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Demystifying the Costs of Electricity Generation Technologies

Govinda R. Timilsina

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Abstract

The levelized cost of electricity is the most common indicator used to compare the cost competitiveness of electricity-generating technologies. Several studies claim that some renewable energy technologies, particularly utility-scale solar photovoltaic and onshore wind, are cost-competitive with fossil fuel–based technologies. However, there is no consensus on this point considering the wide variations in factors that influence the levelized costs of electricity across countries and technologies. This study calculates more than 4,000 levelized costs of electricity for 11 technologies, varying key input variables. The study shows that the levelized costs of electricity for renewable electricity technologies, except concentrated solar and offshore wind, are lower than those for fossil fuel–based technologies at the lower range of capital costs and discount rates of 10 percent or lower. However, for a reasonable range of input variables, calculations of the levelized costs of electricity for renewables based on reasonable parameter values do not justify the low auction prices for solar power, below US$20 per megawatt hour, recently observed in some parts of the world. The study also highlights the shortcomings of the levelized cost indicator for comparing the cost-competitiveness of different types of electricity generation technologies.

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Demystifying the Costs of Electricity Generation Technologies

Govinda R. Timilsina[1]

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[1] Senior Economist, Development Research Group, World Bank, Washington, DC (gtimilsina@worldbank.org).

Demystifying the Costs of Electricity Generation Technologies[2]

1. Introduction

The levelized cost of electricity (LCOE) is the most common indicator to compare costs of electricity generation from various technologies (Aldersey-Williams and Rubert, 2019; Dobrotkova et al. 2018; Ouyang and Lin, 2014; Timilsina et al. 2013; Timilsina et al. 2012). LCOE refers to the cost of producing one unit of electricity from a particular technology, including capital costs, fixed and variable operation & maintenance (O&M) costs, and fuel costs. LCOE also accounts for quality of generation resources (e.g., availability of wind or solar), and other characteristics of the technology (Joskow, 2011; Stacy and Taylor, 2018; IEA, 2015; IRENA, 2020).[3]

LCOE is increasingly used to compare the costs of new and renewable energy technologies with fossil fuel-based technologies. If the renewables are calculated to be cheaper than fossil fuel-based technologies based on LCOE, that could signal the possibility of an expanding market for the renewables (Shea and Ramgolam, 2019; Lazard, 2019; Partridge, 2018; Myhr et al. 2014). If the LCOEs of renewables are higher than those of fossil fuels, or higher than prevailing grid electricity (shadow) prices, policy makers could use the difference as a basis to design subsidies to promote renewables (Ouyang and Lin; 2014). If a carbon tax is imposed on fossil fuels, the size of the carbon tax relative to the difference between LCOEs of renewable- and fossil fuel- based

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[3] The cost of electricity generation from a technology can also be measured in terms of change in electricity supply costs in an electricity grid due to the addition of the technology to meet the future electricity demand (Timilsina and Toman, 2016; Timilsina and Curiel 2020). It is also interpreted as the economy-wide impacts (e.g., impacts on economic welfare, GDP) of including the technology in the power system expansion to meet the demand (see e.g., Timilsina and Landis, 2014; Landis and Timilsina, 2015).

technologies provides some indication of the degree to which renewables can compete with fossil fuel-fired generation once the tax is imposed (Timilsina et al. 2012).

There exist several studies analyzing the costs of electricity generation for different countries, regions, projects, or at the global level. Examples are Shea and Ramgolam (2019), Cartelle Barros et al. (2016), Ouyang and Lin (2014), Candelise et al. (2013), Timilsina et al. (2013), Timilsina et al. (2012), Darling et al. (2011) and Branker et al. (2011). These studies are focused on different sets of technologies with differing geographical coverage. Shea and Ramgolam (2019) compare the LCOE of wind and solar with other technologies in Mauritius and show that the LCOE for bagasse, landfill gas, and utility-scale solar PV is smaller than that of coal and fuel oil. Ouyang and Lin (2014) analyze the LCOE of various renewable energy technologies to suggest the expansion of financial incentives (feed-in-tariffs) to other renewable energy technologies besides wind and solar. Yuan et al. (2014) analyze the LCOE of distributed PV in China and find that these technologies are not economically viable under the current electricity tariff even if these technologies receive government subsidies. Cartelle Barros et al. (2016) compare the LCOE of renewable energy technologies and conclude that conventional sources of electricity generation (e.g. coal, oil, natural gas, and nuclear) are still the most competitive options despite the falling costs of renewable energy technologies. Candelise et al. (2013), Darling et al. (2011) and Branker et al. (2011) analyze the LCOE of solar PV technologies under various conditions. All of these studies either focus on a particular technology or a region. The findings may not hold for other locations or contexts. Timilsina et al. (2012) compare, from a global perspective, the LCOE of solar energy technologies with that of many different technologies under various assumptions, including imposing carbon taxes on fossil fuels. Timilsina et al. (2013) do the same for wind power technologies. Timilsina et al. (2012) and Timilsina et al. (2013) consider multiple values for the main input variable, the capital cost; however, those papers do not consider variations in other input variables.

Some governments, private sector actors, and international organizations regularly publish LCOEs at national, global, and regional levels.[4] For example, a private bank, Lazard, has been

[4] Timilsina and Shah (2020) discuss LCOEs from Lazard (2019), IEA (2015), EIA (2018), IRENA (2020) and NREL (2019).

publishing LCOEs annually for various technologies since 2009. Lazard's estimations of LCOEs reflect investors' perspectives, and the analysis uses data for the United States. The International Energy Agency (IEA) has been doing the same in five-year intervals since 1982. IEA conducts analysis by collecting data from selected countries, but the sample includes mostly the OECD member countries, with only a few non-OECD countries included. The International Renewable Energy Agency (IRENA) publishes its LCOEs of renewable energy technologies every alternate year. IRENA's analysis covers only renewable technologies; it does not include fossil fuels and nuclear technologies. The US National Renewable Energy Laboratory (NREL) and the financial institution Bloomberg also publish their LCOEs. These studies are, however, focus on the United States.

Based on LCOE, several studies claim that renewable energy technologies are cheaper than fossil fuel technologies. For example, Aghahosseini et al. (2020) find that solar photovoltaics (PV) and wind energy are the most cost-competitive technologies for electricity generation in the Middle East and North Africa (MENA) region. Collecting data from many countries around the world on the capital costs and other input data to calculate LCOE, IRENA (2020) finds that renewables are cheaper than fossil fuels to produce electricity on the basis of relative LCOEs. Lazard (2019) shows that LCOEs of utility-scale PV and wind recently have been smaller than that of the cheapest fossil fuel-based technology, gas-fired combined cycle (CC), in the United States despite historically low gas prices.

Over the last two years, utilities have signed power purchase agreements (PPAs) with private suppliers for renewables at very low prices. Deign (2019) reports on solar project auctions in eight countries at prices below \$25/MWh. These are: (1) China's Jinko Power offer at \$24.89/MWh for 150MW in Jordan, (2) Norwegian company Scatec Solar's bid for a 200MW plant at \$24.4/MWh in Tunisia, (3) a joint offer of Abu Dhabi Power Corporation, China's Jinko Solar, and Japan's Marubeni Corporation for a 1200 MW project in Abu Dhabi at \$24.20/MWh; (4) an undisclosed developer's offer for a 900 MW solar power project in Dubai at US\$16.9/MWh; (5) Saudi Arabia's ACWA offer for a 300 MW project at \$23.42/MWh; (6) Italian developer Enel's offer for a 116MW project in Chile at \$21.48/MWh; (7) French developer Neoen's offer for a 375MW project at \$18.93/MWh in Mexico; and (8) Brazilian Milagres project of 163 MW at \$16.95/MWh. In Portugal, 24 utility-scale PV projects with a combined capacity of 1,150 MW were offered through 22 separate offers, most of them at a price below € 20/MWh (Bellini, 2019). The Qatar General Electricity & Water Corporation signed a 25-year PPA at $15.69/MWh for 800 MW of solar power (Kelly-Detwiler, 2020).

These bids raise the question of what values for input variables, such as capital costs, discount rates, and capacity factors, could lead to LCOEs as low as these bids. As discussed subsequently, it is very difficult to rationalize these bids with values of the LCOEs reflecting reasonable measures of those cost components. It also is important to acknowledge up-front the limitations of LCOEs for comparing intermittent and no-dispatchable renewable technologies with fully dispatchable electricity generation technologies (Joskow, 2011; Sklar-Chik et al. 2012). In the absence of storage, renewables do not provide firm capacity and therefore do not help meet the capacity requirement for the reliable supply of electricity. This is equivalent to saying that the actual incremental cost for a power system of intermittent renewables is higher than its LCOE, because of the need to incur additional costs to cope with intermittency. This only deepens the disjunction between observed auction prices for intermittent renewables and the LCOE measure of their cost. As discussed in Section 3, there is an indicator of cost reflecting intermittency that is preferable to LCOE for comparing intermittent and firm power supply costs.

The costs of electricity generation from a given technology vary widely across countries or locations. For example, the LCOE of solar PV in Japan is almost 2.5 times as high as that of India. Similarly, the LCOE of wind power in Italy is almost twice as high as that of China (Timilsina and Kalim, 2020). An LCOE estimation using inputs applicable to a location will not be useful for another place. Moreover, LCOEs reported by various sources or studies cannot be compared because of differences in underlying assumptions and input data. It would be misleading to generalize an LCOE estimate carried out for a country and apply it elsewhere. It is also misleading if particular input data (e.g., capital cost, discount rate, capacity availability factors) applicable for a location, are used to calculate LCOEs somewhere else. Instead, it would be useful to compute a large number of LCOEs considering a range of values for each variable used to calculate the LCOE. This would provide insight into how LCOEs can vary across the values of variables. From the range of LCOEs thus available, one could use values that are most reflective for a given location.

This paper contributes to the literature in two ways. First, it checks whether or not calculated LCOEs based on reasonable values for their determinants are consistent with recent renewable electricity bids. Second, it compares LCOEs of 11 different electricity generation technologies, including both fossil and renewables sources, by considering a wide range of values for each of their determinants. It also illustrates how different factors influence the values of LCOEs of the electricity generation technologies considered in the study.

The paper is organized as follows. The next section presents the methodology and data for the calculations, followed by the presentation of results in Section 3. Section 4 illustrates how different factors influence the costs of electricity generation technologies. Section 5 presents the cost trends for electricity generation technologies. Finally, we draw key conclusions in Section 6.

2. Methodology and Data

In this section, we first present the methodology to calculate LCOE followed by different sets of analyses applying the method.

2.1 Methodology

The LCOEs we calculate and discuss in this section are defined from an economic perspective. They do not include any transfers, such as subsidies and taxes, or any other financial incentives (e.g., grants or concessional loans provided by governments and bilateral/multilateral development partners). The LCOEs calculated from financial or investor perspectives include these transfers.

