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Levelized Cost of Energy Supply for Substantiating the Proliferation of Variable Generating Units in Puerto Rico

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SUMMARY

The Levelized Cost of Energy (LCOE) is signified as an economic indicator to compare electricity supply alternatives based on investment, operation, and maintenance costs of generating units over an assumed financial life and duty cycle. In recent years, renewable power generation has become a more attractive and cost-competitive alternative for power generation. In this paper, we present a detailed LCOE formulation and provide an analysis of LCOE differences for conventional fossil fuel-based and renewable-based power generation units while considering the prevailing uncertainties in the operation and planning of such units.

KEYWORDS

Levelized cost of energy, renewable power generation, battery storage system, power system planning and operation, uncertainty.

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1. INTRODUCTION

Renewable energy technologies (e.g., wind and solar) continue to foster a cost-competitive alternative to large-scale power generation, despite lower natural gas prices, by acting as a serious contender for energy independence in the international arena, delivering a potential solution for aging electricity infrastructure, and presenting a clean energy option for defeating global warming.

Fig. 1 depicts the projection for the deployment and the retirement of various types of generating units in the United States. The figure is a clear manifestation of a significant shift from thermal-based generation (in particular coal) to renewable-based power supply in forthcoming years [1]. Fig. 2 demonstrates that the proliferation of variable energy technologies has intensified the need for the installation and the utilization of battery energy storage systems (BESSs) which can firm up the variability of renewable energy and fulfill the need for a variety of ancillary services in power distribution systems, like frequency regulation and reliability requirements, capacity investment deferrals, and reduction in demand charges [1]. The increased availability of lower-cost BESS will likely facilitate the deployment of additional renewable-based energy technologies like solar and wind units in various parts of the world.

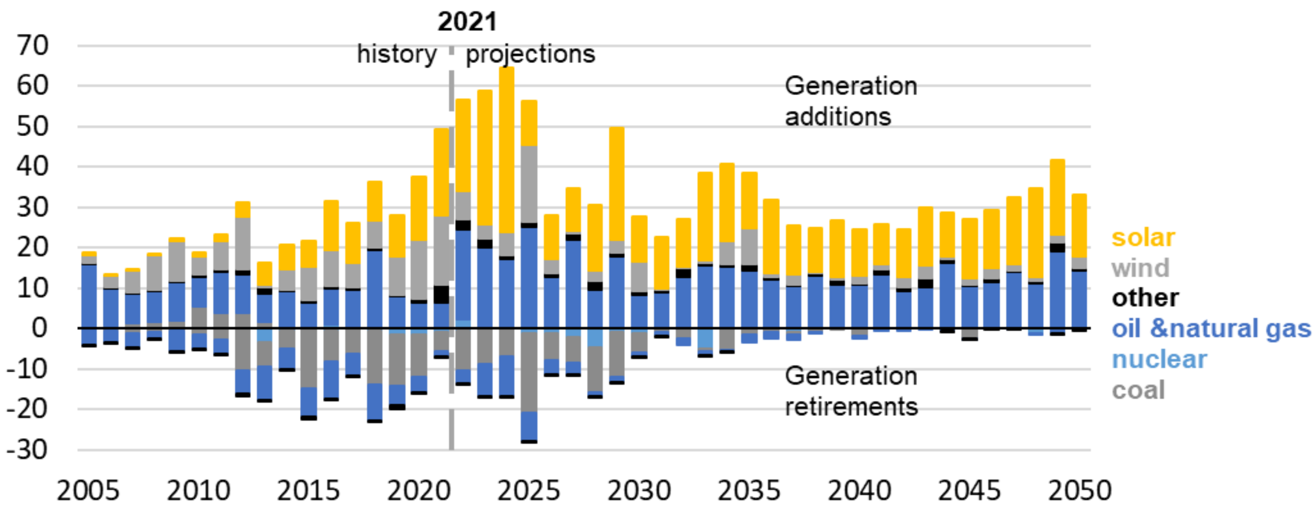


Fig. 1. Annual electricity generating capacity additions and retirements [1].

It is also envisioned that large-scale investment projects for the installation and the utilization of more conventional generation alternatives (e.g., nuclear-based generating units) and unconventional generating units (e.g., solar thermal, geothermal, wave energy, biofuels, etc.) continue to face a number of techno-economic challenges, including significant cost contingencies, permitting and regulatory issues which often culminate in higher installation costs, operating difficulties considering the necessary coordination with smaller and cheaper behind-the-meter energy supply options, and significant concerns with uncertainties in regulatory issues [2].

