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RESEARCH ARTICLE

Evaluating net benefits of electricity generating technologies

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Abstract: Typically, the Levelized Cost of Electricity (LCOE) has been used to compare different electricity generation technologies. As LCOE does not account for intermittency and reliability, the updated net benefits methodology has been used. For various electricity generation technologies, with the use of the updated net benefits methodology, the net benefits of avoided emissions benefits, avoided energy cost benefits, avoided capacity cost benefits, energy costs, capacity costs and other costs at a per MW per year basis have been calculated. The results showed that nuclear generation had the highest net benefits in all of the scenarios considered. The net benefits of solar and wind generation increase when high coal and natural gas fuel price and with technological improvement which would increase the capacity factor and decrease the capital costs. Renewable and nuclear generation sources should play a significant role in the future electricity generation mix.

Keywords: energy policy, solar, wind, nuclear

1 Introduction

Climate change is a significant global challenge and the electricity sector is a major contributor to climate change. Low GHG emitting electricity generation technologies will be an important part of future electricity generation mixes. However, the current energy mix does not contain a large share of lower GHG emitting electricity generation. Coal and natural gas generation comprise over 60% of the electricity generation mix in the US [1] . Both, coal and natural gas electricity generation are CO_2 intensive and coal generation previously had the largest generation share. In 2018, coal electricity generation produced 1150 million metric tons of CO_2, while natural gas electricity generation produced 581 million metric tons of CO_2 [1] . The US electricity generation mix over time can be seen in Figure 1.

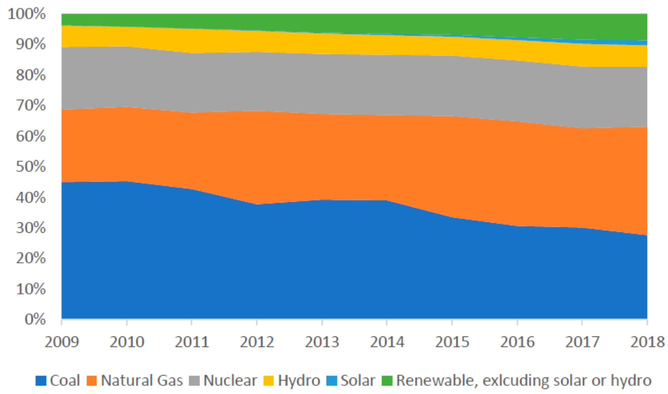

Figure 1 US electricity generation mix over time [1]

The largest generation source had shifted away from coal to natural gas. A combination of regulations and cheaper natural gas has led to coal plant retirements and a reduction in the share of coal electricity generation [2] . The share of nuclear and hydro have stayed relatively constant. The solar and renewable that excludes solar and hydro have increased over time. Different electricity generation technologies have different costs and benefits. There are also different methods to compare electricity generation technologies.

The shift away from coal generation has had emissions reduction benefits as other generation technologies displace coal in the generation mix which are less CO_2 intensive. The total electricity sector CO_2 emissions decreased from 2158 million metric tons of CO_2 in 2009 to 1746 million metric tons of CO_2 [1] . There are other benefits from the shift away from coal generation. There are avoided fuel and energy costs as well as avoided capacity costs associated with the shift away from coal generation. There are also costs associated with other electricity generation technologies that displace coal generation including capacity costs and energy costs. To compare electricity generation sources, the net benefits of electricity generation sources should be examined.

Typically, the Levelized Cost of Electricity (LCOE) has been used to compare different electricity generation technologies. LCOE examines building and operational costs of a generation technology [3] . There has been a rapid decrease the LCOE of solar and wind generation. Technological advancement has helped decrease in LCOE. Solar PV module cost decreased to $1 per watt in 2019 from approximately $4 per watt in 1992 [4] . Figure 2 shows the average LCOE of solar and wind are recently lower than non-interruptible sources such as coal, nuclear and combined cycle natural gas. However, wind and solar generation are intermittent sources of electricity.