The LCOE is calculated as follows[5]:

$$LCOE = ACC + VOMC + FC + FOMC \tag{1}$$

[5] This is a simple formula which is commonly presented in studies calculating LCOE; please see, for example, Timilsina et al. (2012), Timilsina et al. (2013).

Where, ACC, VOMC, FOMC and FC are, respectively, annualized capital cost, variable O&M costs, fixed O&M costs, and fuel costs. All these costs are expressed in terms of energy ($/MWh).[6] ACC and FOMC are calculated as follows:

$$ACC = \frac{OC*CRF*1000}{CAF*24*365} \tag{2}$$

$$FOMC = \frac{FXC*1000}{CAF*24*365} \tag{3}$$

Where OC is the overnight construction cost (or lump-sum investment)[7] expressed in terms of capacity ($/kW), and FXC is the annual fixed costs also expressed in terms of capacity ($/kW). CRF is the capacity recovery factor that converts the costs expressed in terms of capacity to the corresponding costs in terms of energy. CAF is the capacity availability factor.[8]

Fuel cost does not apply to renewable technologies, except biomass. It is determined based on fuel prices (FP), the heat content of a fuel (HC), and the heat rate of a power generation technology (HR). Fuel prices are often available in terms of the physical quantity, such as US$ per metric ton of coal. Heat content refers to the amount of heat, measured in kilocalories (Kcal) or megajoules (MJ), contained by one physical unit of the fuel (MJ/kg). Heat rate is the inverse of

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[6] Note that LCOE does not include other costs, such as costs it would incur to the electricity system or grid where the technology is added. The LCOE we calculate here does not account for environmental costs (negative externality costs) of fossil fuels-based technologies.

[7] The overnight construction cost concept lumps all the capital costs at a single time point, the date of commissioning of the power plant. In the economic analysis it ignores the interest accrued during the construction period and also ignores the source of financing (e.g., debt, equity) and costs of financing. In the financial analysis, however, all these items are accounted for.

[8] CAF is different from capacity utilization factor (CUF). CAF refers to the ratio between the actual energy generated from the nameplate capacity in a year and the theoretical energy if capacity operates for 24 hours a day and 365 days in the year provided that there are no other constraints except the availability of sources of input energy and the plant itself. In practice however, operation or dispatching of a capacity depends on the market situation (total demand of the grid and operational costs of electricity generating units). When the market conditions are accounted for, CAF becomes CUF. The maximum value of CUF is equal to CAF. In the power system planning, where an optimal mix of various generating resources is to be determined to meet the load, CUF is used. For LCOE, where electricity generation technologies are compared independently, CAF is used. Existing literature, such as Lazard (2019) appears to ignore this fact and use CUF instead of CAF. Often CUF and CAF are used synonymously calling it capacity factor (CF).

thermal efficiency of a power plant; it refers to the amount of heat needed to produce one unit of electric power (MJ/kWh). Thus, the fuel cost (FC) is calculated as:

$$FC = \left(\frac{FP}{HC}\right) * HR \tag{4}$$

Finally, the CRF is derived by using the discount rate (r) and the economic life (n) of a plant as follows:

$$CRF = \frac{\{r*(1+r)^n\}}{[\{(1+r)^n\}-1]} \tag{5}$$

2.2 Data and assumptions

As implied by Equations (1) to (5), we need data for investment costs or overnight construction costs, capacity availability factors, economic life, fuel prices, heat rate, discount rate, fixed O&M costs, and variable O&M costs. The big challenge is that the values of these variables not only change across locations and technologies but also within the technology for a given location (e.g., capital costs) and in the same location for a given technology (discount rate, fuel prices). O&M costs would be different across the type and the size of technologies. The discount rate is another critical factor to influence the LCOE. The quality of energy sources (e.g., solar irradiation, wind profile, water flow in hydropower plants) measured in terms of plant efficiency and capacity availability factors are different across locations even within the same country. A technology found cheaper in certain conditions may not hold in other situations. Therefore, calculating LCOE for technology in the global context is challenging.

One technique to resolve this situation is applying multiple values for the most crucial input variable for a given technology and using a single reasonable value for each of the remaining variables corresponding to the technology. Capital cost is the largest component in all renewable energy technologies and nuclear. The same is true in fossil fuel-based technologies. However, the share of capital costs in the LCOE is relatively smaller in fossil fuel-based technologies as compared to that in renewable technologies. In the first set of LCOE calculations, we use multiple values of capital costs for each technology. The capital costs are taken from five sources: Lazard

(2019), IEA (2015), EIA (2020), IRENA (2020), and NREL (2019).[9] All sources, with the exception of EIA, provide ranges of capital costs for a given technology. For example, Lazard (2019) provides maximum and minimum values for capital costs for each technology it has included. Others (i.e., IRENA, IEA, NREL) provide a range of values. We also chose maximum and minimum values from IRENA, IEA, and NREL as well. EIA provides one capital cost for a given technology; we used the same value for the minimum and maximum categories. Whenever the capital costs are used in different years' prices, for example, IEA (2015), we expressed them in the same year (2019 here) using the US GDP deflator.

When selecting maximum and minimum values, there is a danger of choosing an extreme value from an outlier. We dropped such values based on expert judgment. For example, IEA used US$9,400/kW as the maximum value for hydropower capital cost; this is too high so we did not use it. The maximum capital cost used by NREL for geothermal technology is US$35,701/kW; we excluded it as well. IRENA excludes the lowest 5% of samples and the highest 5% of samples. There could be several reasons for these extreme values, such as a reporting error during the survey. The value could be a true value but from a single respondent. For hydropower plants in some developing countries, the construction time is often lengthened by delays. The actual costs of the project would be much higher than the design estimate. It also depends on the cost items included in a project. The capital costs of a project would be high if the project costs include the construction of access roads (especially for hydro or wind projects located away from existing roads). If the project costs include the cost of transmission lines to access the existing grids and the project site is away from the existing grid, it will cause the capital costs of the project to increase.

While we tried to standardize other data except for the capital costs so that the LCOEs are comparable, some data could not be standardized. Heat rate and capacity factors could not be standardized in some cases. For example, a thermal power plant with higher capital costs tends to have higher thermal efficiency or low heat rate. Therefore, we assign a low heat rate for a power plant with higher capital costs. A CSP plant with storage facilities has a higher capacity factor. For

[9] IEA (2015) collected data from 181 electric power plants in 22 countries; IRENA (2020) data are collected through surveys of 17,000 renewable power generation projects around the world that represent more than 1,770 GW of total installed or pipeline capacity. Data used by EIA (2020), NREL (2019) and Lazard (2019) are for the United States.

example, Lazard (2019) uses a 68% capacity factor for CSP technology that has a very high capital cost, US$7,950/kW, due to its 18-hour storage capacity. Therefore, we use a higher capacity factor for CSP technologies with high capital costs.

Table 1 presents the capital costs we used from these five sources. As can be seen from Table 1, some data are not available (n.a.), and some marked (n.u.) are available, but we did not use them as they were outliers. Some data are not available because the corresponding technology was excluded in the original study (e.g., hydro and biomass in Lazard).

It would be interesting to break down further the categories of technologies. For example, coal could be disaggregated by technologies – pulverized coal, fluidized bed combustion, integrated gasification combined cycle (IGCC) without carbon capture and sequestration (CCS), IGCC with CCS. Hydro could be divided into pumped storage hydro, small hydro, and large hydro. Large hydro could be further divided into run-of-river (ROR) and storage or reservoir type hydro. Nuclear technologies could also be divided between small-scale modular technology vs. large-scale plants. Biomass technology could be divided by the type of fuel used, such as bagasse-fired biomass, rice husk-fired biomass, wood-fired biomass, and landfill gas-based biomass. However, having too many technologies is not only challenging from the data availability aspect but also makes the presentation of results possibly confusing. Instead of doing so, we present a wide range for a given source of power generation; the range covers all technologies within the source.

The values for other variables are presented in Table 2. A discount rate of 6% was chosen based on a recommendation in World Bank (2015a). Fixed and variable O&M costs are the average of available data from the five sources from which we took the capital costs (i.e., Lazard, IEA, EIA, IRENA and NREL). For fuel prices, we used international prices of coal and gas in the year 2019 from World Bank (2020). Heat rates are tied to capital costs. Power plants with higher thermal efficiency or low heat rates tend to be expensive. Capacity availability factors are standard values for a given technology in most cases. For concentrated solar power (CSP) and wind (both onshore and offshore), capacity availability factors are also tied with the capital cost. A CSP plant with storage facility costs more than $4000/kW. The storage facility increases its capacity availability factor.

Table 1. Capital cost used from different sources (US$/kW, 2019 price)

Data source	Solar PV - Utility	CSP	Wind Onshore	Wind Offshore	Gas CC	Gas GT	Geother mal	Hydro	Coal	Nuclear	Biomass
Minimum Value											
Lazard	900	6,000	1,100	2,350	700	700	3,950	n.a.	3,000	6,900	n.a.
EIA	1,331	7,191	1,319	5,446	1,017	710	2,680	2,752	3,661	6,317	2,831
IRENA	618	3,704	1,039	2,677	n.a.	n.a	2,020	680	n.a	n.a	422
IEA	1,005	3,831	1,287	3,973	673	536	1,602	1,282	1,072	2,805	630
NREL	1,142	6,574	1,678	3,145	944	937	4,557	3,974	3,867	6,460	3,988
Maximum value											
Lazard	1100	9,100	1,500	3,550	1,300	950	6,600	n.a.	6,200	12,200	n.a.
EIA	1,331	7,191	1,319	5,446	1,017	710	2,680	2,752	3,661	6,317	2,831
IRENA	2,794	7,127	2,482	5,551	n.a.	n.a.	7,280	4,138	n.a.	n.a.	8,742
IEA	2,750	8,735	3,217	6,365	1,383	1,001	7,108	n.u.	3,290	6,668	9,298
NREL	1,142	6,574	1,678	5,318	944	937	n.u.	7,418	4,225	6,460	4,182

n.a. -- not available because the study does not include the particular technology, n.u. -- not used as the values are outliers.

Note: Some values presented here may not necessarily be the same as provided in the sources because we converted the data from the sources to 2019 prices using US GDP deflators.

Sources: IRENA (2020), Lazard (2019), IEA (2015), EIA (2020) and NREL (2019).

Table 2. Other data used for the LCOE calculation

Data source	Capacity factor (%)	Economic life (year)	Fixed O&M costs (%) *	Variable O&M costs ($/MWh)	Fuel price ($/GJ)	Heat rate (GJ/MWh)
PV (Utility)	25%	20	1.1%		n.u.	n.u.
CSP	32%-68%	25	1.8%		n.u.	n.u.
Wind Onshore	35.0%	20	2.6%		n.u.	n.u.
Wind Offshore	45.0%	20	2.3%		n.u.	n.u.
Gas CC	85.0%	25	1.7%	3.25	7.5	5.9-7.3
Gas GT	85.0%	20	1.9%	5.62	7.5	8.0-10. 5
Geothermal	85.0%	25	4.0%	1.16	n.u.	n.u.
Hydro	55.0%	40	1.6%	1.39	n.u.	n.u.
Coal	85.0%	40	1.5%	5.42	3.1	9.0-12.7
Nuclear	90.0%	45	1.9%	4.60	0.8	11.0
Biomass	75.0%	25	3.6%	5.50	0.9	11.6-14.2

n.u. -- not used; * Expressed as a percentage of overnight construction costs.

