International Journal of Electrical, Electronic and Communication Sciences
ISSN: 2517-9438
Vol:15, No:4, 2021

Future of Electric Power Generation Technologies: Environmental and Economic Comparison

Abdulrahman A. Bahaddad, Mohammed Beshir

***Abstract*—**The objective of this paper is to demonstrate and describe eight different types of power generation technologies and to understand the history and future trends of each technology. In addition, a comparative analysis between these technologies will be presented with respect to their cost analysis and associated performance.

***Keywords*—**Conventional power generation, economic analysis, environmental impact, renewable energy power generation.

I. Introduction and Background

SINCE the invention of electric power system by Tomas Edison back in 1882, electricity has become one of the most essential forms of energy in our daily life. Since that time, there are many power generation technologies that were introduced to focus on converting different forms of energy into electricity. For example, one of the oldest generation technologies is burning coal which converts the thermal energy into electricity. In addition, hydroelectric power generation is an old technology that is converting the kinetic energy (from water flow) into electricity.

As per the IEA report [43], the total electricity generated worldwide by fossil fuels is 64% of the total electricity (38% coal, 3% oil and 23% gas) as shown in Fig. 1.

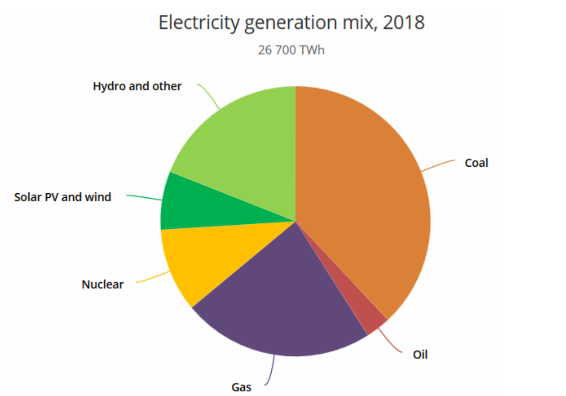

Fig. 1 Electricity energy generation resources distribution worldwide

A. A. Bahaddad is with Saudi Aramco, Dhahran, Saudi Arabia (phone: 00966-555-655-122; e-mail: Abdulrahman.bahaddad@aramco.com).

M. Beshir is with University of Southern California, Los Angeles, United States (phone: +1-(213)-740-6433; e-mail: beshir@usc.edu).

II. Conventional Power Generation

A. Coal Power Generation

1. History and future trend

Coal is one of the oldest resources that humans have used for heat since ancient history. Since the 1880s, coal has been used to produce electricity that supplied many homes at that time [1]. As of today, the total power capacity of coal-based power plants in the world is more than 2,000 GW and almost 50% of this capacity is in China [2].

Despite the fact that coal power generation produces CO_2 emissions, there has been a slight increase in the total power generated by coal power plants around the world. By the end of 2018, there had been a 3% increase worldwide, according to IEA data, and this increase was mainly driven by Asian countries as detailed in Fig. 2 [24]. The EnerFuture forecast states that the world will reduce coal power plants share in electricity generation by 10% by 2040, as shown in Fig. 3 [25].

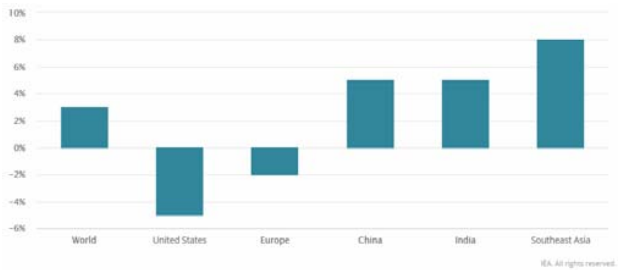

Fig. 2 Coal power generation increase in 2018 worldwide

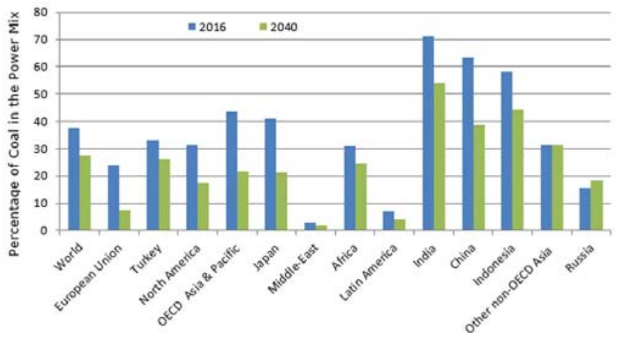

Fig. 3 EnerFuture forecast in Coal generation globally

2. Technology Description

Coal power plant technology is based on using coal as a heat source (by burning) to boil water, and produce steam that can drive the steam turbine. The steam turbine drives the generator that produces electricity. These components are shown in Fig. 4 [3].