In this era of international energy conflicts, public outcry for maintaining a cleaner environment, and cyber and physical threats to the reliable operation of large energy infrastructures, power system analysts in the global arena would be looking for a viable indicator which can substantiate the use of energy options that would offer specific characteristics for confronting local energy challenges.

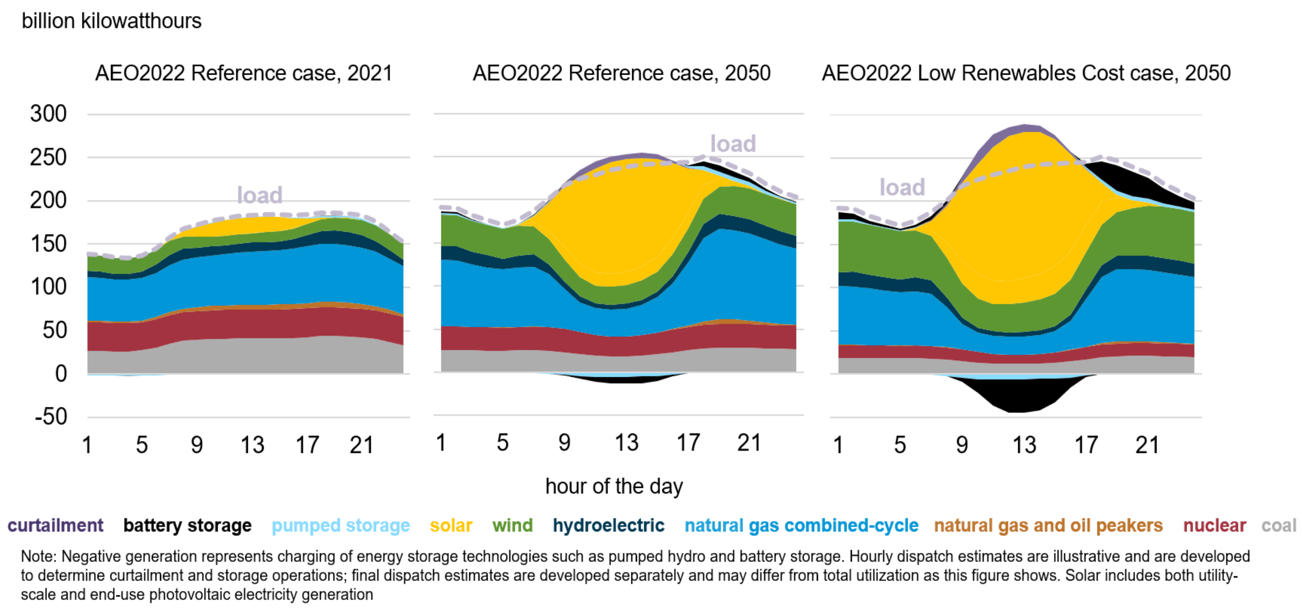


Fig. 2. Hourly U.S. electricity generation and load by fuel for selected cases and representative years [1].

The technoeconomic assessments in such cases have exhibited that the levelized cost of energy (LCOE) is a practical indicator which can manifest the economic merits of energy alternatives.

LCOE is a useful metric as it enables comparisons among different energy installation projects and energy supply sources to determine the most cost-competitive alternative. LCOE is the per unit cost of supplied electricity, which includes those incurred for the installation and the operation of a generating unit during an assumed financial life and duty cycle. LCOE is the ratio of all discounted costs over the lifetime of an electricity generating unit divided by a discounted sum of the actual amounts of delivered energy [3]. LCOE indicates whether the installation of renewable energy units plus BESS, considering their upfront investment costs, will be more economical than paying the electricity bill for that supplied by thermal energy units during the lifetime of the renewable energy plus BESS option.
LCOE is numerically stated as [4]:

$$\text{LCOE} = \frac{\left(\text{Levelized investment cost} + \text{Total O\&M cost} + \text{Production cost}\right)}{\left(\text{Net annual energy production}\right)} \tag{1}$$

The LCOE calculation allows project developers and financiers to make apple-to-apple comparisons among energy generation technologies such as solar, wind, nuclear, gas, and coal, taking into account different project lifespans, capital costs, fuel costs, capacity size, and risk. However, LCOE does not take into account potential social and environmental externalities (e.g., social costs of distributed generation, environmental consequences of conventional thermal generation applications, etc.) or reliability and intermittency considerations (e.g., costs of transmission system and backup generation associated with certain renewable energy technologies) [5].