Notes: the natural gas price is the average European price for 2019; coal price is the average Australian coal price in 2019; the discount rate is 6%.

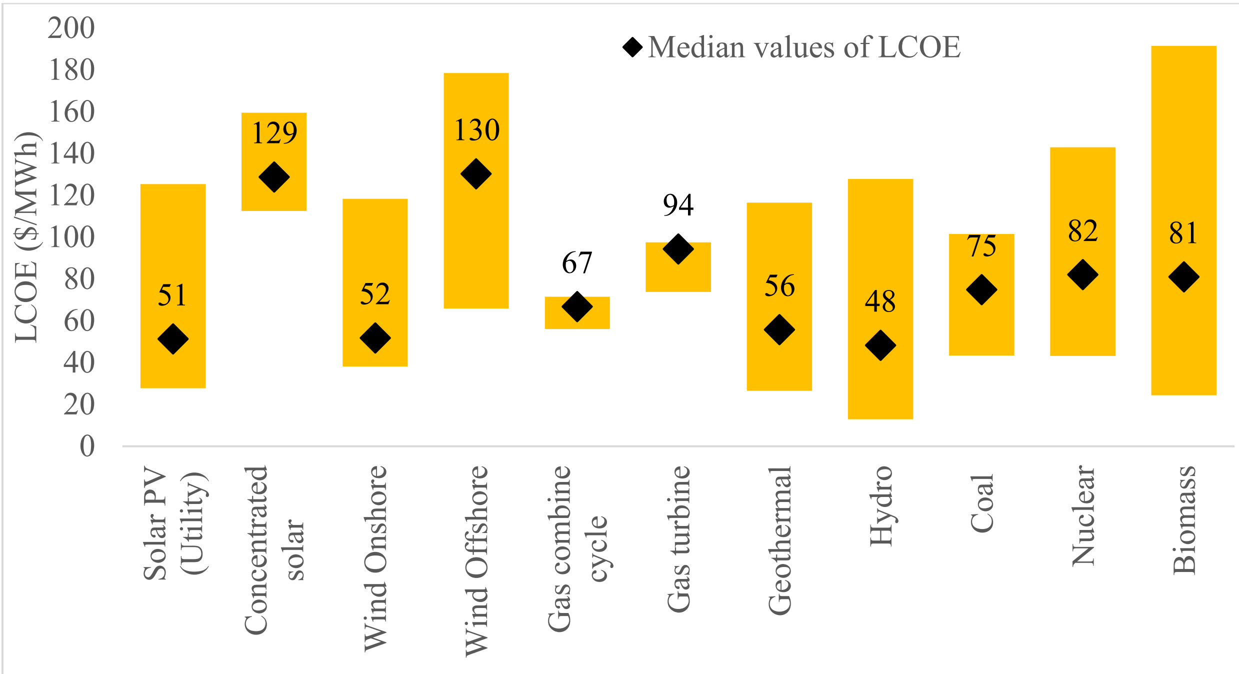
Sources: IRENA (2018), Lazard (2019), IEA (2015) and EIA (2020) for capacity factors and economic life and fixed O&M costs; World Bank (2020) for fuel prices

3. Results and Discussion

The maximum, minimum, and median values of the LCOEs are presented in Figure 1. As illustrated by the figure, if we compare the minimum values of LCOEs across the technologies, all renewable energy technologies, excluding CSP and offshore wind, have lower LCOEs than the fossil-fuel technologies. If the electricity generation technologies are compared in terms of maximum values of their LCOEs, fossil fuel-based technologies are cheaper as compared to renewable energy technologies.

Median values of LCOEs could provide a better ground for a comparison of these technologies. In terms of median values of LCOEs, hydro, solar PV, onshore wind, and geothermal are cheaper as compared to the remaining technologies. Hydro is the cheapest, followed by solar PV, onshore wind, and geothermal. Offshore wind and CSP are the most expensive.

Figure 1. LCOE range for the maximum and minimum values of capital costs when other input variables are standardized ($/MWh)



The values of an LCOE can change along with the values of all seven variables used for its calculation (discount rate, overnight construction costs, O&M costs, fuel prices, heat rate, capacity availability factor, and economic life). One approach to confirm the range of an LCOE is to re-calculate it considering alternative values for all these input variables. Table 3 presents the values for variables we considered under this case. We calculate 4,104 values of LCOEs. The LCOEs for each technology for selected values of the variables are shown in Figure 2.

While calculating the different values for LCOEs, we pay attention to some critical issues. First, it would be misleading to use the extreme values, both low and high, in a global study. We therefore selected values that fall in a reasonable range. For example, NREL (2019) reports very high CAPEX for some geothermal technologies (US$33,365/kW), which is exceptionally high; it would result in an LCOE of around US$700/MWh. It is possible that some experimental technologies could be that costly; but they should not be included in a globally representative analysis. Similarly, IRENA (2020) shows that some hydropower capacity factors could exceed 80%, but there are few hydropower projects around the world with such high capacity factors.

For the capital costs, we started with the lowest values available from the five sources mentioned earlier (Lazard, IEA, EIA, IRENA, and NERL). When the lowest value represents an outlier (e.g., $422/kW for biomass technology), we used the average of the capacity costs available from these five sources. For the maximum values, we used the average of the maximum capital costs available from these sources. We also used the average of the maximum and minimum costs for the third value. Thus, we used three capital costs for each technology. Three values are also used for the capacity availability factor, heat rate, and fuel price for all technologies. For the discount rate, we used six values: 3%, 4%, 5%, 6%, 7% and 10%. Two values are used for economic life and O&M costs.

As mentioned earlier, not all variables used to calculate LCOE are independent of each other. For example, heat rate and capital costs are dependent – more expensive power plants (i.e., higher overnight construction cost) are associated with higher thermal efficiency or lower heat rate. The highest value of capital costs of CSP and offshore wind is associated with the highest value of capacity availability factor. By accounting for these attributes, we avoid any violations of the physical characteristics of the technologies while calculating LCOE. For example, it prevents the possibility of a cheaper coal-fired plant to have higher thermal efficiency. We expressed fixed O&M costs as a fraction of overnight construction costs.[10]

The results are displayed in Figure 2(a) and 2(b). For the lower range of capital costs (see Table 3), hydro and solar PV are found to be cheaper under all discount rates, even if fossil fuel-based generation uses the lowest fuel prices.[11] With the low range of capital costs from Table 3, onshore wind also has a smaller LCOE than that of fossil fuels with the lowest fuel prices if the wind has a higher (35%) capacity utilization factor, and the discount rate is 6% or lower. Onshore wind with the lower range of capital costs would be cheaper than fossil fuels for all discount rates considered if the fuel prices increase to their mid-range (Table 3), and onshore wind operates at 35% capacity factor. With the high range of fuel prices from Table 3, all renewables except offshore wind and CSP would be cheaper than fossil fuel-based technologies, as long as the capital costs are kept at the lower range. The high-range fossil fuel prices presented in Table 3 reflect the market prices in 2019.

[10] It is possible to calculate this fraction on an annual basis by converting overnight construction costs to the annuity but it creates a complication as the annuity differs along with the economic life of a power plant.

[11] At the 10% discount rate, the LCOE of solar PV would be slightly higher than that of gas CC when we use a lower range of capacity factors (20%) for solar PV.

Table 3 Design of cases or (sensitivity analysis) to calculate LCOE varying values of all input variables

Data source	Solar PV - Utility	CSP	Wind Onshore	Wind Offshore	Gas CC	Gas GT	Geothermal	Hydro	Coal	Nuclear	Biomass
DR (r)	3%, 5%, 7%										
Overnight construction cost (US$/kW)	618 1,153 1,688	3,707 5,352 7,000	1,100 1,692 2,255	2,350 3,798 5,246	673 917 1,161	536 700 899	2,680 3,892 5,104	1,282 2,456 3,630	1,200 2,772 4,344	4,000 5,956 7,911	1,968 4,018 6,068
Capacity availability Factor (%)	15%, 20%, 30%	25% to 60%	25% to 45%	25% to 45%	75% 80% 85%	75% 80% 85%	80% 85% 90%	45% 50% 55%	75% 80% 85%	80% 85% 90%	65%, 70%, 75%
Economic Life (Year)	25, 30	25, 30	25,30	25, 30	20,30	20,30	25,35	35,40	35,40	40,50	20,30
Fuel price (US$/GJ)					3.3, 7.5, 12				1.5, 2.0, 3.5	0.7,0.81, 1.0	0.9, 1.0, 1.2
HR (MJ/kWh)					6.5, 6.8, 7.5	8.0, 8.4, 10.3			7.5, 9.1,12.3	10.5, 11.0, 11.5	11, 13,14
Fixed O&M costs (% of OC)	0.9% 1.23%	1.47% 1.71%	2.54% 2.73%	2.20% 2.69%	1.54% 2.34%	1.4% 1.7%	3.6% 4.38%	1.39% 1.7%	1.3% 1.7%	1.7% 2.0%	2.9% 4.2%
No of LCOE	216	216	216	216	648	648	216	216	216	648	648

Capacity factors: CSP -- 55%, 60% 65% for plant with $7000/kW capital cost; 35%, 40%, 50% for plant with $5352/kW capital cost; 25%, 30%, 35% for plant with $3707/kW capital cost. Wind: 30%,35%, 45% for higher capital cost plants and 25%, 30%, 35% for plants with lower and middle values of capital costs. The higher capacity factors for CSP are due to availability of storage facilities.

Heat rate: Gas CC -- 6.5, 6.8, 7.5 for high, middle, and low capital cost plants, respectively; Gas GT -- 8.0, 8.4, 10.3 for high, middle, and low capital cost plants, respectively; coal -- 7.5, 9.1,12.3 for high, middle, and low capital cost plants, respectively; nuclear -- 10.5, 11.0, 11.5 for high, middle, and low capital cost plants, respectively; biomass -- 11, 13,14 for high, middle, and low capital cost plants.

Variable O&M costs are the same as in Table 1.