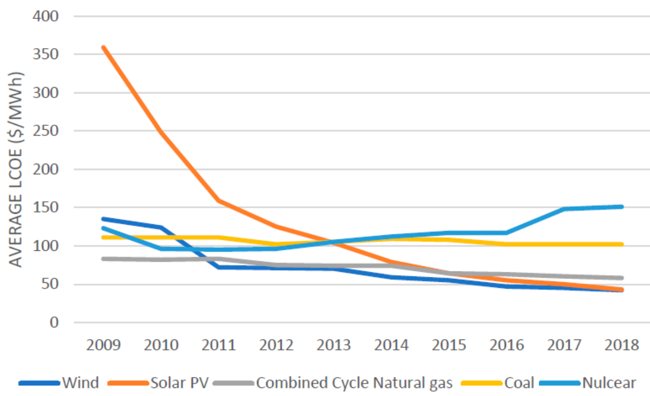

Figure 2 LCOE over time [5]

Generation sources such as coal, nuclear and natural gas are not intermittent sources of electricity. To account for intermittency, alternative methodologies should be considered to compare intermittent and non-intermittent electricity generation sources. As such, comparing net benefits will be used to rank different electricity generation technologies. The research question will address which electricity generation technology had the highest net benefits.

Most common method for comparing technology costs for power generation is LCOE per Megawatt-Hour (MWh). However, there are issues with using the LCOE as a metric to compare different generation technologies. The main issue is that LCOE does not consider the intermittency and reliability of different electricity generation technologies [6] . Joskow PL [6] incorporates the expected market value to compare different generation sources based on the ability to supply, life time costs and profitability of the different generation technologies. This method better accounts for intermittency and leads to the ability to rank generation technologies with and without intermittency.

Frank CR [7] defined benefits to consider avoided emissions costs, avoided capacity costs and avoided energy costs to evaluate different generation technologies. Costs were energy cost, capacity costs and other costs. This methodology would be able better incorporate market value along with emissions costs, capacity costs and energy cost. Using the net benefits approach, Frank CR [7] concludes that natural gas combined cycle (CC), nuclear, hydro have higher net benefits than wind or solar. Over time, certain assumption used will have changed. The average capacity factors for wind and solar generation having been increasing over time. The capital expenditure (Capex) costs of wind and solar generation have been decreasing over time. As such, the data should be updated for fuel cost, capacity factor, and capital cost for each generation technology.

There are improvements that have been made to the net benefits methodology in this study. Avoided emission should consider more than avoided CO_2 emissions. This study also considers avoided NO_x and SO_2 emissions. The capital expenditure cost should include interconnection costs. The updates to the methodology are thoroughly discussed in the methodology section.

2 Material and methods

The different electricity generation technologies were ranked using the net benefits per MW per year criteria. The benefits included: avoided emissions, avoided energy costs and avoided capacity costs. The costs included: energy cost, capacity costs and other costs.

The avoided emissions comparison is done relative to the original scenario technology based on Frank CR [7] . Coal generation is used for off peak and natural gas generation on peak. Avoided emissions are calculated to the product of the heat rate the number of the hours of the year and the change in the emission for the different generation types from displacing coal and generating electricity using the mentioned electricity source. Avoided energy cost is the sum of costs associated with generating electricity from the different generation types which includes the fuel costs and the Variable O&M per MWh from displacing coal and generating electricity using the mentioned electricity source. The avoided capacity costs are costs associated with the construction of the plant for electricity generation which include the Capex costs and Variable O&M per MWh from displacing coal and generating electricity using the mentioned electricity source. The total costs for each generation source are the sum of energy costs, capacity costs and other costs.

Frank CR [7] had used overnight capital costs as the capital cost measure. Capital expenditure costs have been used instead of overnight capital costs as the measure capital costs. Capital expenditure costs include capital costs and interconnection costs, which better capture capacity costs. So, capital expenditure costs have been used in the calculations. The overnight capital costs have decreased significantly from 2010 to 2016 as seen in Table 1. It is important to update the data regard overnight capital costs for the capital expenditure cost to better reflect technological improvement. 2010 data comes from [8] , 2013 data comes from [9] and 2016 data comes from [10] .