2. LCOE CALCULATION METHOD

Determining the LCOE for a given generation technology requires the calculation of the levelized annual owning cost (LC) which is nothing more than the numerator of the expression presented in (1). Thus, *LC* includes the levelized values of the investment cost, production (fuel) cost, and operation and maintenance (O&M) cost. *LC* accounts for the treatment of inflation in power system planning.

2.1 Levelizing factors

The levelizing process converts a yearly escalating cost into a single, constant, present-worth equivalent value, as illustrated in Fig. 3. Here, two principal factors are considered. The levelizing factor (*LF*) is the per-unit multiplier that translates the escalating fuel cost to the levelized value. According to the uniform *LF* concept, we can show that *LF* is given as presented in (2).

$$LF = \frac{\left[1-\left(\frac{1+a}{1+i}\right)^n\right]}{i-a} * \frac{i*(1+i)^n}{(1+i)^n-1} \tag{2}$$

For example, *LF* is 10% if the fuel cost begins at $2.0/MBtu and is escalated at 5% per year with a 10% interest rate. Accordingly, the uniform *LF* for a 20-year period is equal to 1.423. The *LF* of 1.423 is the per-unit multiplier that translates the escalating fuel cost to the levelized value. The levelized fuel cost is stated as $fuel\cos t * LF$ which is equal to 2.845. The levelized fuel cost of 2.845 is the present-worth average of escalating fuel costs (considering the inflation and interest rate) over the 20-year period. In essence, the actual fuel cost will be $5.31/MBtu at the end of year 20.

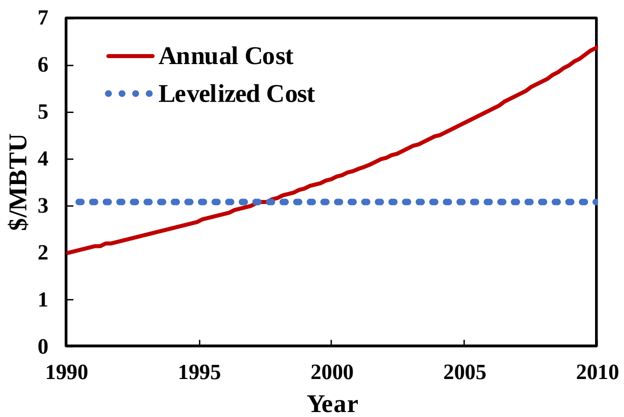


Fig. 3. Levelizing cost of supply planning.

The levelized fixed-charge rate (LFCR) would levelize the investment cost. The LFCR concept, which is similar to that of LF, provides a uniform annual investment payment over the 20-year life of the given unit. However, LFCR also includes depreciation, return on investment, and taxes. LFCR, which has an intrinsic relation with a generating unit design, operation, and maintenance, is typically between 15% and 25% per year for a given unit. LFCR multiplied by the initial capital cost will provide the levelized investment cost of the generating unit.

2.2. Annual levelized owning cost

The annual levelized owning cost of a generating unit, *LC*, generally in $/year, includes both the levelized investment cost (LIC) and the levelized operation cost (LOC) as stated in (3).

$$LC = LIC + LOC \tag{3}$$

The annual levelized investment cost (LIC) is expressed in (4) where CAP is the generating unit capacity in kW, C^{inv} the capital cost for the generating unit in $/kW, and $LFCR$ is the levelized fixed-charge rate.

$$LIC = C^{inv} * CAP * LFCR \tag{4}$$

The annual levelized operation cost (LOC) consists of three terms as presented in (5). The first term OC^{fuel} represents the annual levelized production cost, the second term OC^{fix} represents the annual levelized value for fixed O&M cost and the last term OC^{var} represents the annual levelized value for variable O&M cost. The formulation for each term of LC is provided in (6)-(8) . In (6), N_h represents the number of hours in a year, CF stands for the capacity factor of the generating unit, AHR stands for the average heat rate of the generation technology in Btu/kWh, and C^{fuel} represents the fuel cost in $/MBtu. In (7) , C^{fix} represents the fixed O&M cost in $/kW per year. In (8), C^{var} represents the variable O&M cost in $/MWh per year.