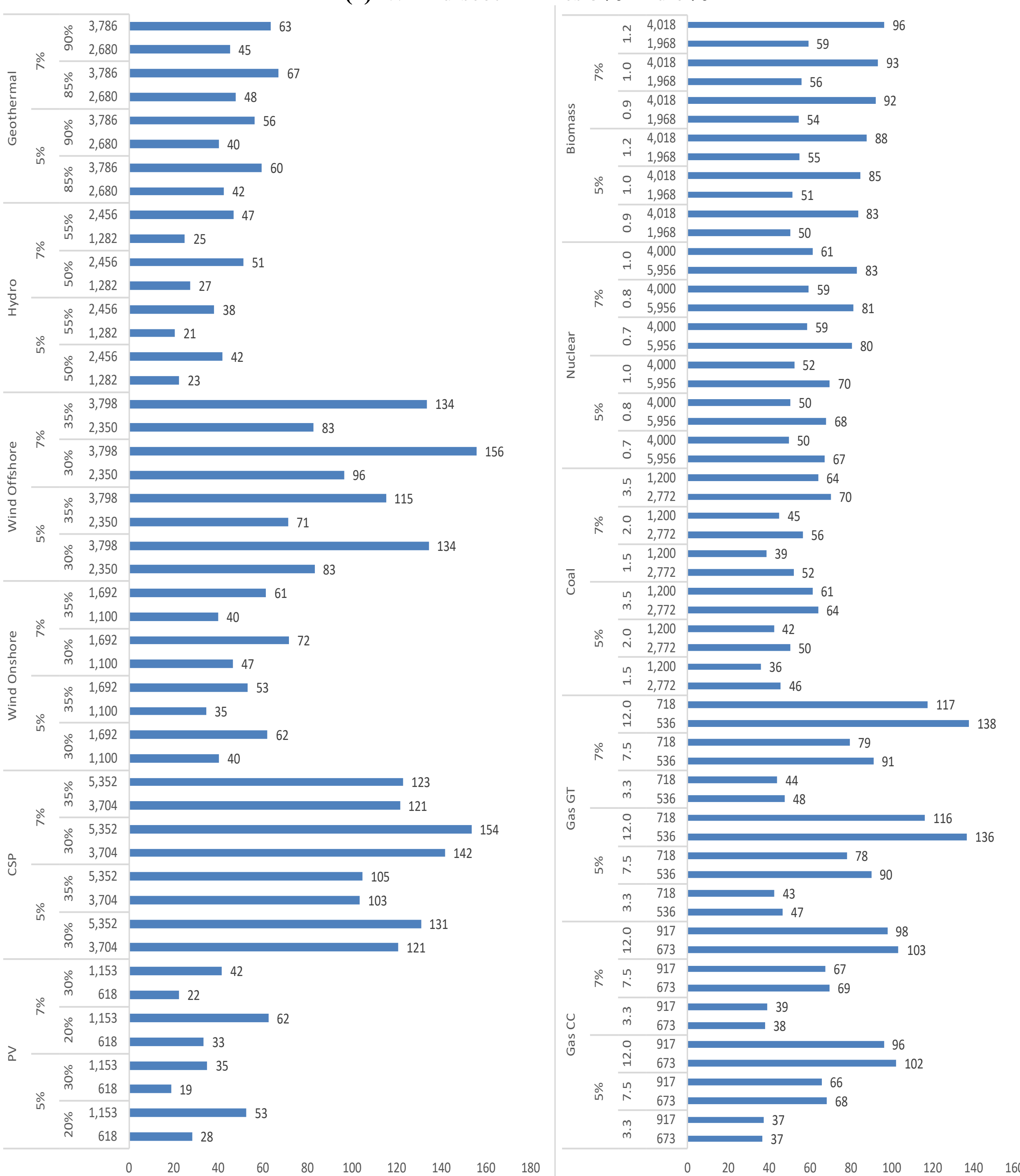
The international price of coal, represented by the price of coal in Australia, one of the main coal exporters in 2019, was $77.89/MT and the international price of natural gas, represented by LNG import price in Japan, the main importer in 2019, was $10.57/MMBTU (World Bank, 2020). These prices are very close to the high values of coal and gas prices considered in our analysis. As fuel prices are volatile, the relative economics of renewable sources for power generation could be affected due to fuel price volatility. This will be discussed in the next section.

Let us compare the LCOEs of various technologies when these technologies are assigned the middle value of the capital costs from Table 3. In this case, solar PV and hydro would be cheaper than fossil fuel-based technologies when we use high fuel prices, which reflect the market prices in 2019 in many countries around the world under all discount rates considered. Onshore wind and geothermal would also compete with fossil fuels only if the renewables have high capacity factors, as specified in Table 3. In the United States, where fossil fuels are relatively cheaper, solar PV would compete with fossil fuels with low fuel prices only at a high capacity factor (30%) and with a discount factor of less than 6%. With the middle value of capital costs from Table 3, other renewables have higher LCOEs than fossil fuels in the United States, even at a lower discount rate (5%) because of low fuel prices.

As mentioned in Section 1, solar power has been supplied at very low prices (< US$20/MWh) through auctioning in many countries in the past few years. Our analysis, however, does not find LCOEs below $20/MW unless the discount rate is 6% or lower, the capacity factor is very high (30%), and economic life is very optimistic (30 years). A 30% capacity factor is high for solar. Similarly, 30 years of economic life is highly optimistic for solar PV. With the highest capacity factor reported to date in MENA countries (27.5%), the lowest capital costs reported to date ($618/kW in India) and an optimistic value of economic life (25 years), the LCOEs would be $20.8/MWh, $22.6/MWh, $24.6/MWh and $30.8/MWh for 5%, 6%, 7% and 10% discount rates, respectively (Figure 3). These LCOEs are higher than $20/MWh. Thus, there is a disconnect between the recent auction prices for solar and the LCOEs, even with highly optimistic assumptions. The lowest value of LCOE calculated by IRENA (2020) for utility-scale solar PV is much higher than the low auction prices observed recently.

Figure 2. Selected LCOEs at varying values for input variables (US$/MWh)

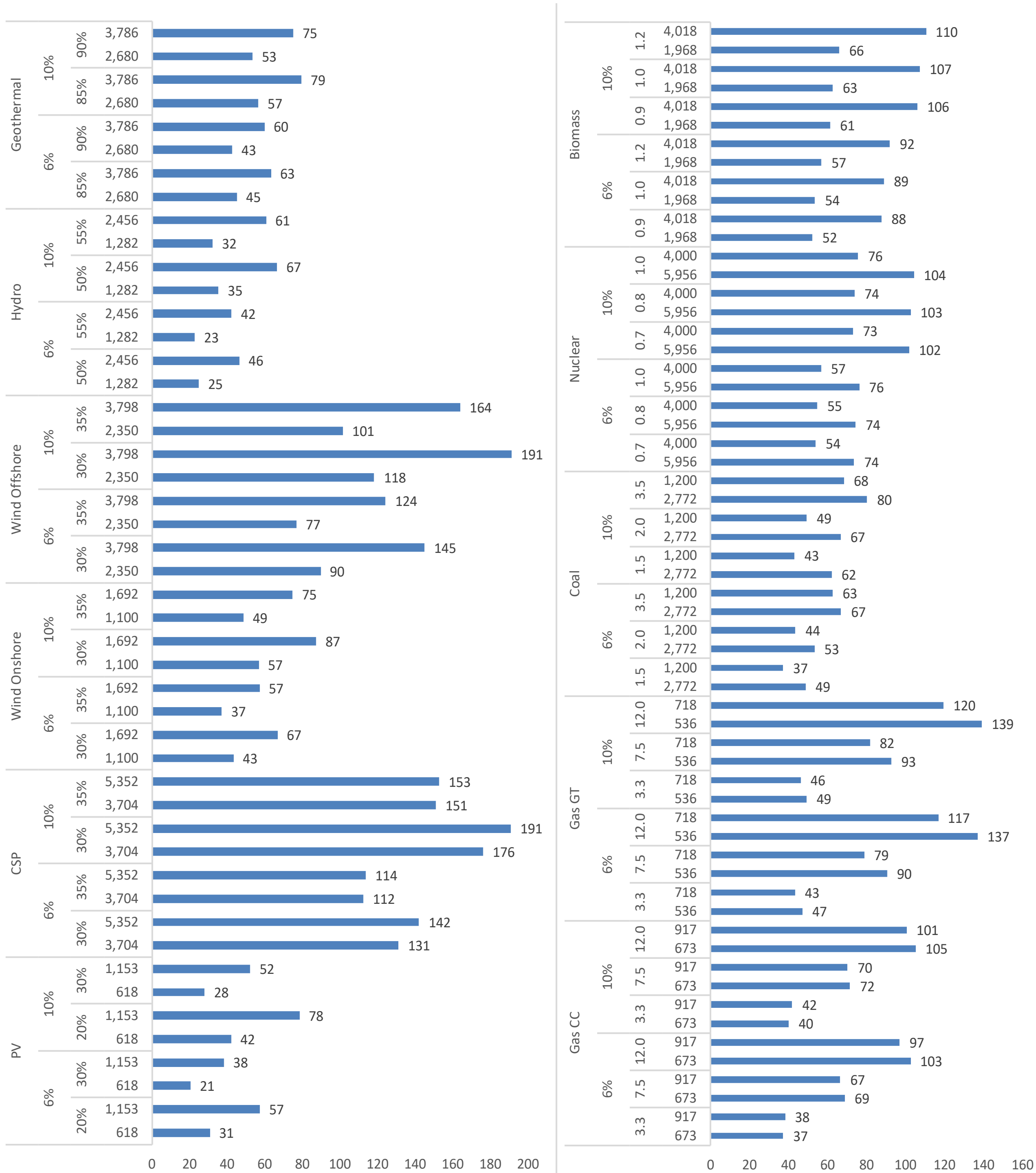
(a) With discount rates 5% and 7%



Note: The innermost vertical axis label is for capital costs ($/kW) in both panels; the next axis label is the capacity factor (%) in the left panel and fuel price ($/GJ) in the right panel. The third vertical axis label is the discount rate (%). Economic lives are: 20 years for CC, GT, biomass; 25 years for PV, CSP, Onshore wind, Offshore wind, geothermal; 40 years for hydro, coal; 50 years for nuclear. Capacity factors are 85% for fossil fuels, 75% for biomass, and 90% for nuclear.

