Impact of Generator Flexibility on Electric System Costs and Integration of Renewable Energy

D. Palchak and P. Denholm

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Abstract

Flexibility of traditional generators plays an important role in accommodating the increased variability and uncertainty of wind and solar on the electric power system. Increased flexibility can be achieved with changes to operational practices or upgrades to existing generation. One challenge is in understanding the value of increasing flexibility, and how this value may change given higher levels of variable generation.

This study uses a commercial production cost model to measure the impact of generator flexibility on the integration of wind and solar generators. We use a system that is based on two balancing areas in the Western United States with a range of wind and solar penetrations between 15% and 60%, where instantaneous penetration of wind and solar is limited to 80%.

We evaluate the impact of reducing the minimum generation level of the coal generation fleet from 60% to 40% of nameplate capacity and observe the corresponding decrease in production costs. At low wind and solar penetration, this increased flexibility provides very little benefit. However, at higher levels of renewable penetration, increased flexibility results in decreased curtailments, which reduces fuel consumption and decreases the system production cost.

We also examine the impact of relaxing the 80% penetration limit, assuming that active power controls and other new technologies allow wind and solar to provide system stability services. This further decreases production costs, particularly in very high penetration scenarios. In all scenarios, emissions of CO_2 decrease as flexibility is increased and more variable generation is accommodated.

1 Introduction

Integration of renewable resources such as wind and solar increases variability and uncertainty in the electric power system. Flexibility of the power system may play a vital role in accommodating the variation in net demand that occurs at increased renewable penetration. Flexibility can come from a number of sources including energy storage, demand-side management, or changes to market structures and operational practices, including increased cooperation across regional grid operators (Lew et al. 2013; Kirby and Milligan 2008; Corbus et al. 2010). Another crucial component of flexibility is the ability of traditional generation resources to change their output based on varying load, which is dictated by the parameters of minimum up/down times, ramp rates, and minimum generation level, along with start-up costs and part load efficiency (NERC 2009).

Less flexible power systems can be more expensive to operate, as they force more expensive units to stay on when less expensive ones could be used to meet load. While flexibility has always been a necessary component of power systems given the uncertainty of demand and conventional generation outages, the growth in variable generation (VG)[1] increases the need for flexible resources (NERC 2009; Adams et al. 2010). The benefits of zero variable-cost VG sources include their ability to displace the operating costs and emissions of the conventional electric power system (Lew et al. 2013; Corbus et al. 2010). This primarily means avoiding the

[1] VG and "wind and solar" are used interchangeably throughout the report.

costs of operating fossil-fueled generators and associated emissions of criteria pollutants and CO_2. If the power system is not sufficiently flexible, the benefits of VG may be reduced. In higher levels of VG penetration, the limited flexibility in the system will lead to fossil-generators remaining online while cost- and emissions-free wind and solar is not able to be accommodated and is therefore curtailed.

Previous analysis has demonstrated the impact of VG deployment on unit cycling (EPRI 2013, Troy et al. 2012), and the relationship between system flexibility and curtailment rates has also been analyzed previously (Troy et al. 2010; Denholm and Hand 2011; Ummels et al. 2007). These studies demonstrate highly non-linear curtailment rates as a function of VG penetration as well as a large sensitivity of curtailment to operational flexibility of the conventional generation fleet. Other studies explore further mitigation options such as interconnection and storage in reducing curtailment (Tuohy and O'Malley 2009; Silva 2010).

This study evaluates several aspects of generator flexibility[2] using a commercial production cost model. It uses a subset of the Western Interconnection electric power system to quantify the impact of increased generator flexibility on overall production costs. Flexibility of this test system has been previously analyzed by Venkataraman et al. (2013), which included a cost-benefit analysis of certain retrofits available for combined-cycle and coal generation plants. They found that increased flexibility of a few plants decreased the costs of operating the system and were commensurate with the costs of installing the necessary upgrades. Here we examine the impact of coal generator flexibility over a range of renewable penetrations to analyze the effect on curtailments, as well as unit commitment and dispatch of various generation types. Our analysis also considers other factors that may be affected by altering generator parameters, such as unit starts and CO_2 emissions. System marginal prices are also examined to quantify the effect that flexibility could have on generator revenues.