$$LOC = OC^{fuel} + OC^{fix} + OC^{\mathrm{var}} \tag{5}$$

$$OC^{fuel} = CAP * N_h * CF * AHR * C^{fuel} * LF \tag{6}$$

$$OC^{fix} = CAP * C^{fix} * LF \tag{7}$$

$$OC^{\mathrm{var}} = CAP * N_h * C^{\mathrm{var}} * CF * LF \tag{8}$$

The LCOE for a given generating unit is obtained by dividing the LC by the annual generation (AG) in MWh. The formulation for AG is given by (9).

$$AG = CAP * N_h * CF \tag{9}$$

3. LCOE FOR NON-RENEWABLE GENERATION UNITS

Table I provides the data for three 500MW generation unit technologies (i.e., coal-fired generating unit, combined-cycle natural gas unit, and single-cycle gas turbine unit). One main observation is that the gas-turbine units have higher fuel costs and lower investment costs than the coal-fired steam unit. The objective is to determine the LC in $/year, based on a 20-year life cycle evaluation for the three alternatives. We assume the annual interest rate i is 10% and the annual inflation rate a is 6%. The detailed *LC* calculation results are provided in Table II, where the coal-fired generating unit is the least expensive.

Also, Fig. 4 illustrates the actual yearly costs over the first 20 years of operation. Note that the coal unit, which has the least cumulative present-worth cost (levelized owning cost), does not have the lowest cost in the first year. The higher cost of the coal unit is composed of high investment cost, which does not escalate with time, and the relatively low fuel and O&M costs. Consequently, a capital-intensive alternative such as the coal unit will have a yearly cost that does not escalate rapidly with annual fuel and O&M cost escalations. A single-cycle gas-turbine unit is, on the other hand, a low-capital but high-fuel cost-intensive alternative, which has a yearly cost that is strongly influenced by the annual fuel and O&M cost escalation. This is further substantiated with the LCOE where the coal-fired generating unit has the least expensive LCOE of 9.959 cents/kWh. The proposed example assumed that each type of power generation technology would operate at a certain capacity factor stated in Table I. If each unit were to be operated at a different (e.g., 65% capacity factor), we would repeat the above calculation process by noting that fuel and variable O&M costs are linearly proportional to the capacity factor. Thus, the previous levelized coal cost would be multiplied by 65% over 78% times the annual levelized production cost. The remaining fixed O&M and investment costs do not depend on operating hours and would not be recomputed for the 65% capacity factor case.

TABLE I
GENERATING UNIT DATA

Generation Unit	**Coal-fired unit**	**Combined-cycle gas turbine**	**Single-cycle gas turbine**
Average Heat Rate (Btu/kWh)	10,450	9,350	12,100
Fuel Cost ($/MBtu)	2.2	5.5	6.7
Plant Capital Cost ($/kW)	1,650	770	385
Fixed O&M Cost ($/kW per year)	22	10	1.2
Variable O&M Cost ($/MWh)	5.6	3.5	5.3
LFCR (% per year)	21	19	22
Capacity Factor (%)	78	74	60

TABLE II
ANNUAL LEVELIZED OWNING COST CALCULATION DETAILS AND LCOE

Annual levelized cos ($M/year)	**Coal-fired unit**	**Combined-cycle gas turbine**	**Single-cycle gas turbine**
IC ($M/year)	173.25	73.15	42.35
OC^{fuel} ($M/year)	120.69	256.12	327.377
OC^{fix} ($M/year)	16.903	7.683	0.922
OC^{var} ($M/year)	29.398	17.432	21.402
OC ($M/year)	46.301	25.115	22.324
LC ($M/year)	340.241	354.384	392.051
LCOE (cents/kWh)	**9.959**	**10.934**	**14.918**

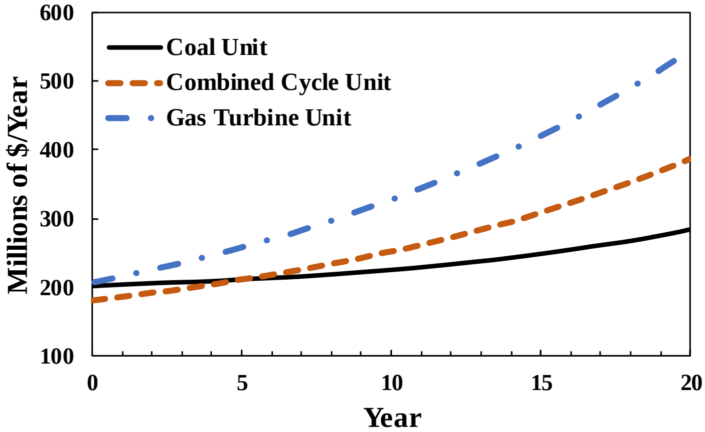


Fig. 4. Annual owning cost.