Figure 2 (Continued). Selected LCOEs at varying values for input variables (US$/MWh)

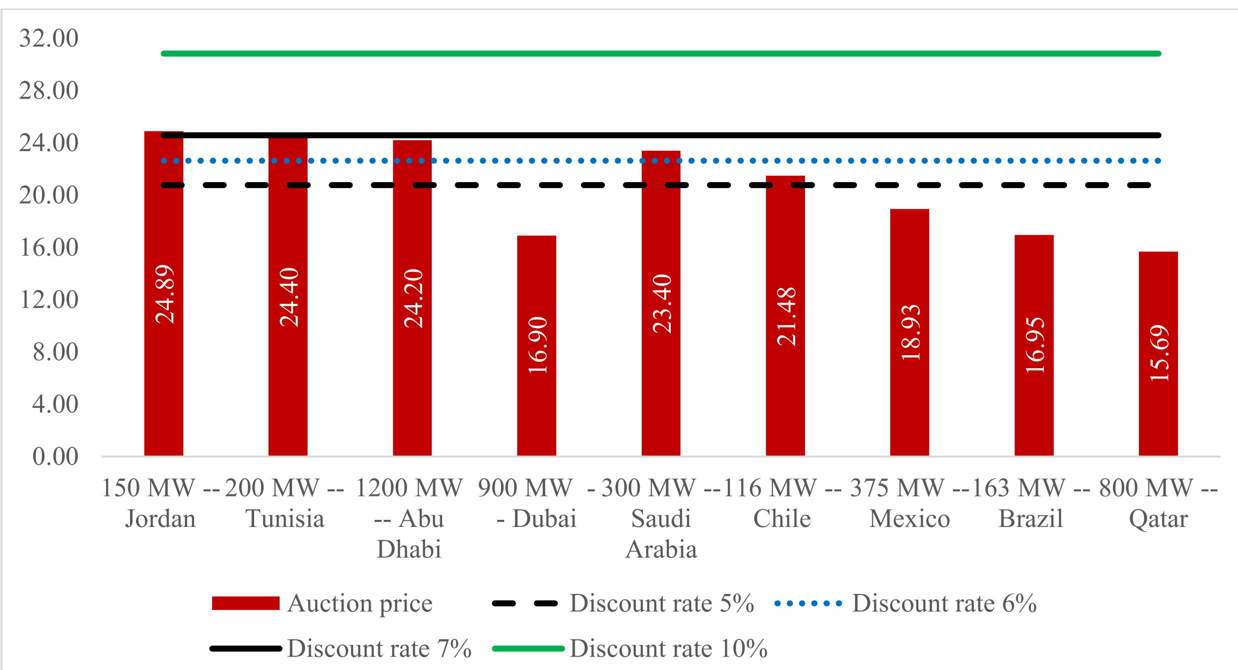
(b) With discount rates 6% and 10%



Note: The innermost vertical axis label is for capital costs ($/kW) in both panels; the next axis label is the capacity factor (%) in the left panel and fuel price ($/GJ) in the right panel. The third vertical axis label is the discount rate (%). Economic lives are: 20 years for CC, GT, biomass; 25 years for PV, CSP, Onshore wind, Offshore wind, geothermal; 40 years for hydro, coal; 50 years for nuclear. Capacity factors are 85% for fossil fuels, 75% for biomass, and 90% for nuclear.

When solar PV prices dropped below \$30/MWh 2-3 years ago in competitive bidding, some studies attempted to investigate the reasons. Examining the PV prices of around \$30/MWh in Saudi Arabia and the United Arab Emirates by 2017, Apostoleris et al. (2018) find that only special conditions allow that price level. These conditions include zero land costs, low labor costs, low financial costs, and preferred access to grids. These countries also have access to low-wage migrant workers. Lower labor costs reduce fixed O&M costs. Similarly, Dobrotkova et al. (2018) point out that only in exceptional conditions, the LCOE of solar PV could go below \$30/MWh. These conditions include a combination of high capacity factors, low equipment prices, low-risk investment environments, and smart project development strategy. Considering the lowest capital costs of solar available today and other favorable conditions, LCOE of solar PV could drop below \$30/MWh. However, as we discussed above, we could not come up with LCOE below \$20/MWh even with the most favorable conditions.

Figure 3. LCOE with favorable conditions and recently observed auction prices of solar-PV (\$/MWh)



Note: Columns represent auction prices, lines represent LCOEs from this study. LCOEs are calculated based on the lowest capital costs reported to date (\$618/kW in India), highest capacity factor recorded (27.5% in MENA countries) and optimistic value for economic life (25 years).

Sources for auction prices: Kelly-Detwiler (2020) for Qatar and Deign (2019) for the rest.

Therefore, further investigations are needed to understand the factors that have driven the auction prices of solar prices so low, especially below \$20/MWh. There could be many reasons. One obvious candidate is the presence of various direct or implicit subsidies. Governments or state-owned utilities might have covered part of project costs, such as costs of connecting the power plant to the existing grids or covered all types of project risks. Governments might have exempted import duties for equipment (e.g., solar panels) used to build power plants. Solar energy subsidies are known to exist (Apostoleris et al. 2018, Dobrotkova et al. 2018). Further investigation is needed to reveal the particular reasons behind the low (< US\$20/MWh) solar bids.

As noted, there are inherent limitations in comparing LCOEs of intermittent and non-dispatchable renewable technologies with LCOEs of fully dispatchable electricity generation technologies. Shah and Bazilian (2020) also highlight the limitations of LCOEs especially in the context of variable renewable energy (VRE) resources. The LCOE could be misleading to investors as well. If an investor decides to invest in a technology based on its low LCOE, the project may not meet the expected rate of return if its actual value to the operator of the power system is less than the LCOE.

These limitations raise the question of whether reliance on LCOE is a good approach for comparing VRE with other technologies for electricity generation. The answer depends in part on the size of the additional cost to cope with intermittency, which in turn depends partly on the scale of intermittent renewables incorporated in a power system. Nevertheless, a one-to-one comparison of the costs of electricity generation technologies is not very meaningful from the perspective of actual operation of a power system (or electricity grid). Electricity demand (or load) varies across hours in a day and across days in a year. For meeting the system load at a given point of time, electricity generation from various technologies are mixed or "stacked." The mix includes power generation technologies with low and high LCOEs.

To address the limitations, a power sector planning approach, such as used in Timilsina and Curiel (2020), Timilsina and Jorgensen (2018), and Timilsina and Toman (2016) should be used. EIA (2020) identifies to use LCOE along with another indicator, LACE or levelized avoided cost of electricity. Formally, the LACE refers to the marginal value of energy and capacity in an electricity grid resulted from the addition of a unit of a given technology. It compares a prospective generation technology to be added into the power system against the mix of new and existing generation and capacity that it would displace.

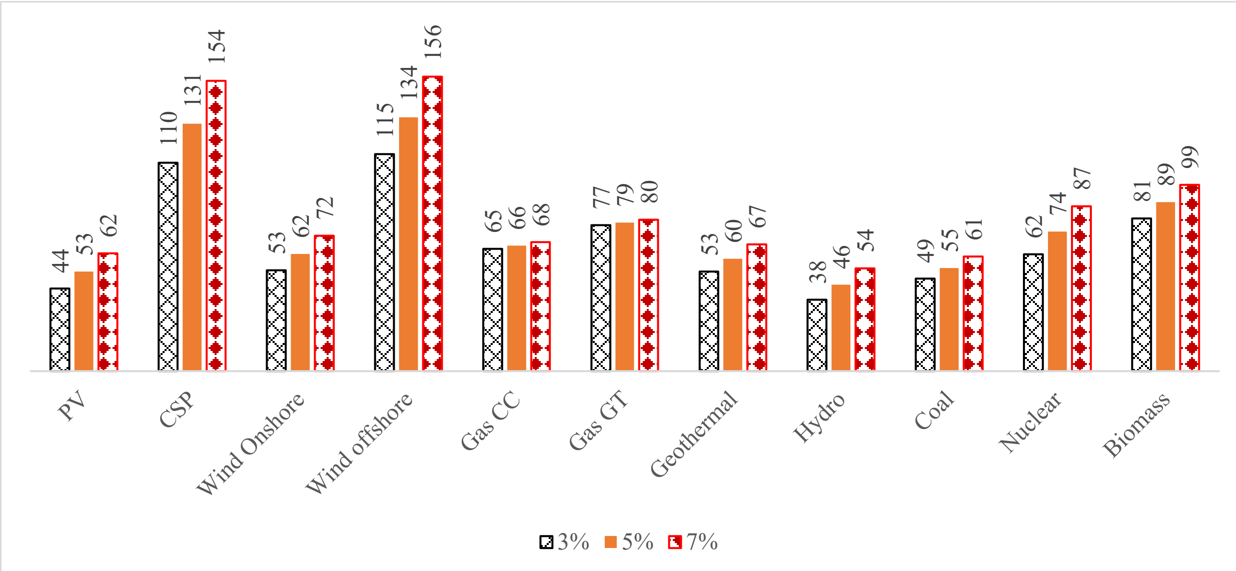
4. Factors Affecting LCOE

As illustrated in Equations (1) to (5), the LCOE of a given technology is influenced by the following factors: (i) discount rate, (ii) overnight construction costs, (iii) capacity factors, (iv) economic life, and (v) O & M costs. In addition to these factors, fuel prices are also responsible in the case of fossil fuel-based and nuclear technologies. Here we illustrate, using the results from our analysis, impacts of each of these factors on the LCOEs of all technologies considered. For the sensitivity analysis of a given input variable, we use the middle values from Table 3 for other variables if there are values. If there are only two values in Table 3, we use the lower values.

4.1 Impacts of the discount rate on LCOE

The discount rate is one of the critical factors affecting the values of an LCOE for a given technology. Figure 4 illustrates how discount rates affect an LCOE. We change only the discount rate keeping other values the same. When the discount rate increases from 3% to 7%, the LCOE of the gas turbine increases by 4%, whereas the LCOE of hydro increases by 44%. The percentage changes in LCOE for one percentage point change in the discount rate are around 1% for gas turbine and combined cycle; about 6% for coal and biomass, 7% for geothermal, about 9% for wind (both onshore and offshore), about 10% for CSP and nuclear, and about 11% for hydro and solar PV. The heterogeneity in the change in LCOE for the same level change in the discount rate can be explained through the different mixes of various LCOE components (e.g., capital costs, fuel costs, O&M costs).

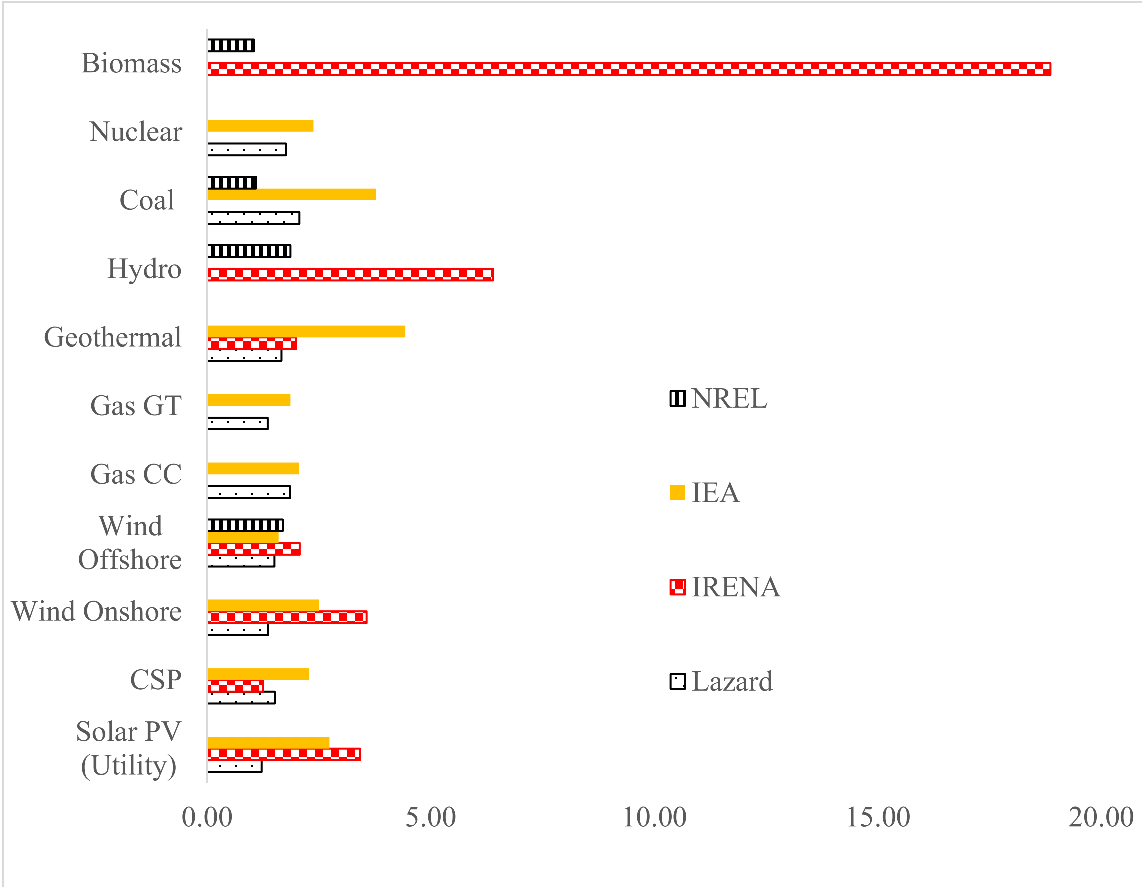
Figure 4. Illustration of the sensitivity of LCOE with the discount rate (US$/MWh)