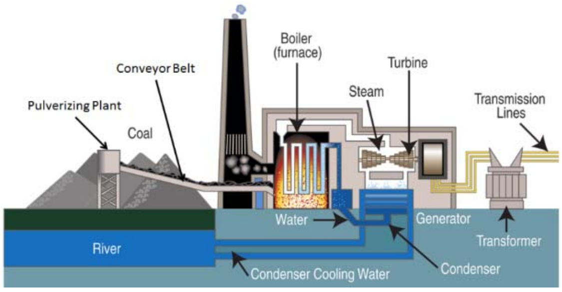

Fig. 4 Coal Power Plant Layout

B. Natural Gas Power Generation

1. History and Future Trend

Natural gas was first used as an energy resource (approximately 500 B.C.) by the Chinese [4]. They used natural gas to boil sea water to make it drinkable. Starting in the 1990s, natural gas has become one of the most important resources for power plants around the world [5]. Today, natural gas power plants worldwide have a total capacity of 1,600 GW, and this is expected to exceed 3,000 GW by 2050 [6] as shown in Fig. 5.

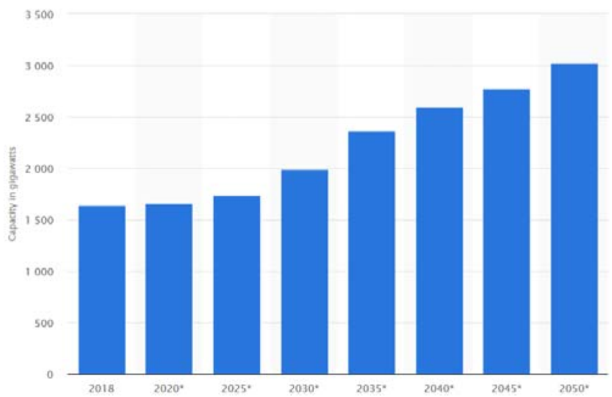

Fig. 5 Natural Gas power plant installed capacity trend

2. Technology Description

There are two main technologies in natural gas power plants; simple and combined cycles. The simple cycle produces electricity by burning natural gas, using a combustion gas turbine that can drive a generator. Because of their quick response during the startup, the main advantage of the simple cycle is that it can supply power during peak demand periods. About 67% of the heat is wasted in this process by the gas turbine. The combined cycle adds another process by utilizing the wasted heat from the gas turbine to produce steam from the water source, which can drive a steam turbine to run another generator. As a result, the combined cycle has a higher efficiency of around 60% compared to only 35% in a simple cycle. Fig. 6 shows the process diagram for each technology [7], [8].

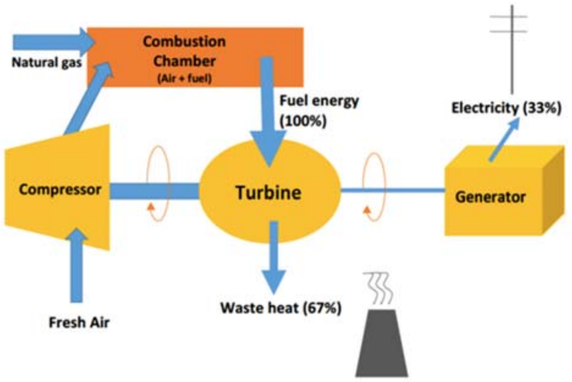

Fig. 6 (a) Simple cycle process

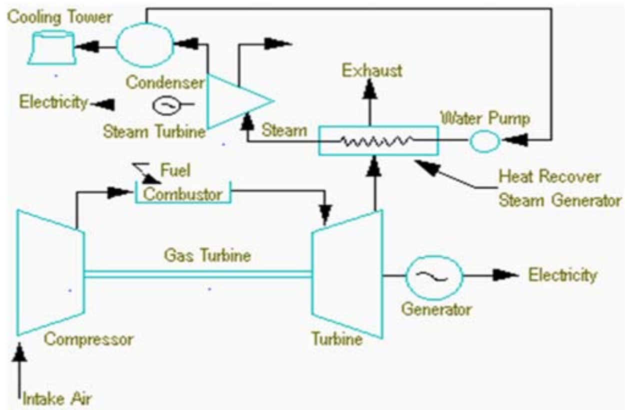

Fig. 6 (b) Combined cycle process

C. Nuclear Power Generation

1. History and Future Trend

In 1954, Russia built the first nuclear power plant in history for electricity production purposes, with a total capacity of 5 MW. After that, in 1956, a 50 MW nuclear power plant was built in England for commercial use [9]. As of today, the USA is leading the world's total installed nuclear power plant capacity by producing 100 GW of electricity from a total of 400 GW worldwide, as shown in Fig. 7 [10]. In addition, it is expected that the total installed nuclear power plants globally will increase to reach 536GW by 2030.

2. Technology Description

The current installed nuclear power plants around the world are mainly divided into two technologies; pressurized water (PWR) and boiling water (BWR) reactors. PWR reactor is more commonly used which represents around 75% of the installed reactors. Fig. 8 shows the main principle behind the PWR, which is putting the primary water under high pressure, to hold the water from boiling under high temperature that is caused by fuel elements (nuclear reaction). After that, the pressurized primary water is going to heat up the secondary water through a heat exchanger (sometimes called steam generator). This results in producing steam that can power the steam turbine. We can notice from this process that the steam is not mixed with radioactive elements because they are

International Journal of Electrical, Electronic and Communication Sciences
ISSN: 2517-9438
Vol:15, No:4, 2021

separated. Fig. 8 also shows that BWR is boiling the water directly, using the nuclear reaction, which results in contaminating the produced steam with the radioactive material [11].