4. LCOE FOR RENEWABLE GENERATION UNITS

We calculate the LCOE for a renewable generation unit (i.e., wind turbine (WT) farm which is coupled with BESS). Table III presents the WT and BESS parameters. The production (fuel) cost of WT is zero. The annual levelized owning cost *LC* of the renewable generation unit is the sum of the annual owning cost of WT and BESS. Therefore, based on Table IV results, the *LC* for the renewable generation unit is $99.52M/year. Subsequently, with a net annual WT energy production of $1.12*10^9$ kWh, the LCOE for the renewable generation unit is 0.089 $/kWh (i.e., 8.9 cents/kWh).

TABLE III
WT AND BESS PARAMETERS

Parameters	WT	BESS
MW size	400	50
Capitalized Plant Cost ($/kW)	800	300
Construction Lead Time (years)	0.5	1
Equivalent Forced Outage Rate (%)	5	0.1
Equivalent Scheduled Outage Rate (%)	15	3
Fixed O&M cost ($/kW/year)	10	6
Variable O&M cost ($/MWh)	15	0.3
Capacity Factor (%)	32	32

TABLE IV
ANNUAL LEVELIZED OWNING COST CALCULATION DETAILS

Annual levelized value	WT	BESS
LIC ($M/year)	64	3
OC^{fix} ($M/year)	6.15	0.46
OC^{var} ($M/year)	25.85	0.06
LOC ($M/year)	32	0.52
LC ($M/year)	**96**	**3.52**
LCOE (cents/kWh)	8.9	

5. DISCUSSION ON GENERATION UNIT PARAMETERS WHICH COULD AFFECT LCOE CALCULATIONS

5.1 Impact of the capacity factor on Wind turbine and gas turbine investments

Fig. 5 depicts the LCOE of WT and gas turbine (GT) versus capacity factor. Also, Fig. 6(a) and (b) depict separately the two respective LCOE components for the same system. Here, WT is equipped with BESS. In Fig. 5, the crossing point of the two LCOEs is at the 18% capacity factor. Accordingly, with the additional penetration of WT (corresponding to a higher capacity factor), the system will face more uncertainty. Here, we could use the more expensive GTs to firm the renewable energy deployment.

In Fig. 6(b), the annual O&M cost (including production cost) per energy production of WT is significantly reduced with higher capacity factors. That is because the energy production is increased with the higher increment of capacity factor while the corresponding O&M cost is almost fixed due to the zero-fuel consumption of WT. Comparatively, the annual O&M cost per energy production of GT is slightly reduced due to the increased fuel consumption with the higher increment of capacity factor.

In Figs 5 and 6(b), when the capacity factor is between 16% and 18%, the annual O&M cost per energy production of WT is lower than that of GT, while the LCOE of WT is higher than that of GT. That is because the annual levelized investment cost per energy production of WT, depicted in Fig. 6(a), is always higher than that of GT.

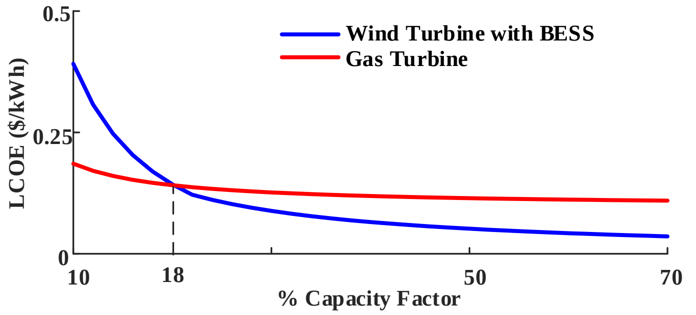
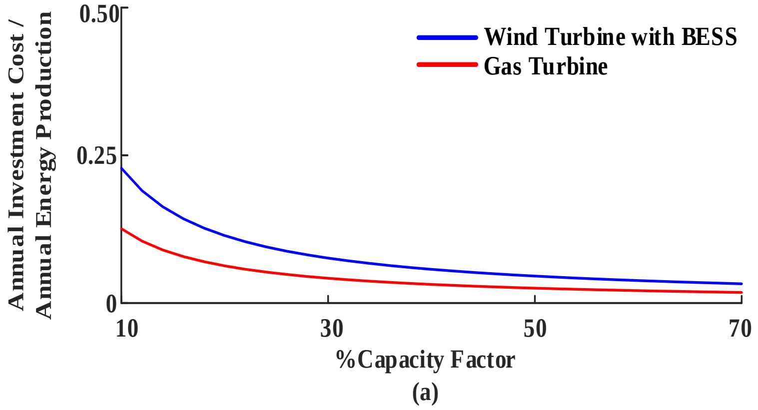


Fig. 5. LCOE of WT and GT as a function of capacity factor.