4.2 Impacts of capital cost on LCOE

Capital cost, or overnight construction cost, is one of the main components of LCOE. For renewable energy technologies, the share of capital in LCOE would be the highest because renewables, except biomass, do not require fuels to produce electricity. In the case of fossil fuels, the share of capital cost varies depending on fuel prices. If fuel prices are high, the share of fuel cost would be higher, thereby substituting the share of capital cost. The variations in the overnight construction costs can be observed in Table 1. Capital costs do not only vary across types of technology but also vary at a wide range for a given technology. Figure 5 illustrates the variation of the capital cost of a given technology. According to IRENA (2020), the higher capital cost of utility-scale solar PV is 3.3 times higher than its lower one. Some technologies exhibit much wider variation, for example, hydro and biomass (IRENA, 2020). In IRENA (2020), the higher capital cost of hydro is 6.4 times greater than the lower capital cost, and the higher capital cost of biomass is 18.9 times greater than the lower capital cost.

Figure 5. The ratio between the high and low values of capital costs



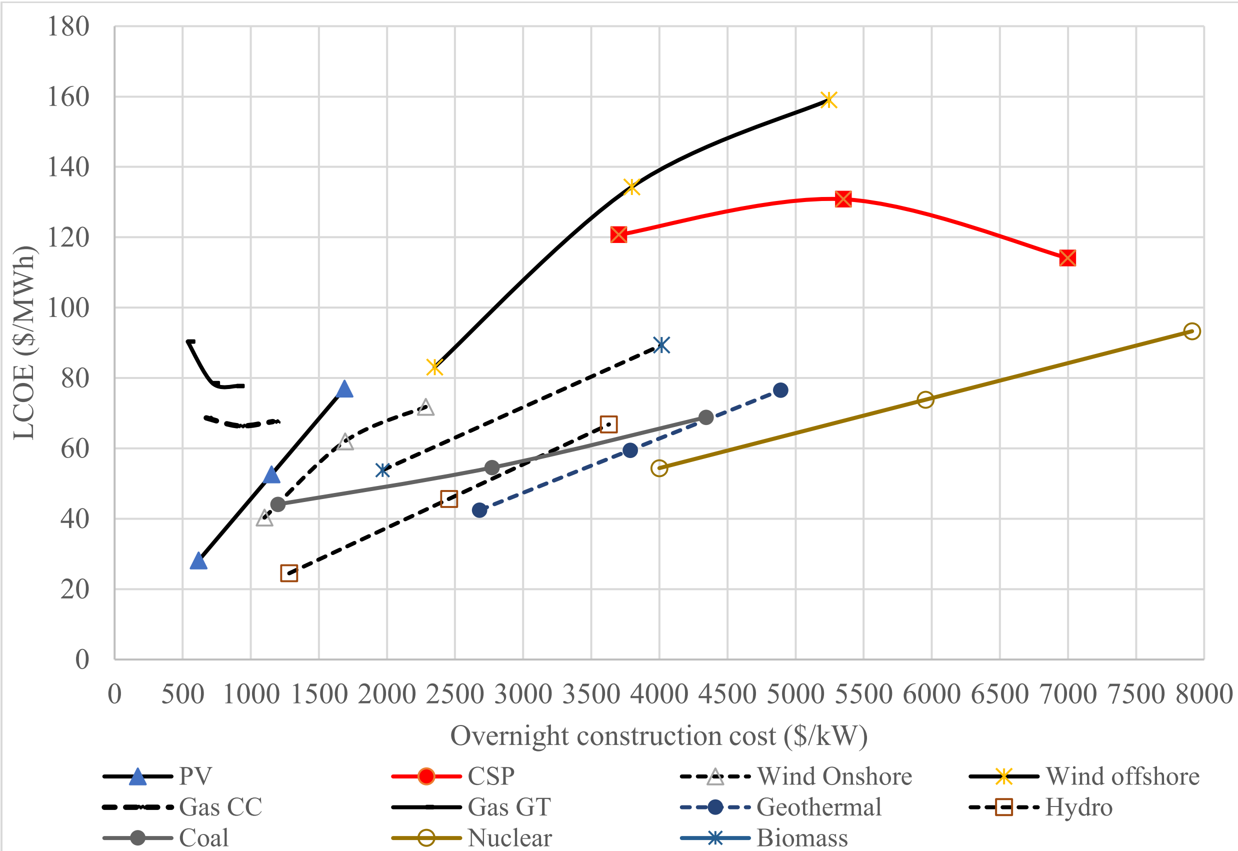
Note: Author's calculations are based on data from Lazard (2019), NREL (2019), IRENA (2020), IEA (2015), and EIA (2018).

There are multiple reasons for the variations of capital costs for the given technology type. Capital costs vary because of different technological configurations. Solar PV panels based on amorphous and crystalline silicon technologies are very different. Gas-fired power generation technologies are either open cycle type or combined cycle type. The former has only one turbine per unit, whereas the latter uses two turbines, one gas turbine and another steam turbine. As such the capital costs would be different between these technologies. For coal, different types of combustion technologies, such as pulverized combustion, fluidized bed combustion, and integrated gasification technology, are possible, and the capital costs of coal-based technologies are different across the technologies. In biomass, the capital costs of technology are vastly different depending on what type of biomass feedstock is used. Technologies burning rice-husk are much cheaper than technologies using municipal solid waste (IRENA, 2018). Costs of reservoir type hydropower plants are much higher than that of run-of-river type hydropower plants. The wider variations of capital costs are also observed in all other types of power generation technologies. The capital costs would be different depending upon the types and brands of various components, such as the turbine, generator, boiler, and other accessories. Capital costs also vary due to the size of power plants (economy of scale) and other specifications.

Figure 6 presents the results of the sensitivity analysis on capital costs. There appear to be three distinct trends of LCOEs when capital costs are increased. LCOEs of PV and partly offshore wind are more sensitive to capital cost as their slopes are steeper as compared to that of others. The slopes of nuclear and coal are flatter indicating less sensitivity to capital costs. The slopes of hydro, biomass, and geothermal are gradual. The slopes of gas CC and GT are declining when capital costs are increased. This is because the gas plants with higher costs have higher thermal efficiency or lower heat rates. The negative impact of increased capital costs on LCOE (i.e., increased LCOE) is more than offset by positive impacts of increased efficiency (i.e., decreased LCOE). A similar phenomenon is also observed in CSP and offshore wind due to increased capacity utilization factors. CSP plants with higher capital costs come with storage facilities, which increase the capacity utilization factors. The higher the capacity utilization factor, the lower would be the LCOE. Offshore wind turbines with larger capital costs tend to have higher capacity utilization factors.

We also calculate the capital cost elasticities of LCOEs (i.e., the percentage change in LCOEs with respect to the percentage change in capital costs). Solar PV has the highest capital cost elasticity, 1.0; hydro and geothermal have 0.94 and 0.97 capital cost elasticities. On the other hand, coal has the lowest positive value capital cost elasticity of LCOEs: 0.21. As explained above, gas-based generation, offshore wind, and CSP have negative capital cost elasticity of LCOEs because their LCOEs are lower at higher capital costs.

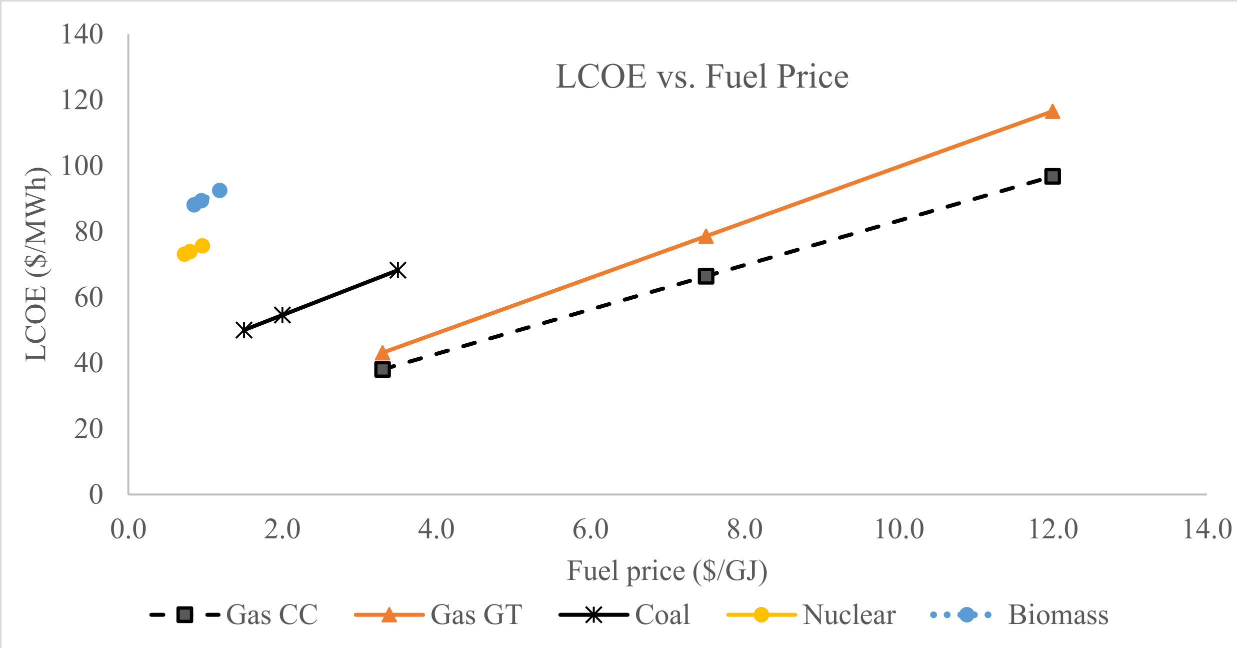
Figure 6. The variations of LCOE due to variations in capital costs



4.3 Impacts of fuel prices on LCOE

The LCOEs of fossil fuel-based, and to some extent biomass-based, technologies are sensitive to fuel prices. Figure 7 presents LCOEs under three alternative fuel prices. The fuel prices used for the sensitivity analysis are provided in Table 3. The LCOEs of gas-based generation are very sensitive to fuel prices. While coal, nuclear, and biomass are not very sensitive. The fuel price elasticities of LCOEs (i.e., percentage change in LCOEs with respect to percentage change in fuel price) are 0.59 and 0.65 for gas-fired combined cycle technology and gas turbine technology respectively. The fuel price elasticities are 0.27 for coal, 0.13 for biomass, and 0.11 for nuclear.