Table 1 Overnight Capital Cost overtime source

	Overnight Capital Cost ($/kW)		
	2010	2013	2016
Wind	2440	2213	1877
Solar	6050	3873	2671

The data has been updated for fuel cost, capacity factor, and capital cost for each technology. The biggest change is that the average capacity factor for combined cycle natural gas is 55%. The average combined cycle natural gas capacity factor [7] used was 92%. The 92% average combined cycle natural gas capacity factor is a technological maximum and not what is observed in [8] . The average capacity factors for wind and solar generation have increased to 34.5% and 25.1% respectively. The average annual capacity factors over time for the different technologies can be seen in Figure 3. The nuclear capacity factor has stayed relatively stable over time. The capacity factor for coal has decreased over time. The capacity factors for wind and natural gas have increased over time.

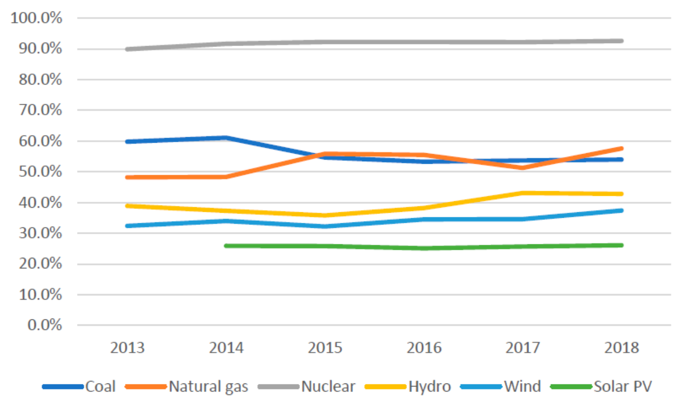

Figure 3 Average annual capacity factors over time [1]

For avoided emission benefits, upstream costs for coal and natural gas have also been incorporated to be better consistent life cycle analysis. The pounds per MWh calculation in Table 3 and these include upstream costs. Frank CR [7] had only looked at CO_2 emissions.

However, when discussing avoided emission, other emissions that are avoided generation technologies such as NO_x and SO_2 need to be included. Avoided emissions gives a measure in terms of pounds per MWh. This measure needs to be converted to economic benefits. CO_2 has been valued at $40/ton based on the Social Cost of Carbon (SCC) [12] , NO_x has been valued at $665/ton based on the marginal damage costs [13] . SO_2 has been valued at $95/ton based on the average of the damage function over time [14] .

Following [7] , there are 800 on peak hours per year and 7960 off peak hours per year. The coal used in the data is ultra-supercritical coal data. The natural gas used in the data is combined cycle natural gas data. The solar used in the data is solar PV data. The heat rates for coal and natural gas plants comes from EIA [9] . The heat rate is shown in Table 2.

Table 2 Heat rate of coal and combined cycle natural gas

	Coal	Natural Gas
Heat Rate (Btu/kWh)	10498	7050

The emissions data for CO_2, NO_x and SO_2 comes from a combination of sources that include [9] , [10] , [15] and [16] . The power plant emissions data is shown in Table 3.

Table 3 Emissions of coal and combined cycle natural gas

	Coal	Natural Gas
CO_2 (lb/MWh)	2,162.60	824.9
NOX (lb/MWh)	11.56	11.21
SO_2 (lb/MWh)	30.78	1.78

The fuel data for coal and natural gas plants comes from comes from [10] . The fuel cost per MWh comes from the product of the heat rate from Table 1 and the fuel cost for coal and natural gas respectively. The operation and maintenance data come from [17] . The total cost is the sum of the fuel costs, variable O&M costs for coal and natural gas respectively. Table 4 contains the fuel and operation and maintenance costs.

Table 4 Fuel and operation and maintenance costs of coal and combined cycle natural gas

	Coal	Natural Gas
Fuel Cost per MWh	22.78	15.72
Variable O&M per MWh	4.60	3.50
Total cost	27.38	19.22

The overnight capital, operation and maintenance and capital expenditure data come from [17] . The Capex cost is the sum of the overnight capital costs and the interconnection costs for coal and natural gas respectively. Table 5 contains the capital expenditure for coal and combined cycle natural gas.