2 Test System

2.1 Base System Description

The purpose of this analysis is to explore the general relationships between generator flexibility and overall operational cost, including the ability to accommodate variable generation resources.[3] For this analysis, we used a test system derived from a subset of the Western Electricity Coordinating Council (WECC) Transmission Expansion Policy Planning Committee (TEPPC) model and other publicly available datasets (TEPPC 2011). The system is large enough to be realistic but small enough to isolate the impact of changing generator flexibility parameters. A number of previous studies use this test system (Hummon et al. 2013a; Jorgenson et al. 2013; Hummon et al. 2013b). Transmission is simplified in our representation of this system to focus on the relationship of traditional generators to VG resources. We assume that sufficient transmission would be available to accommodate new and existing generation resources.

[2] From this point on, flexibility will refer specifically to individual generator flexibility as defined in (NERC 2009).

[3] We used PLEXOS version 6.300 R03 x64 Edition and the Xpress-MP 24.01.04 solver, with the model performance relative gap (MIP gap) set to 0.5%.

The test system consists of two balancing authorities—Public Service Company of Colorado (PSCo) and Western Area Colorado Missouri (WACM). Multiple individual utilities operate within this region, which is referred to in this study as the Colorado test system. These vertically integrated utilities balance their own operation and interact with their neighbors under confidential bilateral agreements. Because the bilateral contracts are not publicly available, this analysis assumes an optimal, least-cost dispatch. Hourly load profiles were scaled from 2006 data to match the projected TEPPC 2020 forecast for annual load. The peak demand is 13.7 GW with an annual energy demand of 79.0 TWh. Table 1 shows the installed capacity of the generators in the test system.

Table 1. System Capacity in the Base Case

System Capacity (MW)	
Coal	6,178
Gas Combined Cycle	3,724
Gas Turbine/Gas Steam	4,045
Hydro	773
Pumped Storage	560
Wind	3,347 (10.7 TWh)
Solar PV	878 (1.8 TWh)
Other[a]	513
Total	15,793

Generator parameters are based largely on the database used in the Western Wind and Solar Integration Phase 2 Study (2013). Key assumptions regarding generator flexibility in our base case include:

- Coal units have a minimum stable level at 60% of rated capacity with typical minimum run times of 168 hours (seven days).
- Combined-cycle units have a minimum stable level of 55% with typical minimum run times of eight hours.
- Combustion turbines have unit-specific minimum stable levels in a range of 35%-45% with typical minimum run times of two hours.
- Instantaneous penetration of wind and solar is limited to 80%.

Ten VG scenarios are considered for this study, with details provided in Table 2. The scenarios include total *potential* (before curtailment) penetrations ranging from 16% to 55% in roughly 5% increments on an energy basis. The ratio of wind to solar is held close to a 5.5:1 ratio, respectively, in all scenarios.[4] As noted previously, instantaneous VG penetration is limited to 80% of the total load. This means that at least 20% of the generation in each hour must come

[4] In the lowest penetration scenario, this corresponds to about 2.3% from PV and 13.4% from wind. For comparison, Colorado received about 11% of its electricity from wind generation in 2012. (EIA 2013)

from traditional thermal or hydro generators. Any VG above this threshold is either curtailed or can be held for operating reserves.[5] This 80% limit is somewhat arbitrary, but reflects concerns about stability limits and other technical constraints regarding systems with large amounts of non-synchronous generators (Ela et al. 2014; Ruttledge et al. 2012). As a result, we use this 80% limit to explore the impacts of placing limits on instantaneous penetration of VG. We also examine the impact of relaxing this constraint in section 3.3.