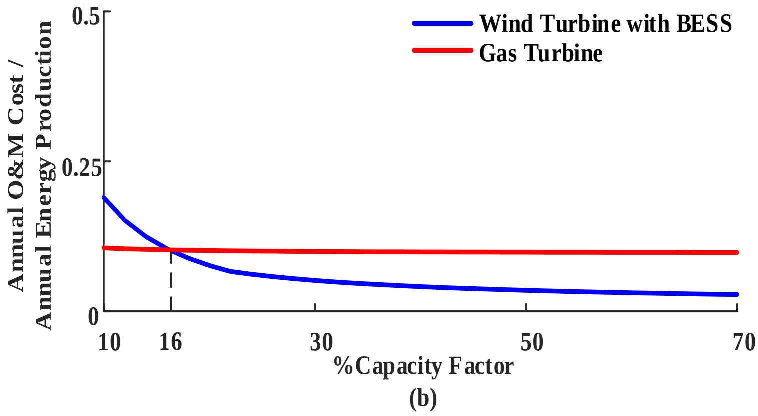
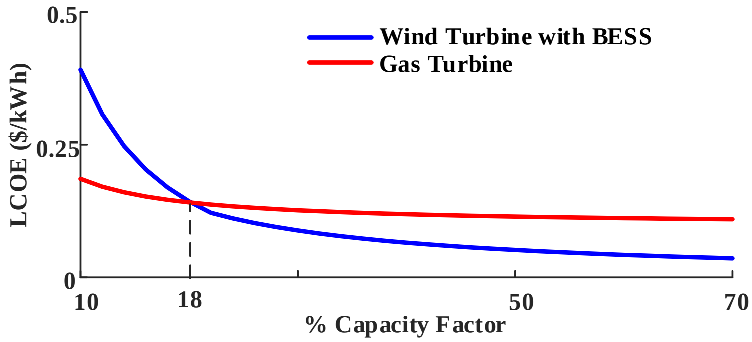


Fig. 6. Comparison of WT with GT: (a) Annual investment cost (b) Annual O&M cost.

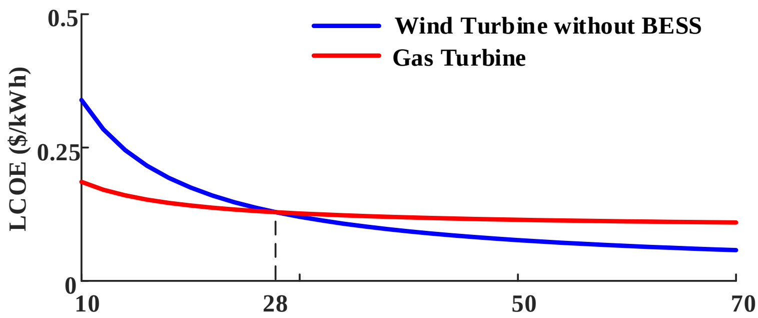
5.2 LCOE of wind turbine with and without BESS

Considering the distribution grid congestion, WT without BESS would have a lower capacity factor than WT with BESS, though the two WTs would have the same capacities. Fig. 7 depicts the comparison between the two LCOEs. In Fig. 7(a), although the WT with BESS has a higher investment cost, its LCOE decreases significantly with the higher increment of capacity factor. When the capacity factors of WT and GT are above 18%, the WT with BESS would have a lower LCOE compared to that of GT.

Comparatively, the WT without BESS presented in Fig. 7(b) has a lower investment cost as compared to that with BESS, while the descending speed of the LCOE with the higher increment of capacity factor is much slower than the case with BESS, which implies that the energy production of WT without BESS is not fully utilized due to the grid congestion. The LCOE of WT without BESS is higher than the LCOE of GT when the capacity factor exceeds 28%.



(a)



(b)

Fig. 7. Comparison of LCOEs of WT versus GT: (a) WT with BESS (b) WT without BESS.