Figure 7. The variations of LCOEs due to changes in fuel prices



4.4 Impacts of the economic life of technologies on their LCOE

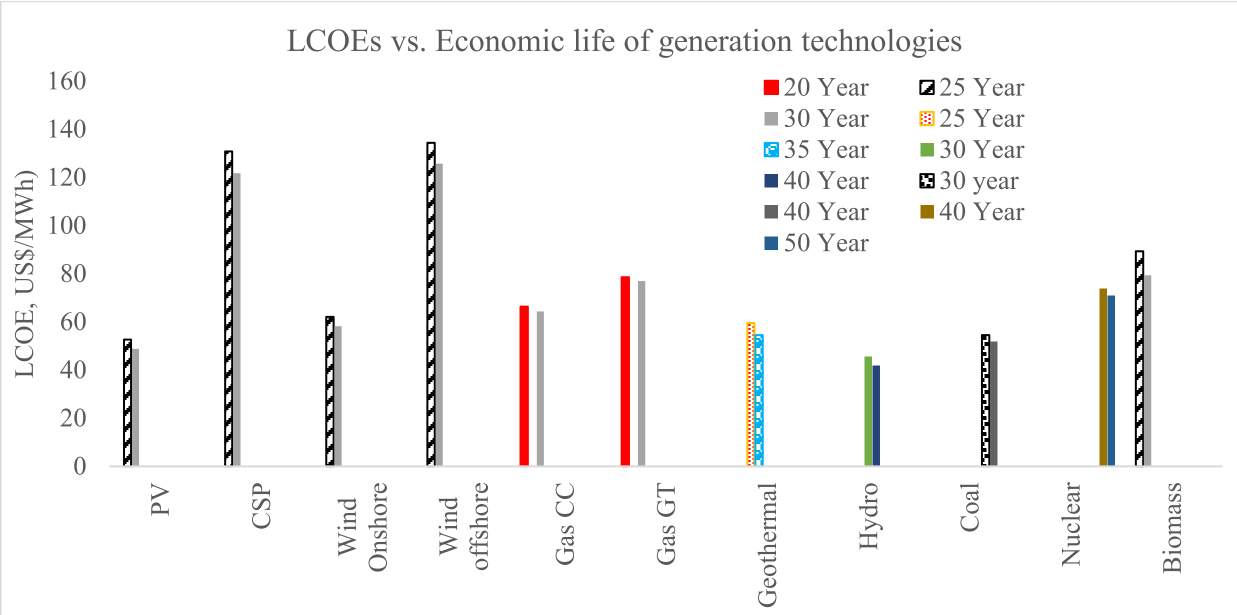
The economic life of a technology is another factor causing LCOEs to vary across technologies. For a given technology, economic life could also be different across power plants considering the physical environment (e.g., weather, climate) faced by the plants. Table 4 presents the economic lives of various technologies considered by different studies. The longer is the economic life of the technology, the lower would be the LCOE, keeping other factors constant. This is the reason for the relatively lower LCOE for hydro and nuclear technology as reported by IEA (2015) despite their higher overnight construction costs. Figure 8 presents the variations in LCOEs when the economic lives of power plants are changed.

Table 4. The economic life of power plants (Year)

Technology	Lazard (2019)	IEA (2015)	IRENA (2018)	EIA (2020)	NREL (2019)
PV (Utility)	20	25	25	30	20-30
CSP	35	25	25	30	20-30
Wind Onshore	20	25	25	30	20-30
Wind Offshore	20	25	25	30	20-30
Gas CC	20	25	n.a.	30	20-30
Gas GT	20	25	n.a.	30	20-30
Geothermal	25	40	25	30	20-30
Hydro	n.a.	80	30	30	20-30
Coal	40	40	n.a	30	20-30
Nuclear	40	60	n.a.	30	20-30
Biomass	n.a	40	20	30	20-30

We find that solar PV, CSP, offshore wind, and biomass are relatively more sensitive to their economic lives keeping the values for other input variables constant. If the economic life of solar PV increases by one year, its LCOE decreases by 1.7%. Similarly, if the economic lives of CSP, offshore wind, and biomass are increased by one year, their LCOEs decrease by, respectively, 1.6%, 1.5% and 1.1%. Fossil fuel technologies and nuclear power plants are found relatively less sensitive to their economic lives. The LCOEs of gas GT, gas CC, nuclear, and coal decrease by, respectively, 0.2%, 0.3%, 0.4% and 0.5% for a one-year increase in their economic lives. The corresponding values for onshore wind, hydro and geothermal are, respectively, 0.6%, 0.8% and 0.9%. The interdependency between the variables (e.g., capital costs and economic life) and the mix of various cost components in LCOEs causes the different levels of sensitivity of LCOEs with economic lives across the technologies. For example, economic life affects the distribution of investment costs to its annuity. It affects more the technologies which are capital intensive (i.e., have higher shares of capital costs in their LCOEs) such as CSP and offshore wind. For fossil fuels, the share of fuel costs in LCOEs is relatively higher. As the fuel cost is independent of the economic life of a technology, LCOEs of fossil fuel-based technologies are relatively less sensitive to their economic lives.

Figure 8. LCOEs along with economic lives of electricity generation technologies



4.5 Impacts of the capacity availability factor on LCOE

Capacity availability factors represent the quality of resources (inputs) available to produce electricity. Since fossil- and nuclear- fuels are storable, they are available throughout the year. Therefore, they have very high capacity factors. On the other hand, renewable energy resources (solar, wind, run of river hydro) are not storable; their capacity factors are relatively smaller. Table 5 provides capacity factors from IEA (2015), IRENA (2018), NREL (2019), and Lazard (2019).

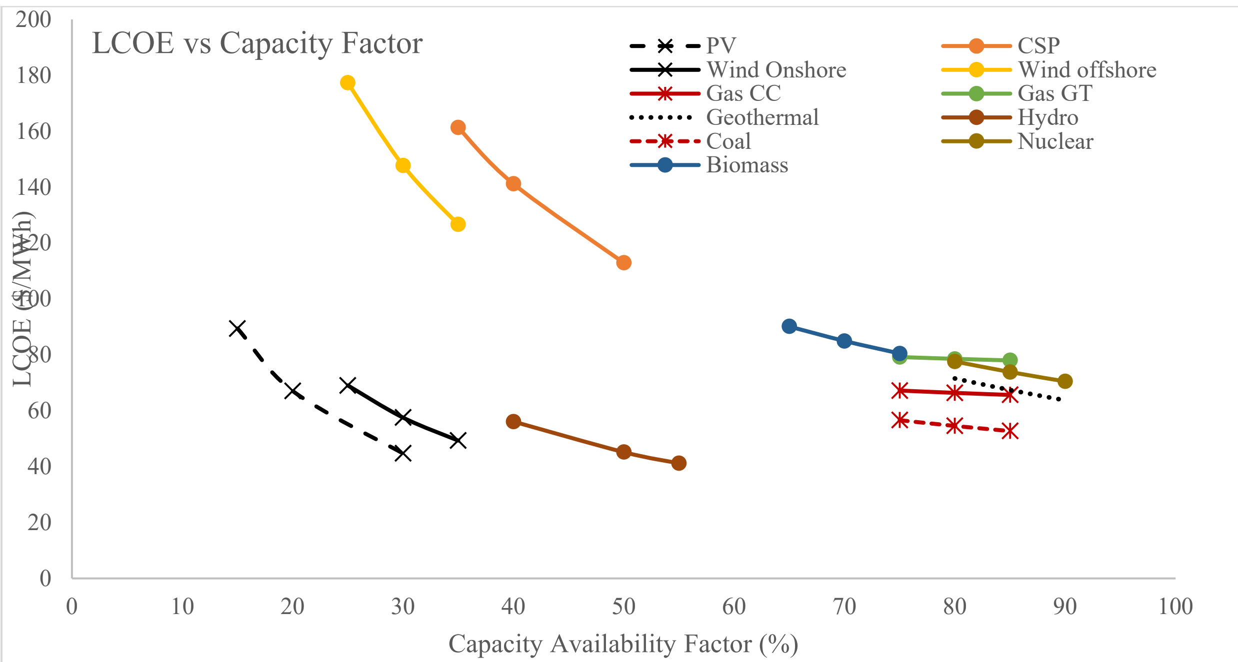
Figure 9 reflects the sensitivity of LCOEs with capacity availability factors. An increase in the capacity availability factor decreases LCOEs. Like in the case of economic life, renewable energy technologies are more sensitive to their capacity availability factors than fossil fuel-based electricity technologies. The latter are more susceptible to fuel prices, as discussed earlier. For one percentage point increase in capacity availability factors, LCOEs of solar PV and wind both onshore and offshore decrease by about 3%, whereas LCOEs of gas-based technologies decrease by 0.2%. Geothermal, coal, nuclear, and biomass exhibit 1% reduction in their LCOEs for each percentage point increase in their capacity availability factors. The corresponding value for CSP and hydro is about 2%.

Table 5. Capacity utilization factors of electricity generation technologies (%)

Technology	IEA (2015)	Lazard (2019)	IRENA (2018)	NREL (2019)
PV (Utility)	11 - 21	21-34	12-27	15-27
CSP[#]	34 - 60	39-68	32-60	50-64
Wind - Onshore	20 - 49	38-55	25-54	23-48
Wind - Offshore	30 - 48	45-55	26-50	28-45
Gas - CC	85	55-70	n.a.	87
Gas - GT	85	10	n.a.	30
Geothermal	80-92	n.a.	68-94	80-90
Hydro	40-63	n.a	23-74	60-66
Coal	85	66 - 83	n.a.	85
Nuclear	85	90-91	n.a.	92
Biomass	48-80	n.a.	44-94	56

[#] Higher values (> 40%) correspond to CSP with storage facilities.