Three spinning reserve products are being held in our model: contingency, regulation, and a load-following service. The spinning contingency reserve requirement is based on the single largest unit in the system and is not changed in all scenarios. The regulation and load following reserve requirement is based on the combination of the wind and solar penetration in a given interval. The technique to calculate the reserve is outlined in Lew et al. (2013) and Ibanez et al. (2012), which uses uncertainty in the forecasts of wind and solar in determining the reserve requirement. Table 2 shows the annual wind and solar penetration as a percentage of total generation, as well as the total wind and solar generation and the total annual reserve requirement. It includes the potential generation, as well as the actual (post- curtailment generation) discussed in more detail in the results section.

Table 2. Total VG Penetration and Reserve Requirement for the Base Case

VG Penetration (Potential/Actual) (%)	VG Generation Potential/Actual (GWh)		Annual Reserve Requirement (GW-h)		
	PV	Wind	Contingency	Flex	Regulation
16 / 16	1,834 / 1,834	12,539 / 12,539	3,548	502	1,050
21 / 21	2,556 / 2,556	16,394 / 16,393	3,548	600	1,134
27 / 27	3,168 / 3,163	21,266 / 21,254	3,548	769	1,281
32 / 32	3,755 / 3,723	25,200 / 25,102	3,548	855	1,364
36 / 35	4,276 / 4,202	28,080 / 27,836	3,548	918	1,422
40 / 39	4,805 / 4,595	31,776 / 31,042	3,548	1,096	1,626
45 / 44	5,379 / 4,976	35,664 / 34,325	3,548	1,183	1,702
50 / 47	5,991 / 5,303	39,666 / 37,053	3,548	1,304	1,835
55 / 50	6,549 / 5,370	43,603 / 39,127	3,548	1,456	2,091
60 / 52	7,165 / 5,679	47,330 / 41,193	3,548	1,511	2,140

We examine two opportunities to increase system flexibility, described in Table 3. The first is modifying assumptions regarding the minimum stable operating level of coal plants. Because this system derives a large fraction of its energy from coal, this study focuses on the impact of coal generator flexibility. Future analysis will consider additional generator mixes and the impact of various other generator flexibility parameters. The second flexibility option considered is increasing the maximum instantaneous penetration of VG. We also consider a scenario where the two flexibility options are combined. All flexibility scenarios are run for all ten VG penetration levels to show how the value of flexibility changes with increasing penetrations of wind and solar.

[5] Wind generation is already used for provision of operating reserves by some utilities (Bird et al. 2014).

Table 3. Summary of Main Scenarios

Scenario	Description
Base	Base system including 60% minimum stable level of coal plants and 80% maximum instantaneous wind and solar penetration
Inc. Coal Flex	Decrease $minimum\ stable\ level/\ maximum\ capacity$ of coal units to 40% from 60% and 80% maximum instantaneous wind and solar penetration
100 Max VG	Base system including 60% minimum stable level of coal plants and 100% maximum instantaneous wind and solar penetration
100 Max VG + Inc. Coal Flex	Decrease $minimum\ stable\ level/\ maximum\ capacity$ of coal units to 40% from 60% and 100% maximum instantaneous wind and solar penetration

3 Results

3.1 Base Case

We begin with an examination of the operation of the test system in its base case configuration in all renewable scenarios.

Figure 1 shows the annual generation mix of the VG scenarios for the base case. At low penetration, wind and solar tend to displace natural gas (primarily combined-cycle) generators. As penetration increases, coal begins to be displaced, particularly in the off-peak periods. Figure 1 also shows increased levels of curtailment at the higher VG penetrations (the x-axis represents the penetration after curtailment).