Fig. 7 (a) Nuclear power plant future trend

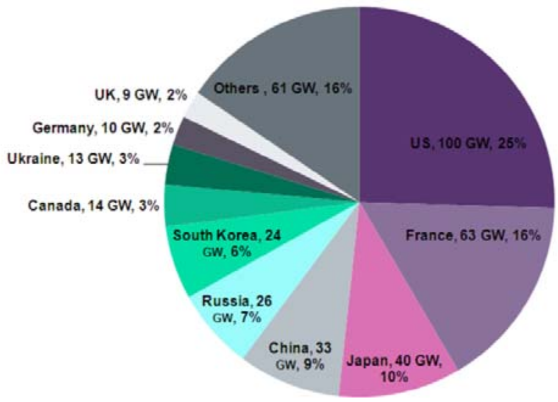

Fig. 7 (b) Nuclear power plants courtiers share

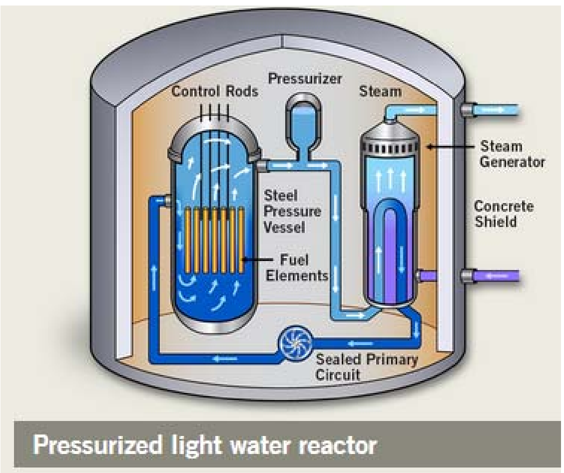

Fig. 8 (a) PWR Reactor

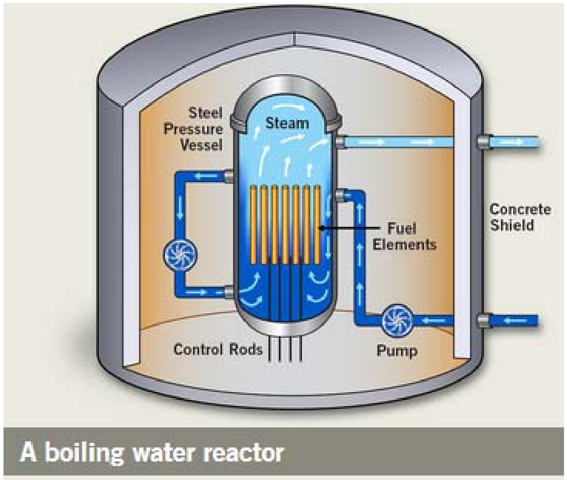

Fig. 8 (b) BWR Reactor Processes

III. Renewable Energy Power Generation

A. Solar

1. History and Future Trend

It was documented that solar energy has been used since the 7th century B.C.E., when people were using sunlight to start fires, using glass. In 1873 it was discovered that solar energy can be converted into electricity using selenium [12]. After that, the solar PV industry started to grow up slowly in the 19th and 20th centuries. By the start of the 21st century, and due to the development of PV technology, the total installed capacity has reached around 500 GW globally by the end of 2018, as shown in Fig. 9. This figure also shows that the solar capacity will exceed 1 TW by 2023 in the low scenario [26].

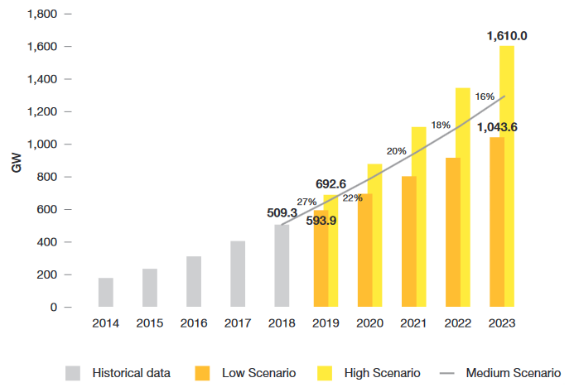

Fig. 9 Solar Power installed capacity trend

2. Technology Description

There are two main technologies where solar energy can be harvested and converted into electricity; Solar Photovoltaics (PV), and concentrated solar power (CSP). Solar PV is the most common and advanced technology in solar energy industry. The concept behind this technology is to convert sunlight into electricity, using a semi-conductor material, such as silicon. Nowadays, solar PV is one of the fastest growing technologies in renewable energy. Concentrated solar power (CSP) uses solar energy as a heat source by concentrating sunlight using mirrors to generate hot steam that will power a steam turbine. Fig. 10 shows the current growth trend in the installed capacity of both technologies globally, in which it can be noticed that the growth in solar PV is much higher, due to the maturity of the technology and its feasibility [14].