Figure 9. Trends of LCOEs along with capacity availability factors



5. Historical Trends of Electricity Generation Costs

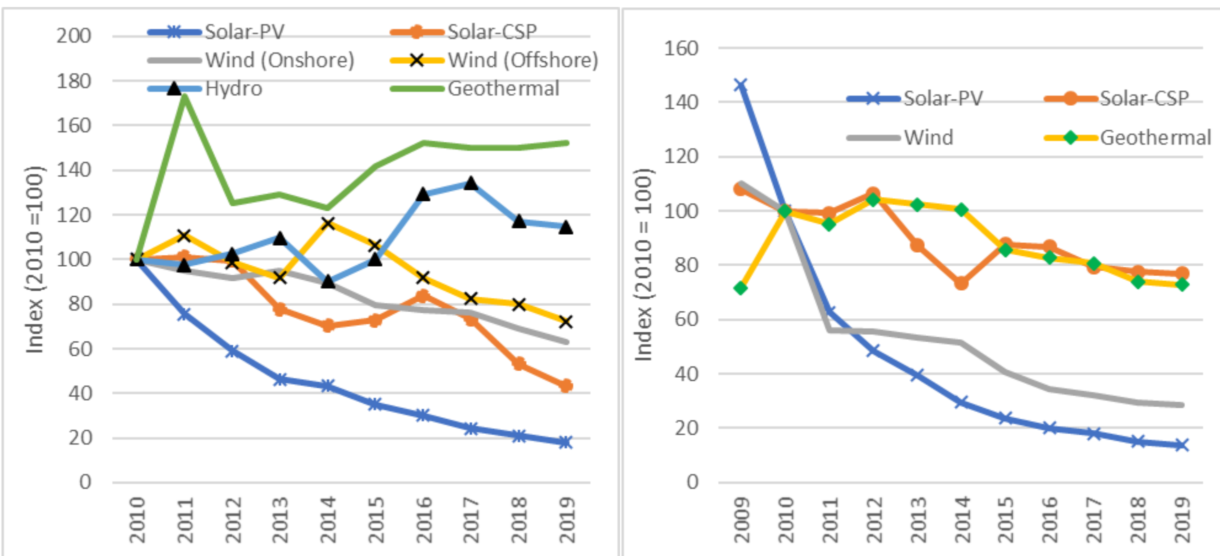
How do the costs of electricity generation technologies evolve over time? Costs of renewable energy technologies are rapidly declining; what about electricity generation costs with fossil fuel-based technologies and nuclear technology? In this section, we try to answer these questions.

5.1 Trends for renewable electricity costs

Figures 10(a) and (b) present the trends of LCOEs of renewable energy technologies. Since the estimates of LCOEs vary across estimations presented in various studies, we present the trends based on three studies, IEA (2015), IRENA (2020), and Lazard (2019). The trends are presented through indices, where values in 2010 are assigned to be 100.

Figure 10. Trends of renewable electricity costs (LCOE, US$/kWh)

(a) IRENA (2020) **(b) Lazard (2019)**



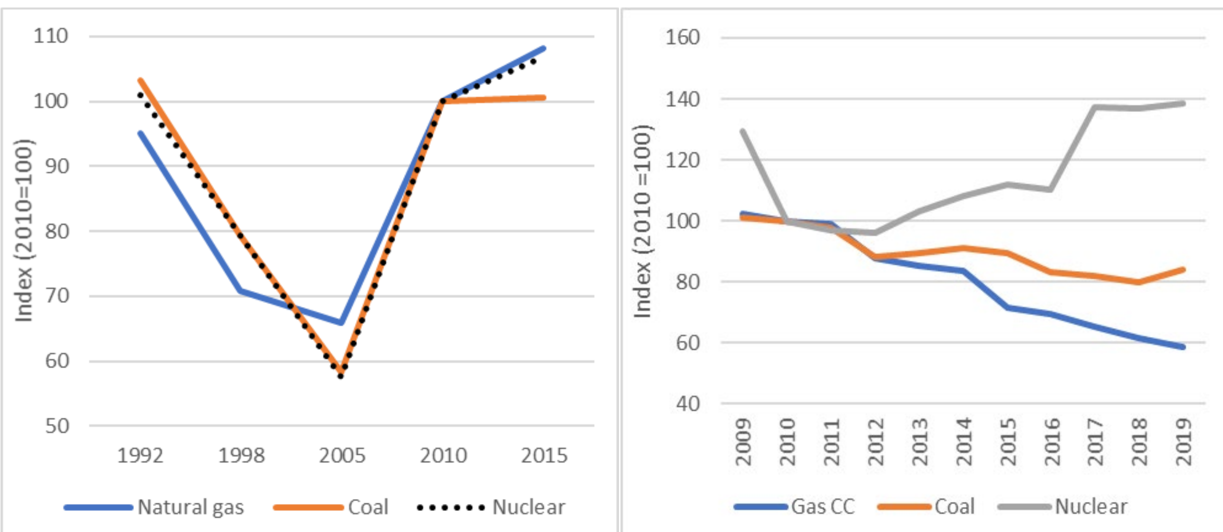
According to Lazard (2019), the prices of solar PV, wind and solar CSP in the United States have dropped by, respectively, 11, 4, and 1.5 folds during the last decade (2009-2019). IRENA (2020) shows that the global average prices of solar PV, wind, and solar CSP have dropped by 4.2, 1.5, and 2.3 folds respectively during the same period. The difference between these studies is governed by many factors, such as differences in input data (e.g., capital costs and O&M costs) and underlying assumptions (e.g., economic life, capacity factors). The most important factor is that Lazard costs are only for the United States, whereas IRENA costs are global averages weighted by installed capacities. Different countries have experienced different declining slopes for their LCOE curves.

5.2 Trends for fossil fuel-based electricity generation costs

Figures 11(a) and 11(b) illustrate changes in LCOEs of fossil fuel-based and nuclear technologies. While Lazard (2019) shows declining LCOEs for gas and coal in the United States, IEA (2015) reports sharp increases in LCOEs of fossil fuel-based technologies during the 2005-2015 period. If we consider a longer time frame, since the early 1990s, the LCOE curve is almost flat. One needs to be careful while presenting the LCOEs of fossil fuel-based power generation technologies because fuel cost is a major component of LCOEs in fossil fuel-based generations; fuel prices have moved up and down depending on demand. Since Lazard (2019) provides LCOEs for US plants only, and fuel prices, especially natural gas prices, are declining, LCOE trends are also declining. On the other hand, IEA (2015) provides an average LCOE of many countries around the world. Global coal and LNG prices have been facing irregular trends.

Figure 11. Trends of renewable electricity costs (LCOE, US$/kWh)

(a) IEA (2015) **(b) Lazard (2019)**



6. Conclusions

The levelized cost of electricity generation or LCOE is the most commonly used indicator to compare electricity generation costs of various technologies. It is often used for comparing renewable energy technologies with their fossil fuel counterparts in terms of their electricity production costs. If the LCOEs of renewables are seen to be lower than those of fossil fuels, that might signal an opportunity to private investors; if they are higher than the conventional sources, they could provide a basis for policy makers to design financial incentives (e.g., various types of subsidies) to renewables.

Several studies find some renewables, particularly utility-scale solar PV and onshore wind, as the cheapest sources of electricity in terms of their LCOEs. However, there does not exist a consensus in the literature on these findings because input data for a given technology widely vary. Our study calculates more than 4,000 values of LCOE for 11 technologies (seven renewable technologies and three fossil fuel technologies and one nuclear technology), varying all seven input variables (i.e., capital costs, operation and maintenance costs, fuel costs, heat rate, discount rate, capacity availability factor, and economic life).

Some renewable energy technologies, particularly solar energy technologies, have experienced a rapid decline in electricity generation costs. For example, the global average costs of electricity supply from utility-scale solar PV and onshore wind have dropped, respectively, by 4.2 and 1.5 folds over the last decade. Such a large drop in costs has seen entry by utility-scale solar PV and onshore wind to compete with fossil fuel-based power generation technologies. Our study shows that for the lower range of capital costs, the LCOEs of renewable energy technologies, except concentrated solar power and offshore wind, are lower than those of fossil fuel-based technologies. Since the capital costs of biomass-based technology vary widely depending upon the feedstock type, the cost competitiveness of biomass with fossil fuels and nuclear depends on the type of feedstock.

In many parts of the world (e.g., the Middle East and North Africa, northern Chile, Brazil), with high-quality solar resources, electric utilities are offered very low prices for solar power through auctioning. However, our study could not establish values of LCOEs for renewables that could match auction prices below $20/MWh, using reasonable values for input variables. More is at work here than cost differences, especially given the shortcomings of LCOE for intermittent resources. One obvious candidate for further research is the presence of explicit or implicit subsidies of various types.

Our study illustrates how much values of input variables, particularly capital costs, vary for a given technology, by pulling together data from many sources. It also presents the effects of various factors (i.e., input variables) on the LCOEs of all the technologies considered in the study. Since capital cost is the main component of the LCOE in renewable technologies, LCOE is sensitive to this variable. The capacity cost elasticities of LCOE of renewables sources are found to vary between 0.7 to 1.0 if the capital costs are not tied with other input variables, such as capacity factors. Renewables are also sensitive to the capacity utilization factors and economic lives of the technologies. This is also true for nuclear technology. On the other hand, fossil fuel-based technologies are sensitive to fuel prices. The fuel price elasticities of LCOEs are found to be 0.3, 0.6, and 0.7 for coal, gas, turbine, and combined cycle technologies, respectively.

Although LCOEs for renewables are competitive with LCOEs for fossil fuels, electric utilities discount this seeming cost-competitiveness because LCOE is not an accurate measure of actual cost-competitiveness. The LCOE serves as an indicator to compare the costs of electricity production between individual technologies. In practice, however, it does not address the costs of managing intermittency. Moreover, electricity generation technologies are mixed or stacked to meet the demand at a given point in time. From an electricity system perspective, the cost-competitiveness of electricity generation technologies can be determined based on their impact on the electricity system cost, which is reflected in electricity prices in the competitive market. Electricity planning models, such as used by Timilsina and Toman (2016) and Timilsina and Curiel (2020), are better suited to estimate the electricity system costs. EIA (2020) suggests using levelized avoided cost of electricity (LACE) instead of LCOE.

Because of their intermittency, higher penetration of solar or wind would mean the need for higher installed capacity compared to the peak load on a grid so that enough 'ready to run' capacity is present in the system when renewables electricity plants cannot run. World Bank (2015b) also points out that integrating the variable renewable energy resources (e.g., wind and solar) into a grid increases the system cost of the grid to supply electricity. Inter-connections of the grid to other grids, on the other hand, help reduce the scale of the intermittency problem.

Renewables provide environmental, health, and climate change benefits. If these benefits are accounted for – in particular, if fossil fuel based power outputs are taxed based on environmental externalities – the economics of renewables would improve. Moreover, the modular and distributed nature of some renewable energy technologies, particularly solar and micro-hydro, has great value for providing access to electricity in more remote and rural areas around the world. These are important issues to consider in extending this study.

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