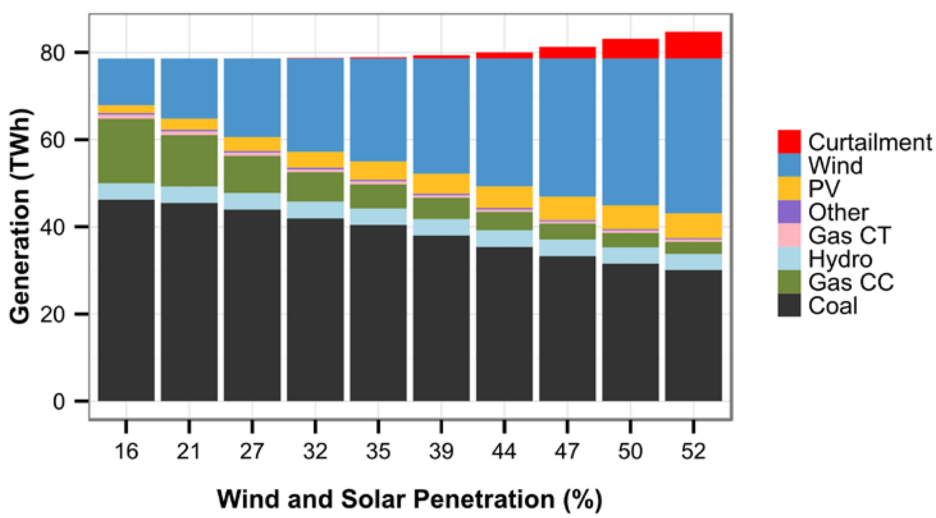

Figure 1. Annual energy generation by renewable penetrations in the base case

Curtailment is an important economic challenge to large-scale deployment of renewables. Figure 2 summarizes the total and marginal curtailment rates in the base case. Total curtailment is defined as the total amount of renewable energy curtailed divided by the total potential generation in that scenario. Marginal curtailment represents the incremental curtailment from one scenario to the next divided by the incremental potential generation between one scenario and the next. Overall, curtailment in these simulations is quite low until penetration of about 32%, and then rises steadily. The relatively low curtailment rates are due in part to the assumption that sufficient transmission capacity exists or is constructed to accommodate 100% of all wind and solar generation. While we effectively ignore transmission constraints due to our objective of understanding the impact of generator flexibility, transmission constraints are a major source of curtailment in the existing grid. Additional discussion of current curtailment rates is provided by Bird et al. (2014), who find that while a large fraction of historic curtailments in the U.S. appear to be driven by transmission constraints, other operational practices lead to curtailment at penetration levels below those simulated here. Many of these practices, such as manual dispatch, are evolving, and curtailment rates in the U.S. are generally dropping even while penetrations are increasing.