In Fig. 8, the LCOE of WTs with and without BESS are compared to analyze the economic merits of the BESS installment. Here, BESS investment and O&M costs are considered in WT with BESS. When the capacity factor is below 13%, the LCOE of WT with BESS is higher than that of WT without BESS. Thus, BESS installation will lead to a higher LCOE, which implies that the BESS should not be installed. Comparatively, when the capacity factor is above 13%, the LCOE of WT with BESS is lower, which would reduce the LCOE and implies that the BESS should be installed.

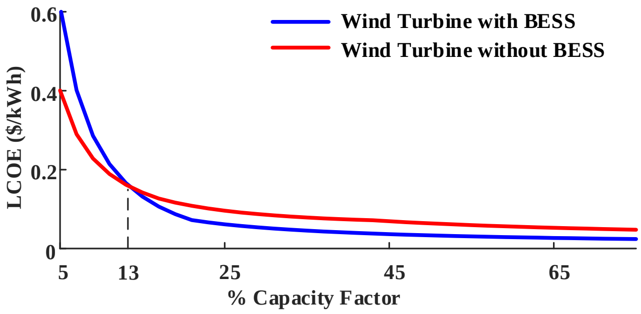


Fig. 8. LCOE comparison for a wind turbine with and without BESS.

In Fig. 9, the LCOE of WT with BESS is depicted. The optimal LCOE occurs when the installed BESS is around 100 MW indicating the break-even economic energy price, where the revenue meets the investment. In other words, if you cannot sell energy at that LCOE level, your BESS investment will not be economically justified. This case helps compare alternatives for grid enhancement.

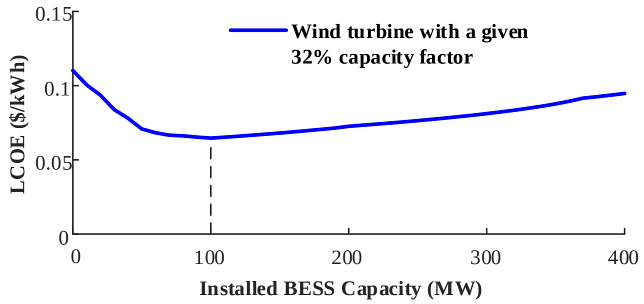


Fig. 9. LCOE of BESS capacity for WT.

5.3 Uncertainty of capacity factors

Fig. 10 shows the lower and upper bounds of LCOE for WT with BESS by considering the capacity factor uncertainty. Fig. 11 shows the lower and upper bounds of LCOE for the GT by considering the uncertainty of capacity factor. Here, the actual capacity factor falls within [a-4, a+4] in a normal distribution corresponding to the value ‘a’ on the x-axis. Different probability distributions are assigned to different capacity ranges. Specifically, the discrete probability distribution for capacity factor within [10, 30] is assumed as (0.10, 0.10, 0.60, 0.10, 0.10). For instance, corresponding to the capacity value 20 on the x-axis, the probabilities of the actual capacity factor fall in 16, 18, 20, 22, and 24 are 0.10, 0.10, 0.60, 0.10, and 0.10, respectively. The discrete probability distribution for capacity factor within [30, 50] is assumed as (0.15, 0.15, 0.4, 0.15, 0.15). The discrete probability distribution for capacity factor within [50, 70] is assumed as (0.10, 0.25, 0.30, 0.25, 0.10).

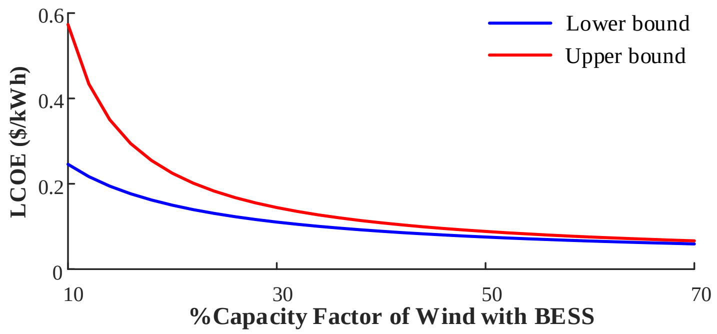


Fig. 10. LCOE of WT with BESS considering the capacity factor uncertainty.