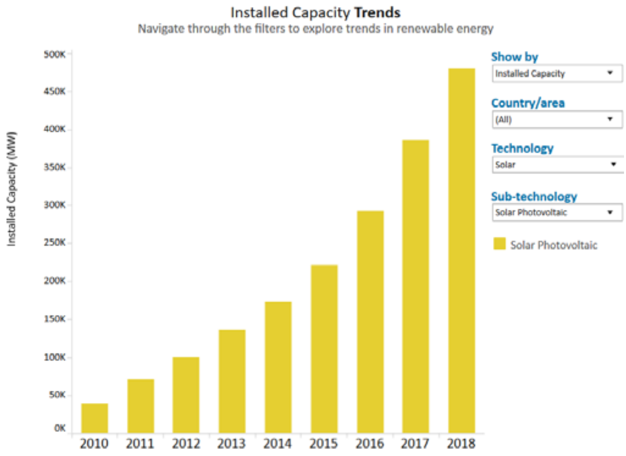

Fig. 10 (a) Solar PV growth

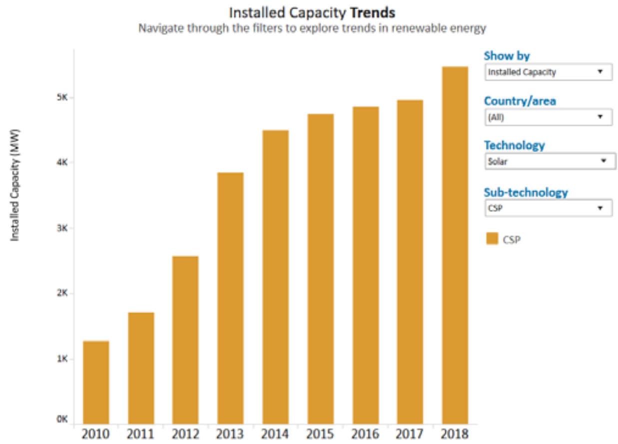

Fig. 10 (b) Concentrated Solar Power growth

B. Wind

1. History and Future Trend

Human have used wind energy for marine transportation since 5,000 BCE, when they utilized it on Nile River. In 200 BCE, it was documented that the Chinese started to use simple water pumps operated by wind energy resources [15]. At the beginning of the 20th century, people started to use wind to produce electricity using wind turbines on a small scale. In the last decades, wind turbine technology has been developed dramatically, due to the enhancement in efficiency, and the reduction in capital cost. As of 2018, the total installed capacity has reached around 560 GW globally, in which China has the highest contribution with a total of 185 GW [13]. Furthermore, it is expected that the wind power industry will become one of the main electricity resources around the world, and it is forecasted to exceed 9 TW of installed capacity by 2050, as shown in Fig. 11 [27].

2. Technology Description

A wind turbine captures wind energy using blades, and converts the kinetic energy into electricity, by rotating a generator. Wind turbines can be categorized as vertical or horizontal axis turbines, as shown in Fig. 12 [16].

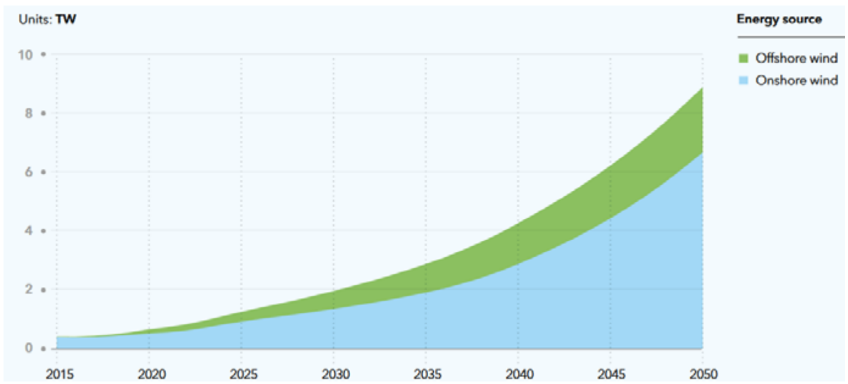

Fig. 11 Forecasted trend in the installed capacity of wind power plants

C. Biomass

1. History, Technology Overview and Future Trend

The use of biomass can go back in history to the cavemen who utilized wood as a raw material to light a fire for heating purposes [17]. Today, biomass is considered one of the renewable energy resources that can be used to produce electricity. There are different methods to produce electricity utilizing biomass. The most popular method is to burn biomass materials such as wood or agricultural waste to produce electricity [18]. Fig. 13 shows the process in any biomass power plant in which it starts from storing the biomass material, such as wood, and then burns it to heat up the water, to generate steam, which will drive a steam turbine to run a generator.