Table 5 Fuel and operation and maintenance costs of coal and combined cycle natural gas

	Coal	Natural Gas	Nuclear	Hydro	Wind	Solar
Overnight Capital Cost per kW	3636	1032	5945	3123	1877	2671
Interconnection Cost	318	23	495	135	38	24
Capex Cost per kW	4499	1186	7,5545	3,844	2,032	2,862

Table 6 Capacity costs of electricity generation technologies

	Coal	Natural Gas	Nuclear	Hydro	Wind	Solar PV
Expected Economic Life	30	30	40	50	20	40
Capital Cost per MW per year	380970	100470	599844	330758	249698	350089
Fixed O&M Cost per MW per year	41579	15812	107311	17393	42817	26455
Total Capacity Cost per MW per year	422549	116282	707155	348151	292515	376543

The expected economic life data comes from [7] . The capital expenditure costs from Table 4 have been converted to per MW per year terms. The total capital cost per Year per MW is the sum of the sum of the capital cost per year per MW and the fixed operation and maintenance cost per year per MW for coal and natural gas respectively. The capital expenditure Table 6 contains the capacity costs of electricity generation technologies.

3 Results

The results section first looks at each of the avoided emissions, avoided energy costs and avoided capacity costs separately. Then the costs are examined, followed by net benefits under various scenarios.

3.1 Avoided emissions

For each generation source, CO_2, NO_x and SO_2 avoided emissions have been calculated in tons per MW per year. Figure 4 shows the results avoided CO_2, NO_x and SO_2 emissions calculations. The results show that nuclear generation achieved the highest avoided emissions for CO_2.

Combined cycle natural gas had the next highest avoided emissions followed by hydro, wind and finally solar. For NO_x, nuclear generation achieved the highest avoided emissions followed by hydro combined cycle natural, solar and wind. Nuclear generation achieved the highest avoided emissions for SO_2. Hydro had the subsequent highest avoided emissions followed by combined cycle natural, wind and solar. In terms of overall avoided emissions on a tons per MW per year basis, nuclear generation achieved the highest avoided emissions. Hydro had the subsequent highest avoided emissions followed by combined cycle natural, wind and lastly solar. As the results are per MW per year basis, the results are not necessarily surprising. Nuclear generation had the highest average capacity factor and had the highest avoided emissions.

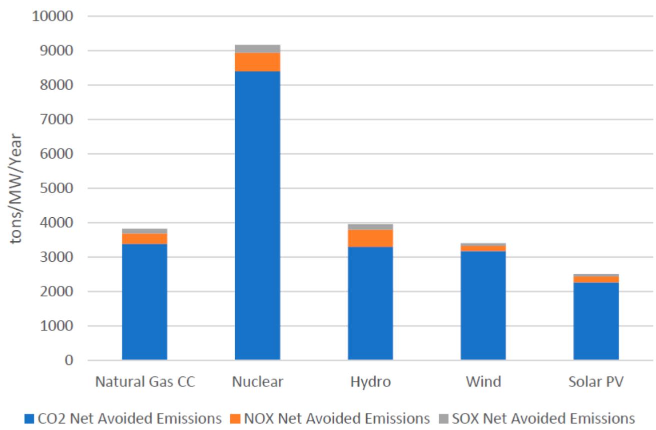

Figure 4 CO_2, NO_x and SO_2 avoided emissions of different generation technologies displacing coal

3.2 Avoided energy cost

For each generation source, avoided energy costs have been calculated in financial terms. Figure 5 shows the total net avoided energy costs calculation for each generation technologies. The results show that nuclear generation achieves the highest total avoided energy costs. Hydro had the next highest avoided energy costs followed by wind and solar. Combined cycle natural gas had negative benefits in terms of avoided energy costs as the new plant would still have energy costs and natural gas as an input would be more expensive than nuclear. While nuclear also had energy costs, these costs are less than that of natural gas. The renewable generation sources did not have new plant energy costs as there are no fuel costs for renewable generation sources. In terms of overall avoided energy costs on a financial basis, nuclear generation achieved the highest net avoided energy costs. Hydro had the subsequent highest net avoided energy costs followed by wind. Solar and lastly combined cycle natural. Nuclear generation had the highest average capacity factor and had the highest net avoided energy costs.

3.3 Avoided capacity cost

For each generation source, avoided capacity costs have been calculated in financial terms. Figure 6 shows the total net avoided capacity costs calculation for each generation technologies. The results show that nuclear generation achieves the highest total avoided capacity costs.

