBiH" No. 32/01 and 48/11), article 200. Of the Law on Administrative Procedure ("Official Newspaper of FBiH" No. 2/98 and 48/99) and Article 10, paragraph 2 of the Decision on Freedom of Access to Information in the possession of the [redacted], No. U-01-33606/11-25/11 dated 13.12.2011 and No. U-01-15187/12-/56.-7 date 04.06.2012, the Executive Director for Capital Investments issues

DECISION
on free access to information
I

to Durakovic Faris, a student of the Faculty of Mechanical Engineering Sarajevo, is GRANTED free access to information in the possession of [redacted], which the appointee requested in a written request, No.01-7-8244 date 12.03.2021.

II

Along with the Decision, the requested person shall be provided with the requested data in digital format. The data and information that are the subject of the Decision will be used exclusively and only for the purpose of preparing the final work on the II cycle of studies MSc. ENTER (joint study program UNSA, LUT Finland and TUBAF Germany).

Justification

Faris Durakovic, st. Nedima Filipovica 25 Sarajevo, student of the Faculty of Mechanical Engineering University of Sarajevo, sent a request for access to information, No. 01-7-8244 date 12.03.2021, requesting information within the competence of [redacted].

The access for information has been requested for the following Projects:
- [redacted] *– technical description and data needed for the development of the LCOE.*

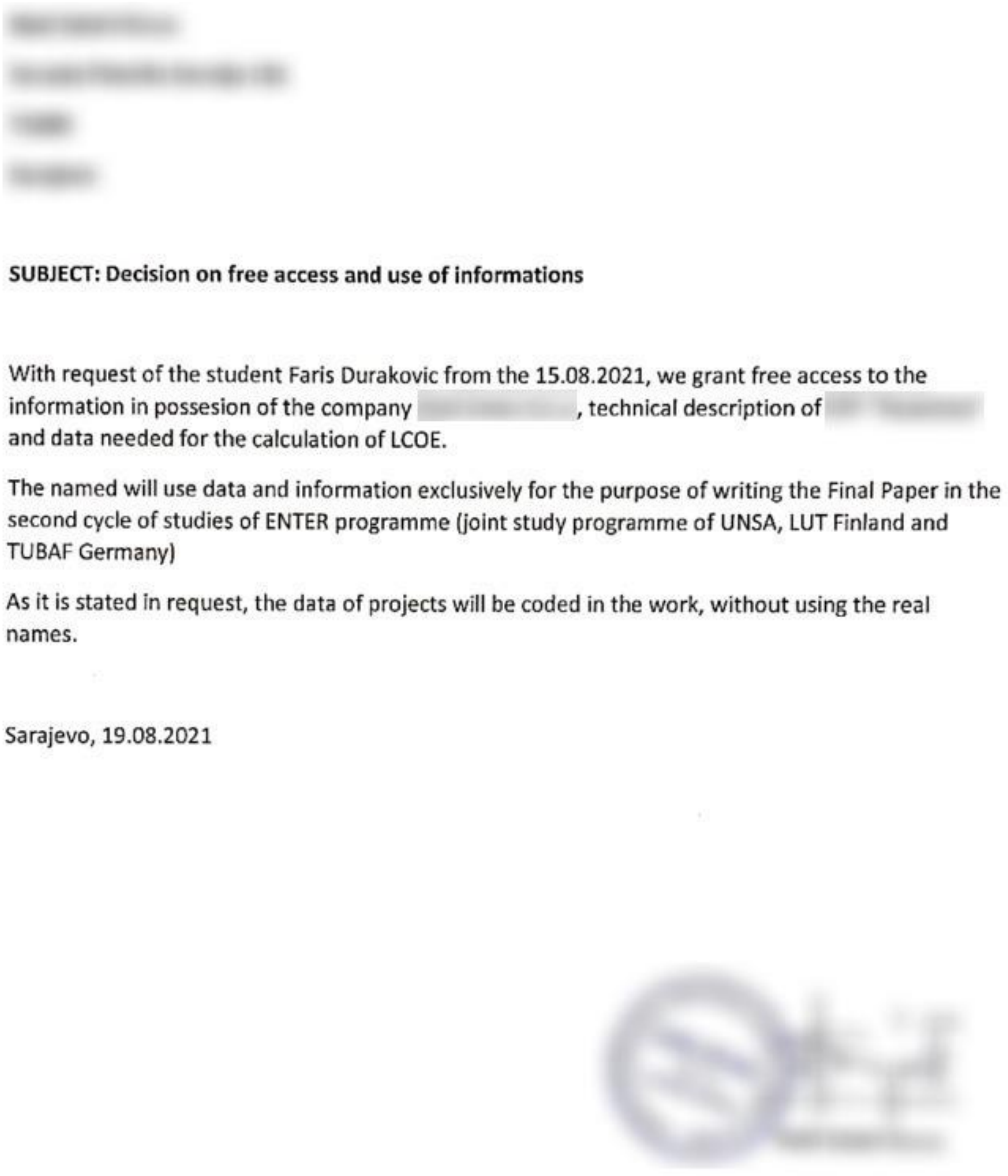
The purpose of the requested data is to prepare the final paper on the second cycle of studies MSc. ENTER program (joint study program Unsa, LUT Finland and TUBAF Germany). As stated in the Request, the projects will be managed under a code without specifying the real names.

Considering that [redacted] possesses the requested information and appreciating the provision of the Decision on freedom of access to information in the possession of [redacted] (No. U-01-33606/11-25/11 of 13.12.2011 and No. U-01-15187/12-/56.-7.a from 04.06.2012) was resolved as in the enacting clause.

Instruction on legal remedy: An objection may be filled against this Decision to the Management Board within 8 days from the day of receipt of the Decision. The Applicant may also contact the Office of the Ombudsman.

[redacted]

- Decision on free access to data of Company B



[redacted]

SUBJECT: Decision on free access and use of informations

With request of the student Faris Durakovic from the 15.08.2021, we grant free access to the information in possesion of the company [redacted], technical description of [redacted] and data needed for the calculation of LCOE.

The named will use data and information exclusively for the purpose of writing the Final Paper in the second cycle of studies of ENTER programme (joint study programme of UNSA, LUT Finland and TUBAF Germany)

As it is stated in request, the data of projects will be coded in the work, without using the real names.

Sarajevo, 19.08.2021

[redacted]