Fig. 12 Horizontal vs. Vertical Axis Wind Turbines

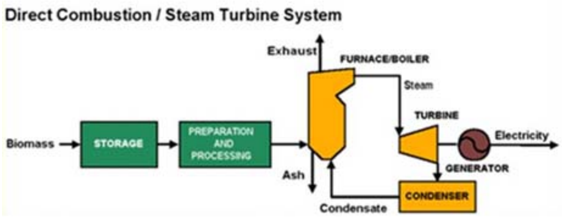

Fig. 13 Biomass power generation process

In the last decade, there has been a steady increase in the total installed capacity of biomass power plants globally, and by the end of 2018, the total electricity generated has reached 592.2 TWh, and it is forecasted to exceed 764 TWh by 2023, as shown in Fig. 14 [28].

D.Geothermal

1. History and Future Trend

10,000 years ago, Indians in North America discovered geothermal energy by using hot springs, coming from underground, in their daily life activities, such as cooking and cleaning. Later in the 18th century, Italy became the first country that used geothermal energy in the industrial sector, by utilizing the hot underground steam for extracting boric acid. In 1904, the first geothermal power plant in history was commissioned by an Italian scientist called Piero Ginori Conti, who used the geothermal hot steam for electricity generation [19]. Over the years, geothermal power plant capacity has grown steadily, and the United States has a total installed capacity of 3.7 GW compared to 13.3 GW installed globally [13]. Furthermore, this trend is expected to continue and reach 17 GW by 2023 as shown in Fig. 15 [29].

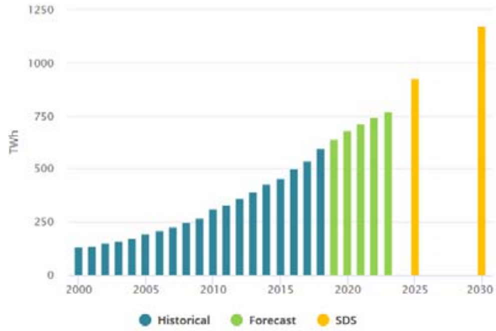

Fig. 14 Biomass electricity generated trend

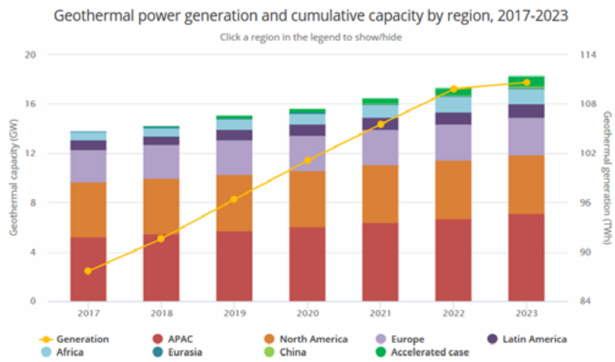

Fig. 15 Geothermal installed capacity trend worldwide

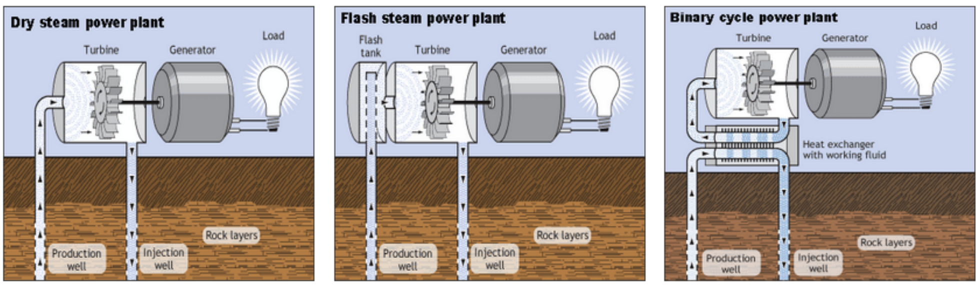

Fig. 16 Different Types of Geothermal Power plants

2. Technology Description

Geothermal power plant technology mainly utilizes hydrothermal energy, which consists of water and heat, to generate electricity by running the steam turbine. Fig. 16 illustrates the process of the main three types of geothermal power plants [20]:

- A Dry Steam Power Plant (DSPP) is the simplest design for a geothermal power plant. A DSPP takes the hot steam directly from underground to power a steam turbine.
- A Flash Steam Power Plant is the most common type and takes the hot steam mixed with water, and use a flash tank to fully convert the input into steam — before going to the

steam turbine.

- A Binary Cycle Power plant extracts the geothermal hot water and runs it through a heat exchanger, to heat up a separate water source and convert it into steam. This type of technology avoids the direct contact of the geothermal water, to ensure the cleanliness of the steam going through the turbine.

E. Hydropower

1. History and Future Trend

Over 2,000 years ago, the Greeks used the energy generated by the moving water to rotate wheels to grind grain [21]. In 1882, hydropower was first used to generate electricity by commissioning the Fox River hydroelectric power plant in the United States [22]. This technology is considered one of the oldest technologies for generating electricity, and it has been growing over the last two centuries in which the overall installed capacity worldwide has reached to approximately 1,200 GW. Due to the maturity of this technology, the world will continue to install more hydropower generation plants, and it is forecasted to reach 1,325 GW by 2023, as illustrated in Fig. 17 [30].