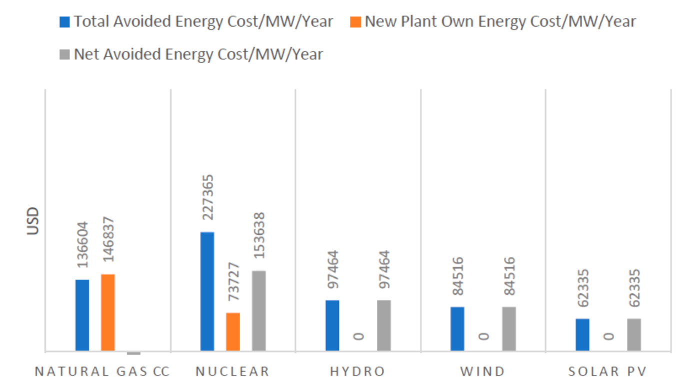

Figure 5 Total net avoided energy costs of generation technologies displacing coal

Nuclear had the next highest avoided capacity costs followed by natural gas and hydro. Wind and solar generation had the lowest avoided capacity costs.

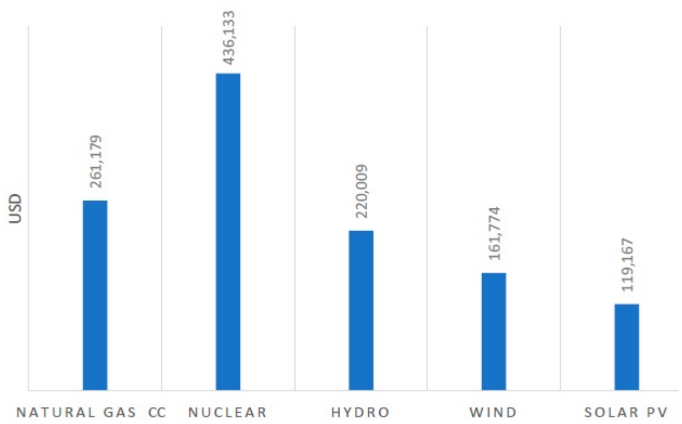

Figure 6 Total avoided capacity costs of generation technologies displacing coal

For each generation source, avoided capacity costs have been calculated in financial terms. Figure 6 shows the total avoided capacity costs of each generation technologies. The results show that nuclear generation achieves the highest avoided capacity costs. Combined cycle natural gas had the next highest avoided capacity costs followed by hydro, wind and finally solar. Nuclear generation had the highest average capacity factor and had the highest net avoided capacity costs. Nuclear generation had the highest capital expenditure costs, followed by solar, hydro, wind and lastly natural gas. Even though nuclear generation had high capital expenditure costs, the high average capacity factor leads to high total avoided capacity costs.

3.4 Costs

For each generation source total cost has been calculated in financial terms. The new plant emissions have been given valuation for CO_2, NO_x and SO_2 to convert to economic terms. Figure 7 shows the total costs of each generation technology. Combined cycle natural gas generation was the only source that had new plant emissions. Nuclear generation had the highest capacity costs, followed by solar, hydro, wind and lastly natural gas. Nuclear had other costs due waste management, while wind and solar generation had other costs due grid balancing [7] . The results show that nuclear generation had the highest total costs in terms emissions, energy, capacity and other costs. Solar had the next highest avoided capacity costs followed by hydro, combined cycle natural gas and wind.

3.5 Net benefits

For each generation source, the net benefits is the difference of benefits and costs in economic terms. The avoided emissions have been converted to economic terms by valuing the avoided emissions. The avoided energy costs and avoided costs are in financial terms. The results

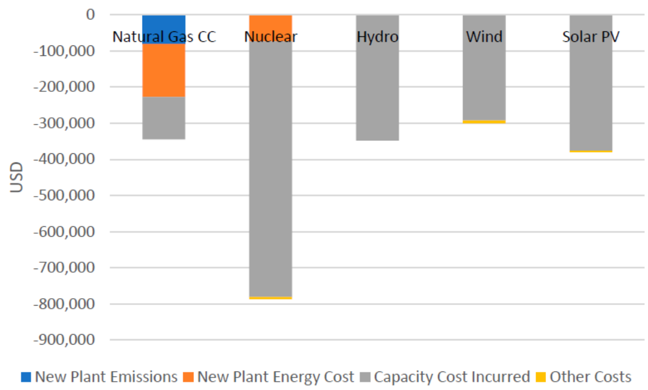

Figure 7 Total costs of generation technologies

show that nuclear generation achieves the highest benefits. Hydro had the next highest benefits followed by combined cycle natural gas, wind and solar. Figure 8 shows the base case total net benefits.