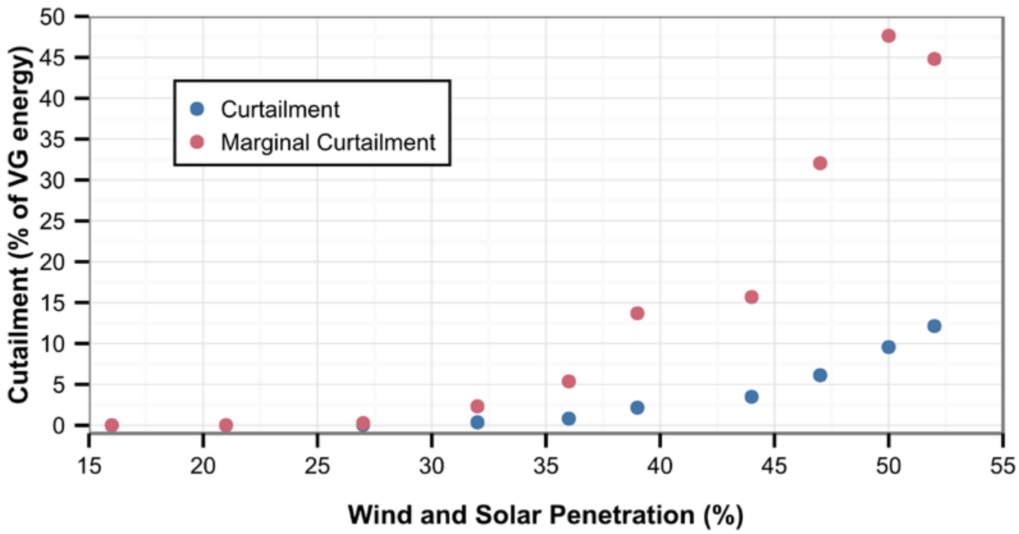

Figure 2. Total and marginal curtailment rates in the base case

An additional source of relatively low curtailment rates is our assumption that curtailed wind and solar can be used to provide operating reserves, enabling de-commitment of thermal units during extended hours of high solar and wind production. The model assumes that each MWh of curtailed energy can provide 1 MW-h of reserves (1 MW of reserves service for one hour). If wind and solar were not allowed to provide reserves, more thermal units would have to stay committed, and would likely result in a greater number of committed units during certain periods. In this study, more than 50% of the curtailed capacity is typically providing reserves (Figure 2 shows curtailment that represents both lost energy and curtailment that provides at least some value in the form of reserve provision). Had those reserves been provided by partially loaded generation, it is possible that the curtailment rates would have been even higher than that simulated here. While VG providing reserves is not as valuable to the system as delivering energy,[6] it still provides significant system value, as discussed by Hummon et al. (2013a). For this reason, this analysis considers all VG that is not providing energy to be "curtailed" even though there are periods where reserves are more valuable than energy. Bird et al. (2014)

[6] For example, the average price of energy in the lowest penetration case is $33.0/MWh, while the average price of reserves is $12.7/MW-h, with regulation, (the most valuable reserve), averaging $16.6/MW-h. In the 39% VG case the average price of energy is $24.4/MWh, while the average price of reserves is $11.0/MW-h with regulation averaging $17.8/MW-h.

discusses current curtailment practices in more detail, including the use of curtailed capacity for reserve provision.

An example of VG providing reserves is provided in Figure 3. It shows the impact of wind and solar on the system dispatch for the period of September 18-21 for three different penetrations of wind and solar. Of note in the highest penetration is the significant curtailment, and also the use of curtailed energy for provision of reserves. A large portion of the total VG curtailed as energy actually holds reserve provision. For example, in the 39% case, while about 5% of the VG energy is curtailed, 80% of this energy (or about 4% of the total curtailment) is effectively used to provide reserves (where 1 MWh of energy provides 1 MW-h of reserve capacity). In the highest VG case, where about 12.5 % of VG is curtailed, about 75% of this curtailed energy is used to provide reserves, and actually provides about 80% of the system reserve requirements. Further analysis is needed of the ability of VG to provide reserves considering resource uncertainty and operational implications of curtailed VG providing a large fraction of system reserve requirements.