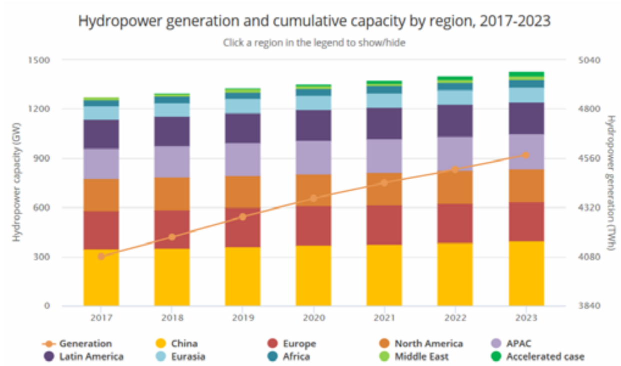

Fig. 17 Installed Capacity Trend of Hydropower Generation

2. Technology Description

Hydropower plants generate electricity by converting the kinetic energy from the water flow into electricity, utilizing water turbines. There are three main types of hydropower plant technologies [23]:

- Run-of-River Hydropower plant: The main concept behind this type of plant is to divert part of the route of a river into a canal that captures the energy using turbines, as illustrated in Fig. 18. Since this type does not use dams or any storage facility, the output power depends on the flow of water, and hence it is considered as intermittent electricity generation.
- Storage Hydropower plant: This is the most common type in hydroelectric power plants, where it uses dams to store and control the flow of water that passes through the turbines. Therefore, it is considered a dispatchable generation source because of its ability to control the output electricity.
- Pump Storage Hydropower plant: This type is similar to the storage hydropower plant, but it has a reversible water turbine that can pump the water back to the reservoir during the low demand period (when the electricity is cheaper) to increase the water head. Then, during the peak demand period (when electricity is more expensive), the water from the reservoir is released to generate electricity.

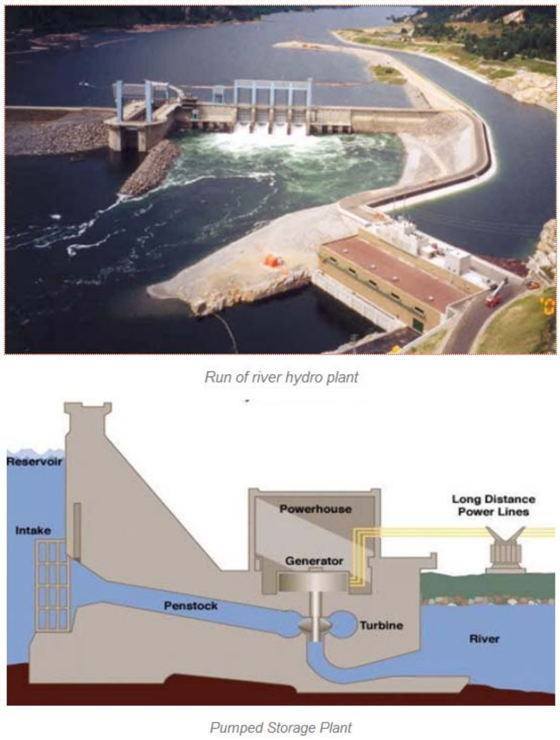

Fig. 18 Run of River vs. Pumped Storage Plant

IV. Comparative Analysis

In this chapter, different types of power generation technologies will be compared and analyzed based on two major aspects; technology performance, and economic analysis. Table I summarizes the comparative analysis done, with respect to the following:

- The technology performance in each generation type was evaluated based on the energy efficiency, as well as the average capacity factor of the power plants. The capacity factor is equal to the actual electrical energy generated, over the maximum electrical energy that can be generated, based on the installed capacity over a specific period.
- The cost aspect of different power generation technologies is compared based on two parameters; the installed cost (or capital cost) and the levelized cost of energy (LCOE). The LCOE is the best parameter to economically assess different types of power generation resources, because it considers the total lifetime cost — including installation, operation, and maintenance — over the total energy produced in the lifecycle ($/KWh). Therefore, LCOE is used to determine the average cost of producing electricity per KWh.

- The environmental impacts are measured based on the quantity of CO_2 emitted from the power generation over 100-year period taking into account the CO_2 emissions resulted from the whole lifecycle of the plant [42].

TABLE I
GENERATIONS RESOURCES COMPARATIVE ANALYSIS SUMMARY

Power Generation Type	Technology Performance		Economic Analysis		Environmental impact
	Efficiency	Capacity factor	Total installed cost ($/KW)	Levelized cost of electricity ($/KWh)	g-CO_2/Kwh over 100 years [42]
Coal	33% [39]	54% to 85% [38]	4,600 to 5,200 [41]	0.088 to 0.16 [38]	282-1,011
Natural Gas CC	60% [8]	51% to 87% [38]	900 to 1,200 [41]	0.033 to 0.039 [38]	230-481
Natural Gas CT	35% [7]	7% to 30% [38]	1,100 to 1,600 [41]	0.066 to 0.155 [38]	230-481
Nuclear	33% [40]	92% [38]	5,700 to 6,500 [41]	0.07 [38]	78-178
Solar PV	15% to 22% [32]	18% [31]	1,210 [31]	0.09 [31]	7.85-26.9
Concentrated Solar Power (CSP)	up to 25% [33]	45% [31]	5,204 [31]	0.19 [31]	6.43-25.2
Onshore Wind	35% to 45% [34]	34% [31]	1,497 [31]	0.06 [31]	4.8-8.6
Offshore Wind	35% to 45% [34]	43% [31]	4,353 [31]	0.13 [31]	6.8-14.8
Hydropower	Up to 90% [35]	47% [31]	1,492 [31]	0.05 [31]	61-109
Geothermal	12% [36]	84% [31]	3,976 [31]	0.07 [31]	29-79
Biomass	20% to 40% [37]	78% [31]	2,105 [31]	0.06 [31]	86-1,788