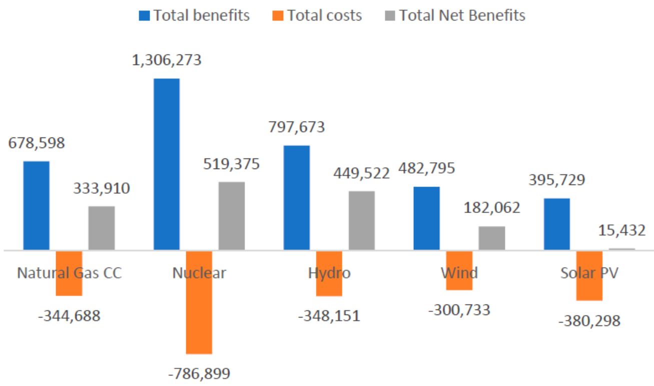

Figure 8 Base case total net benefits

Nuclear generation had the highest total costs followed by solar, hydro, combined cycle natural gas and lastly wind. The sum of total benefits and total costs gives the total net benefits. The total net benefits are in economic terms. The results show that nuclear generation achieves the highest total net benefits. Hydro had the next highest total net benefits followed by combined cycle natural gas, wind and lastly solar. This result of the total net benefits is the base case.

3.6 Sensitivity analysis

It is important to do sensitivity analysis to check for the robustness of results. In this first scenario with more favorable assumptions for wind and solar, the average capacity factor for wind is set to 45.5%, while the capacity factor for solar is set at 35.9%. The overnight capital cost is set to $1500 per kW for wind and $1200 per kW for solar. With technological improvement the overnight capital cost can decrease and the average capacity factor for wind can increase. The capacity factor in June 2017 was 35.9% for solar PV, while the capacity factor in April 2019 was 45.5% for wind [1] . Augustine C, *et al*. [17] show projections that overnight capital costs could be as low as $1500 per kW for wind and $1200 per kW for solar. Figure 9 shows the total net benefits with more favorable assumptions for wind and solar compared to the base case.

The total net benefits for combined cycle natural gas, nuclear and hydro do not change in this scenario. The total net benefits for wind and solar generation have increased significantly. The total net benefits for wind and solar are now higher than combined cycle natural gas. With more favorable assumptions for wind and solar, the results show that nuclear generation achieves the highest net benefits. Hydro had the next highest total net benefits followed by wind, solar and lastly combined cycle natural gas. Further technological development could lead to lower overnight capital cost and higher average capacity factors which would further increase total net benefits for wind and solar generation.

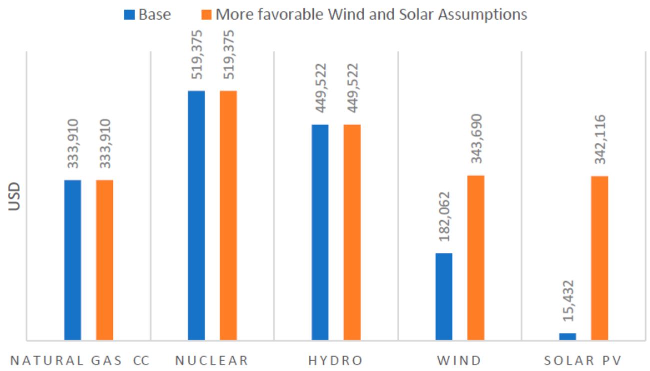

Figure 9 Total net benefits with more favorable assumptions for wind and solar

Fuel prices are an important component of sensitivity analysis. In this scenario, the natural gas fuel price is doubled ($4.46) and the coal fuel price is also doubled ($4.34). Figure 10 shows a comparison of total net benefits with higher natural gas and higher coal price to the base case. The results show that nuclear generation achieves the highest net benefits. Hydro had the next highest net benefits followed by wind, solar and lastly combined cycle natural gas.