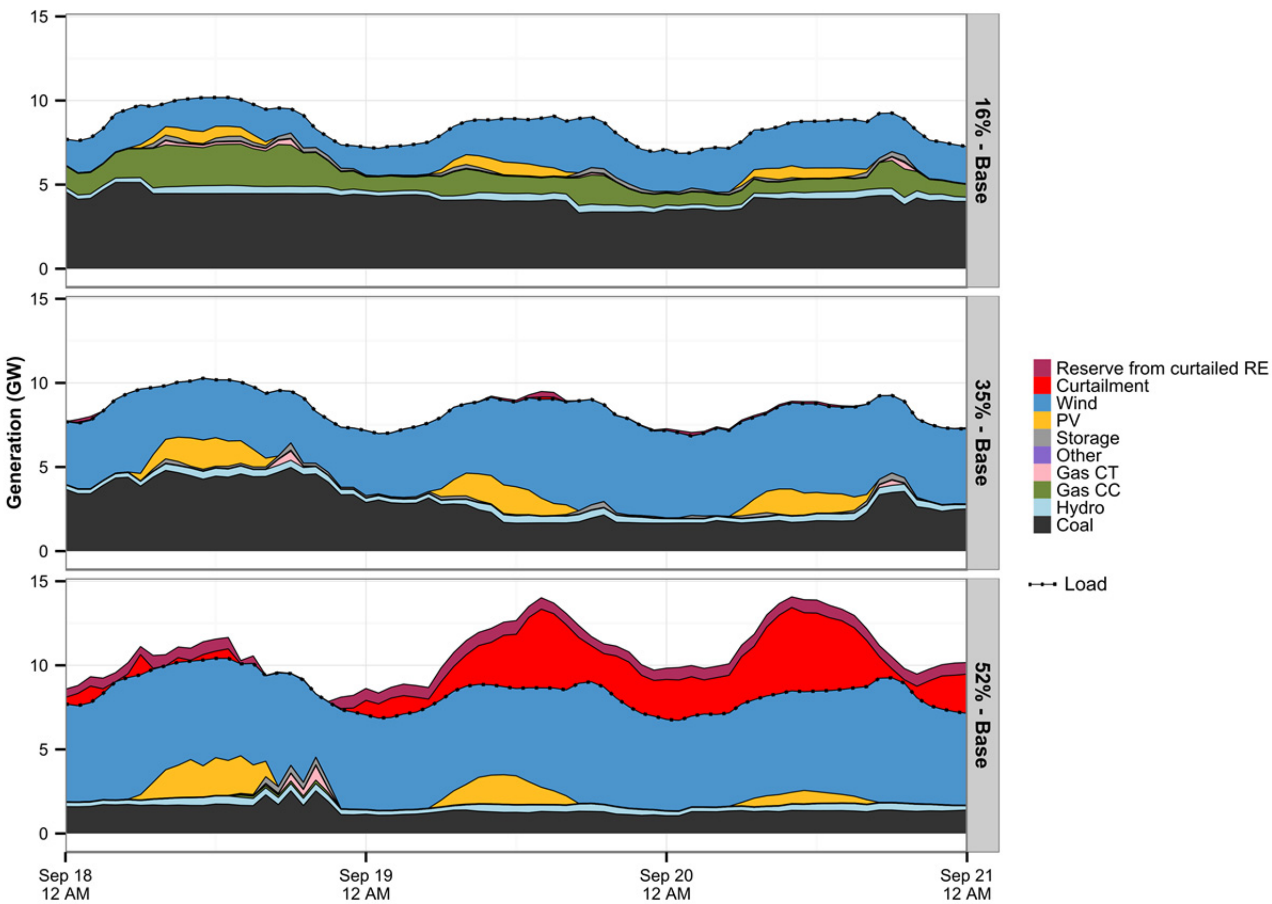

Figure 3. Generation dispatch of resources for three days in September in three RE cases

Figure 3 illustrates multiple challenges of high VG penetration, as well as possible opportunities for increased generator flexibility to accommodate RE. Specifically noticeable in the 56% case are two separate instances where inflexibility is causing higher production costs: 1) during high load the VG contribution is being capped at 80% (midday September 19), but 2) during succeeding hours when load decreases, the coal units online are not turning down by the same margin as the load, meaning they are operating at or near their minimum generation. The following sections address both of these opportunities for increased system flexibility.

3.2 Increased Flexibility

We begin our examination of flexibility by looking at the scenarios where we decrease the minimum generation point of coal from 60% to 40% of the maximum capacity. The expectation is that reducing the minimum generation of the coal units will increase flexibility in the system, and therefore, reduce curtailments and potentially improve the unit commitment and dispatch of the system. Table 4 summarizes the total production cost for the base case and increased coal flexibility case.

Table 4. Total Production Cost Summary for Increased Flexibility From Coal for All VG Scenarios

VG Penetration[7]	Base	Inc. coal flex	Savings from increased flexibility	
(%)	$M			(%)
16	1423.6	1423.6	0.0	0%
21	1306.4	1305.8	0.6	0%
27	1169.8	1167.8	2.0	0%
32	1072.5	1066.4	6.1	1%
36	1006.4	997.6	8.8	1%
40	943.0	927.0	16.0	2%
44	874.3	856.1	18.1	2%
48	817.0	796.0	20.9	3%
50	776.0	751.9	24.1	3%
52	725.9	701.8	24.1	3%

Table 4 demonstrates that at low penetration, the flexibility of the coal units, which are traditionally used as baseload plants, has little impact on system savings. At low penetration of VG these plants are rarely cycled, indicating that there is no savings associated with allowing a lower minimum generation point. As the penetration of wind and solar increases, the system requires more coal cycling, and there is greater opportunity for savings associated with improved coal flexibility.