V. CONCLUSION

Based on the previous analysis, it can be shown that renewable resources technologies have become more feasible. Based on the current trend, the world could replace coal generation power plants with alternative sources of energy, since these new technologies are able to compete, as shown in the previous table. Many studies have been conducted that forecast renewable energy resources will comprise a major share pf the overall energy resources for electricity generation. For example, according to BP Energy Outlook report, it is forecasted that the renewables will overtake coal's share in electricity generation by 2040, as shown in Fig. 19 [44].

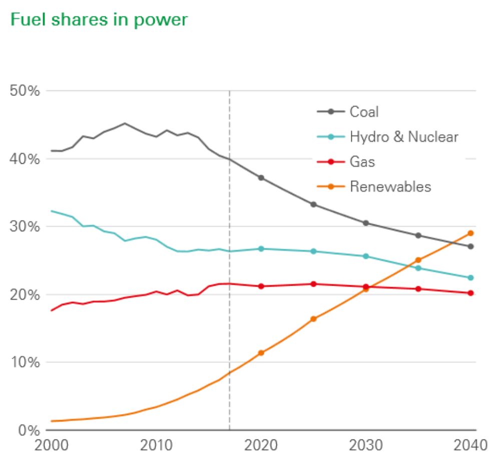

Fig. 19 The electricity generation share future trend worldwide

REFERENCES

[1] Energy.gov. 2021. (online) Available at: <https://www.energy.gov/sites/prod/files/Elem_Coal_Studyguide.pdf>.
[2] Carbon Brief. 2020. Mapped: The World'S Coal Power Plants In 2020. (online) Available at: <https://www.carbonbrief.org/mapped-worlds-coal-power-plants>.
[3] Mishra, P., 2017. How Coal Power Plant Works? - Do You Know? - Mechanical Booster. (online) Mechanical Booster. Available at: <https://www.mechanicalbooster.com/2017/12/coal-power-plant.html>.
[4] Naturalgas.org. 2013. » History Naturalgas.Org. (online) Available at: <http://naturalgas.org/overview/history/>.
[5] Naturalgas.org. 2013. » Electrical Uses Naturalgas.Org. (online) Available at: <http://naturalgas.org/overview/uses-electrical/>.
[6] Statista. 2021. Installed Natural Gas Generation Capacity Globally 2050 | Statista. (online) Available at: <https://www.statista.com/statistics/217252/global-installed-power-generation-capacity-of-natural-gas/>.
[7] Afework, B., Hanania, J., Stenhouse, K. and Donev, J., 2018. Simple Cycle Gas Plant - Energy Education. (online) Energyeducation.ca. Available at: <https://energyeducation.ca/encyclopedia/Simple_cycle_gas_plant>.
[8] Brian Williams. 2020. Combined Cycle Power Plants - Power Generation Technologies. (online) Available at: <https://www.briangwilliams.us/power-generation-technologies/combined-cycle-power-plants.html>.
[9] World Nuclear Association. Outline History of Nuclear Energy (online) Available at: < https://www.world-nuclear.org/information-library/current-and-future-generation/outline-history-of-nuclear-energy.aspx>.
[10] Power Technology. Global nuclear power capacity expected to reach 536GW by 2030 (online) Available at: <https://www.power-technology.com/comment/global-nuclear-power-capacity-expected-reach-536gw-2030/>.
[11] Cameco.com. n.d. Cameco U101 - Types of Reactors. (online) Available at: <https://www.cameco.com/uranium_101/electricity-generation/types-of-reactors/>
[12] Solar News. n.d. History of Solar Energy: Timeline & Invention of Solar Panels | Energysage. (online) Available at: <https://news.energysage.com/the-history-and-invention-of-solar-panel-technology/>.
[13] bp global. n.d. Renewable Energy | Energy Economics | Home. (online) Available at: <https://www.bp.com/en/global/corporate/energy-economics/statistical-review-of-world-energy/renewable-energy.html>
[14] Irena.org. n.d. Solar. (online) Available at: <https://www.irena.org/solar>
[15] Eia.gov. 2020. History of Wind Power - U.S. Energy Information Administration (EIA). (online) Available at: <https://www.eia.gov/energyexplained/wind/history-of-wind-power.php>
[16] Energy.gov. n.d. How Do Wind Turbines Work? (online) Available at: <https://www.energy.gov/eere/wind/how-do-wind-turbines-work>.
[17] Society, N., n.d. Biomass Energy. [online] National Geographic Society. Available at: <https://www.nationalgeographic.org/encyclopedia/biomass-energy/>
[18] Wbdg.org. 2016. Biomass for Electricity Generation | WBDG - Whole Building Design Guide. (online) Available at: <https://www.wbdg.org/resources/biomass-electricity-generation>
[19] Conserve Energy Future. n.d. History of Geothermal Energy (And Emergence Over the Years). (online) Available at:

International Journal of Electrical, Electronic and Communication Sciences
ISSN: 2517-9438
Vol:15, No:4, 2021

<https://www.conserve-energy-future.com/geothermalenergyhistory.php>

[20] Eia.gov. n.d. Geothermal Power Plants - U.S. Energy Information Administration (EIA). (online) Available at: <https://www.eia.gov/energyexplained/geothermal/geothermal-power-plants.php>

[21] Irena.org. n.d. Hydropower. (online) Available at: <https://www.irena.org/hydropower>

[22] National geographic. Hydropower, explained (online) Available at: <https://www.nationalgeographic.com/environment/global-warming/hydropower/>

[23] ElProCus - Electronic Projects for Engineering Students. n.d. Types and Working Functionality of Hydroelectric Energy Power Plants. (online) Available at: <https://www.elprocus.com/types-and-working-functionality-of-hydroelectric-energy-power-plants/>

[24] IEA. n.d. Coal. (online) Available at https://www.iea.org/fuels-and-technologies/coal

[25] The Conversation. 2019. Explaining the Increase in Coal Consumption Worldwide. (online) Available at: <http://theconversation.com/explaining-the-increase-in-coal-consumption-worldwide-111045>

[26] Solar Power Europe. (online) Available at https://www.solarpowereurope.org/global-market-outlook-2019-2023/

[27] Our Energy Policy. (online) Available at https://www.ourenergypolicy.org/wp-content/uploads/2017/09/DNV-GL_-Energy-Transition-Outlook-2017_renewables_lowres-single_0109.pdf

[28] IEA. n.d. Bioenergy. (online) Available at https://www.iea.org/fuels-and-technologies/bioenergy

[29] IEA. n.d. Other Renewables - Fuels & Technologies - IEA. (online) Available at: <https://www.iea.org/topics/renewables/geothermal/>

[30] IEA. n.d. Hydropower - Fuels & Technologies - IEA. (online) Available at: <https://www.iea.org/topics/renewables/hydropower/>

[31] International Renewable Energy Agency. Renewable Power Generation Costs in 2018. (online) Available at: <https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2019/May/IRENA_Renewable-Power-Generations-Costs-in-2018.pdf >

[32] Solar News. n.d. Solar Panel Efficiency: What Panels Are Most Efficient? | Energysage. (online) Available at: <https://news.energysage.com/what-are-the-most-efficient-solar-panels-on-the-market/>

[33] Solar News. n.d. Concentrated Solar Power: What You Need To Know | Energysage. (online) Available at: <https://news.energysage.com/contentrated-solar-power-overview/>

[34] Kinhal, V., n.d. (online) Greenliving.lovetoknow.com. Available at: <https://greenliving.lovetoknow.com/Efficiency_of_Wind_Energy>

[35] Sciencedirect.com. n.d. Hydro Power - An Overview | Sciencedirect Topics. (online) Available at: <https://www.sciencedirect.com/topics/engineering/hydro-power>

[36] sciencedirect. Efficiency of geothermal power plants: A worldwide review. (online) Available at: < https://www.sciencedirect.com/science/article/pii/S0375650513001120>

[37] Renwable Energy Institute. Recommendations for Woody Biomass Power Generation under FiT. (online) Available at: < https://www.renewable-ei.org/en/images/pdf/20161226/REI_Proposal_20161226_BiomassFIT_EN_FINAL.PDF>

[38] Atb.nrel.gov. n.d. 2019 ATB Cost and Performance Summary. (online) Available at: <https://atb.nrel.gov/electricity/2019/summary.html>

[39] Santoianni, D., 2015. Setting the Benchmark: The World's Most Efficient Coal-Fired Power Plants. (online) World Coal Association. Available at: <https://www.worldcoal.org/setting-benchmark-worlds-most-efficient-coal-fired-power-plants>

[40] Nuclear Power. n.d. Thermal Efficiency of Nuclear Power Plants. (online) Available at: <https://www.nuclear-power.net/nuclear-engineering/thermodynamics/laws-of-thermodynamics/thermal-efficiency/thermal-efficiency-of-nuclear-power-plants/>

[41] Eia.gov. 2020. (online) Available at: <https://www.eia.gov/outlooks/aeo/assumptions/pdf/table_8.2.pdf>

[42] Jacobson, M., 2020. (online) Web.stanford.edu. Available at: <https://web.stanford.edu/group/efmh/jacobson/Articles/I/NatGasVsWWS&coal.pdf>

[43] IEA. Data and statistics - IEA. (online) Available at:<https://www.iea.org/data-and-statistics/data-tables/?country=WORLD&energy=Electricity/>