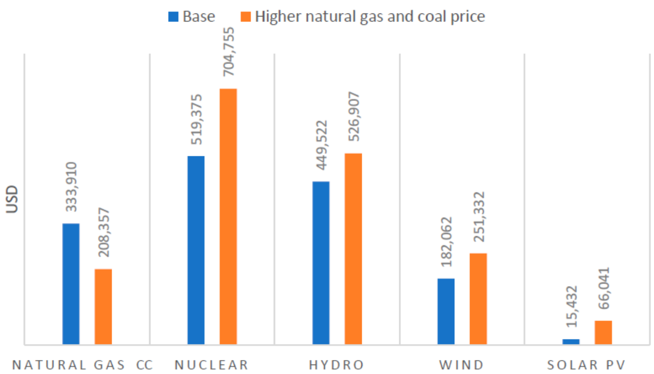

Figure 10 Comparison of net benefits with higher natural gas and higher coal price

With a higher natural gas and higher coal fuel prices, all of the generation sources see an increase in total net benefits except combined cycle natural gas generation. The reduction in combined cycle natural gas generation comes from the increased fuel price which would generation costs more expensive. The increased cost of generation leads to lower avoided energy cost benefits and increased new plant energy costs, which leads to lower overall total net benefits compared to the base case. The increase in fuel price for coal generation leads to increased coal generation costs, so for other remaining generation technologies the total net benefits are higher are due increased avoided emissions benefits and increased avoided energy cost benefits.

Another important sensitivity analysis would be that of higher natural gas and coal prices and more favorable wind and solar assumptions. This scenario combines contains the doubling of natural gas and coal fuel prices along with the average capacity factor for wind is set to 45.5% and overnight capital cost is $1500 per kW, while the capacity factor for solar is set at 35.9% and overnight capital cost is $1200 per kW for solar. Figure 11 shows the total net benefits with higher fuel price and more favorable wind and solar assumptions compared to the base case.

For each generation source, the total net benefits are sum of benefits and costs in economic terms. The results show that nuclear generation achieves the highest net benefits. Hydro had the next highest net benefits followed by wind and solar. Combined cycle natural gas had lowest net benefits. The higher fuel cost for natural gas leads to lower avoided emissions and avoided energy cost benefits. There are also higher also higher new plant emissions and energy costs which leads to higher costs overall and lower net benefits. The more favorable wind and solar assumptions along with increased fuel costs for natural gas and coal lead to higher total net benefits for solar and wind due to higher avoided energy cost benefits. The increased costs for natural gas and coal lead to higher total net benefits for nuclear and hydro due to higher avoided energy cost benefits.

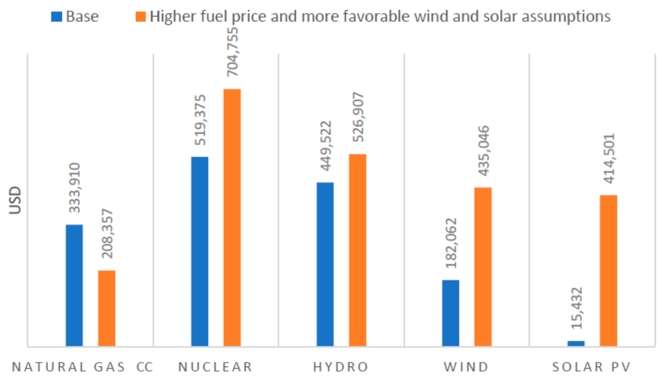

Figure 11 Net benefits with higher fuel price and more favorable wind and solar assumptions

4 Discussion and conclusion

Net benefits are highest for nuclear in all of the scenarios examined except when combined cycle natural gas was displaced as off peak generation in which hydro had the highest net benefits.

These results were different from Frank CR [7] which concluded that combined cycle Natural gas had the highest net benefits followed by nuclear, hydro, wind or solar. It is important to keep in mind that the methodology and data have been updated in this study. When looking at total net benefits on a per MW per year metric, the capacity factor plays a large role. Nuclear had the highest average capacity factor of all the generation technologies and had the highest benefits in all but one of the scenarios. Figure 12 shows the outlook for the electricity generation mix based on [1] .