There are several sources of the savings associated with increased flexibility. Figure 4 demonstrates the source of the savings in each scenario, measured by the difference between the base case and increased flexibility case. Variable operations and maintenance (VO&M) refers to the costs associated with operation of a generator that is not fuel, while start and shutdown costs are the VO&M attributed specifically to starting or shutting down a unit. Regulation cost represents the additional cost to the system associated with providing operating reserves.

[7] These penetration numbers represent the wind and solar penetration in the base case, as do the rest of the tables in the report. The Inc. coal flex case has slightly higher penetrations due to its ability to accommodate more VG.

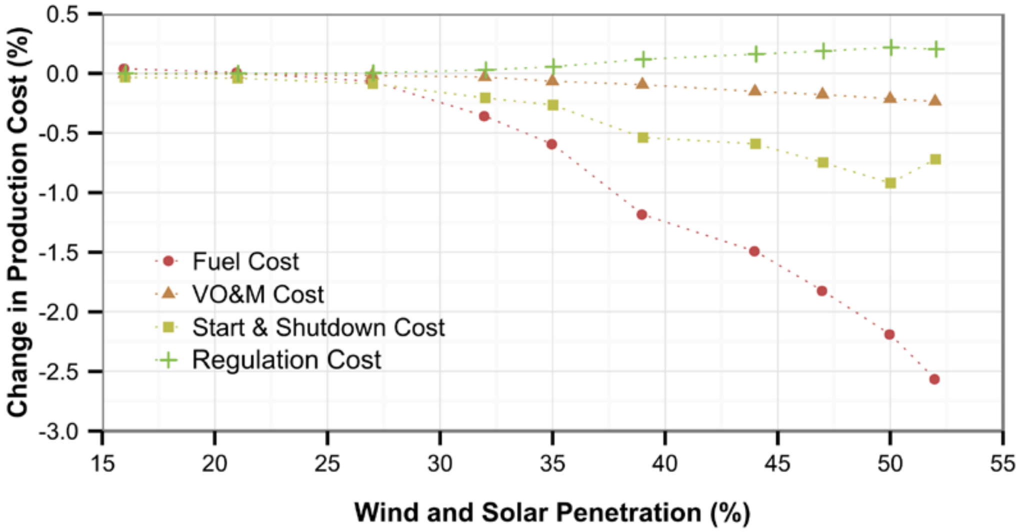

Figure 4. Changes to the components of the total production costs with increased coal plant flexibility

The dominant source of savings associated with increased flexibility is a reduction in fuel costs. This reduction is itself associated with two factors—reduced curtailment and more efficient commitment and dispatch. Both of these factors are illustrated in Figure 5, which represents the 40% VG case. The ability to decrease coal generator output accommodates more wind and solar generation. This can be observed during the overnight hours on September 23, 24, and 26, where coal is being displaced by the zero-cost VG and hydro resources. In addition, there are instances when increased coal flexibility allows coal to displace higher cost CC generation, such as during the middle of the day, September 23 and in the nighttime hours of September 25. Figure 5 (bottom) illustrates this more directly. The shaded regions show the operating ranges allowed for the coal based on the committed units' maximum and minimum generation levels. The solid lines show the actual dispatch. The most obvious change is the ability of the coal to decrease to a lower combined generation which causes VG and hydro to increase generation output (reduce curtailment). The other change is the range increase due to the maximum generation (grey area above) which is a result of more committed units. This leads to coal displacing gas because the combination of units have a higher ramp capacity and can maintain a higher output during multiple hours in the timeframe.