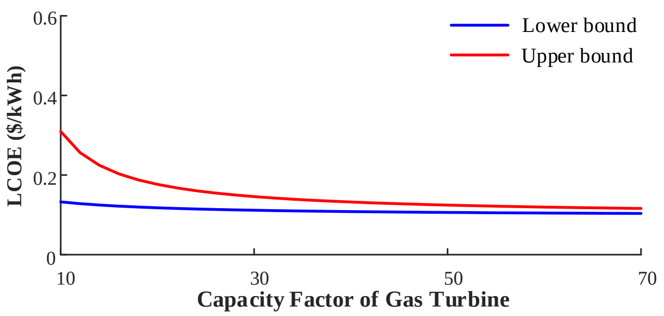


Fig. 11. LCOE of GT considering the capacity factor uncertainty.

Thus, Fig. 12 shows the weighted LCOE for considering capacity factor uncertainty, and that without considering capacity factor uncertainty is also presented for comparison. As discussed before, both the weighted LCOE and the original LCOE decrease with the increasing capacity factors. In addition, since the LCOE versus capacity is a convex function, the weighted LCOE is always slightly higher than the original LCOE, i.e., without considering the capacity factor uncertainty.

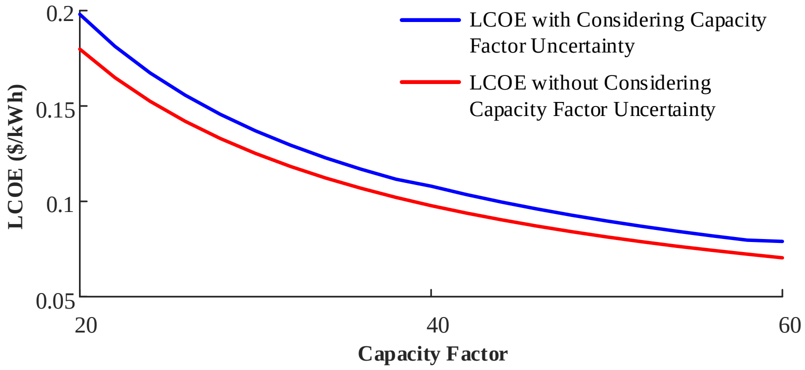


Fig. 12. LCOE with and without the inclusion of capacity factor uncertainty.

6. Conclusions

The cost of energy supplied by traditional fossil fuel generating units depends largely on international market prices for gas, coal, or nuclear fuel, as well as the O&M costs of respective units. Renewable energy installations, on the other hand, can be installed more expeditiously, tend to have lower O&M costs, and do not largely bear any fuel costs. As sunlight and wind are free sources of energy, the renewable energy cost depends mostly on the cost of technology. Furthermore, improved inverter reliability, remote monitoring technologies, and prevailing innovations in solar PV panel cleaning have continued to reduce O&M costs of renewable energy production in recent years. In such environments, gas and coal-fired power generation units would need to sell their respective electricity productions at higher prices than those of solar and wind units to remain profitable in a competitive energy market. Meanwhile there is a growing and concerted international effort to eliminate greenhouse gas emission and promote the use of cleaner options for generating electricity.

The more recent proliferation of renewable energy units, as confirmed by Fig. 1, has indicated that such generating units would no longer require previously designated large subsidies to offset their respective generation costs. By reaching grid parity in many regions, renewable energy units can compete directly with conventional thermal generating units without requiring financial or regulatory support.

The international energy-related conflicts in various parts of the world and the demonstrated public outcry for a cleaner environment have driven up oil and gas prices and made renewable energy even more attractive from an LCOE perspective. The LCOE of oil and gas plants has risen, while the LCOE of renewable energy has been lowered. Higher electricity prices based on thermal units could culminate in higher profits for renewable generators.

In practice, LCOE is considered a significant economic indicator for the comparison of energy supply alternatives. However, there are potential limitations for the implementation of LCOE in electric power system planning. A critical limitation is that the related analyses might not adequately consider the indirect costs of power generation pertaining to the social cost of greenhouse gas emission and other environmental externalities such as air pollution and grid upgrade requirements. The limitations could also be extended to the lack of indicators for the growing cyber and physical threats with a devastating impact on power system security [6].

The LCOE for a large generator has traditionally been viewed as being inversely proportional to the generator size. In essence, larger generating units tend to be more efficient and possess a lower LCOE than those of smaller generating units [7]. Therefore, making investment decisions based on insufficiently comprehensive LCOE can lead to a bias towards larger generation installations while overlooking opportunities for energy efficiency and conservation unless such costs and effects are precisely calculated and included for comparison alongside LCOE numbers for other options such as generator size and infrastructure [8]. If such concerns are overlooked or included haphazardly, LCOE might not provide a comprehensive picture of potential options available for meeting energy needs in the foreseeable future [9].

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