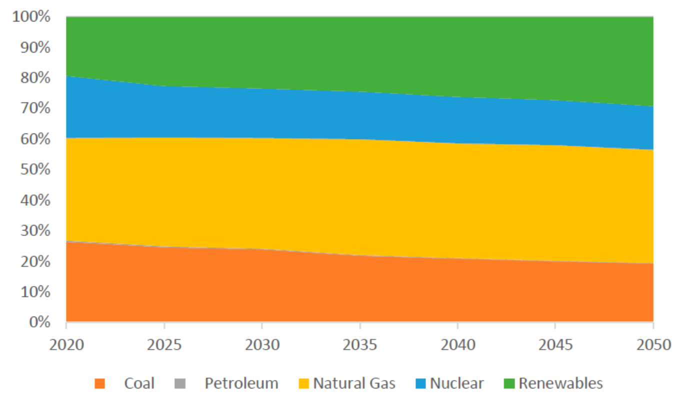

Figure 12 Outlook for the electricity generation mix based on [1]

The share of nuclear generation is expected to decrease over time in the future with the retirement of nuclear generation plants. However, given that nuclear tends to have the highest net benefits, the role of nuclear generation in the generation mix should possibly be reconsidered. Although there are retirements of existing nuclear power plants, advanced nuclear generation plants should be considered for the future electricity generation mix.

There is spatial variation in benefits and costs, which is lost in means as this looks at the on aggregate. The fuel costs for coal and natural gas electricity generation differ from one part of the US to other parts. The capacity factors of different electricity generation technologies also differ from one part of the country to other parts of the country. Therefore, total net benefits would have significant variation across the US. Repeating the calculations for different geographical regions could lead to different results, which is not captured by averages for the data used in this study.

This study looks at the per year per MW level, not aggregate level. When a coal plant retires a certain amount of capacity is displaced. The benefits and costs would also be more comprehensive at the aggregate level. The per year per MW metric would not necessarily capture all of the benefits and costs of a certain electricity generation being displaced. The use of partial equilibrium model or a computable general equilibrium model would better capture displacement benefits and costs of electricity generation technologies as it would look at the aggregate level benefits and costs.

There is empirical evidence that renewable solar and wind are much more expensive than meets the eye. Frank CR [7] does not find system integration costs to be high. Marcantonini C, *et al*. [18] found that grid balancing costs for wind is approximately €2 per MWh. Van den Bergh K, *et al*. [19] found that increasing renewable generation leads to a limited change in residual demand and 50 TWh of wind and solar result in an increase in start-up costs of €0.19 million for Europe. The costs used in this study did not include all the network integration and systems cost. A complete account of network integration and systems costs lead to a different picture.

Hirth L, *et al*. [20] consider integration costs of temporal variability, uncertainty, and location-constraints for wind generation. The study found that at 30-40% of wind generation in the electricity mix, the integration costs are up to 25-35 €/MWh, which can be up to 50% of overall generation costs. Gowrisankaran G, *et al*. [21] considered integration costs, variability costs and back up generation to calculate total social cost. The study found that at 20% of wind generation in the electricity mix for southeastern Arizona, there is a $46/MWh intermittency cost and a $138 total social cost. So, when all network integration and systems costs are considered, the other costs used in this study for solar and wind generation increase and would lead to lower total net benefits. Even though renewable costs appear to be higher than conventional sources, that does not mean that renewable generation sources should not be used.

Technological improvement would improve, solar and wind economics. Technological improvements can increase capacity factor for wind solar generation and can decrease capital costs for wind and solar generation. Even though renewable costs appear to be higher than conventional sources, that does not mean there should be no investment in renewable generation technologies. In fact, further investment into research and development would further benefit wind and solar generation technologies. As the future goal would be to have a lower GHG or non-GHG emission electricity generation mix, renewables and nuclear generation should play a significant role in the future electricity generation mix. This study had not considered subsidies for renewable generation technologies. There are some states that offer incentives such as tax breaks and subsidies for distributed solar generation. However, there is no national policy mechanism. As such, were not considered for the purposes of this study. Adding in policy mechanisms could lead to higher net benefits for solar and wind generation. Renewable and nuclear generation sources should play a significant role in the future electricity generation mix.

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