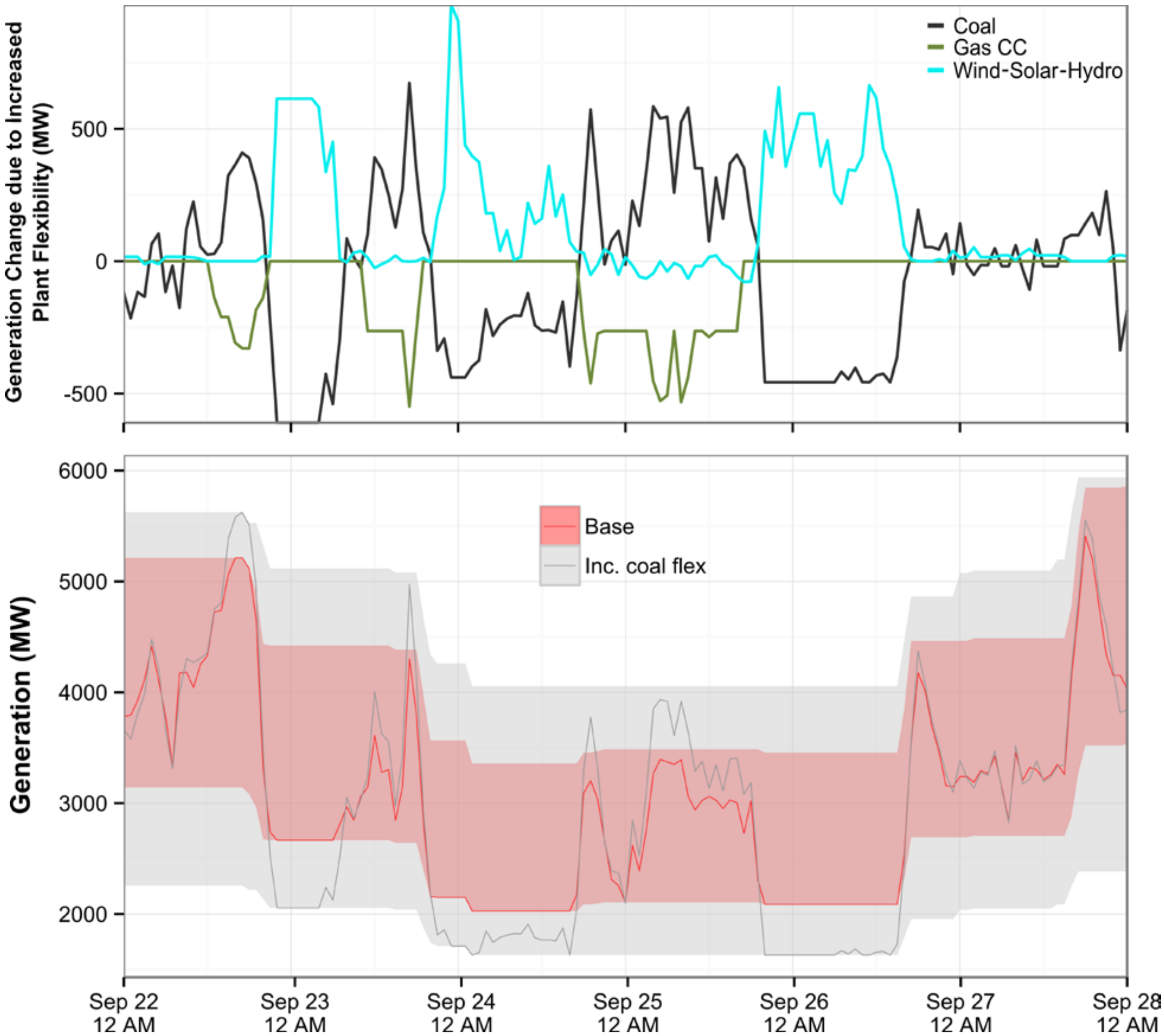

Figure 5. Change in dispatch for the 40% RE scenario from Base to Inc. coal flex case (top) and range of operation for coal given unit commitment (red and gray shaded areas) and the actual dispatch (lines) for the two cases (bottom). The top graph has some smaller generation types omitted for clarity and includes the changes to load which are a result of changes to pumped storage operation. Wind, solar, and hydro are also combined for clarity.

The annual reduction in curtailment and fuel use associated with increased flexibility are illustrated in Figure 6.

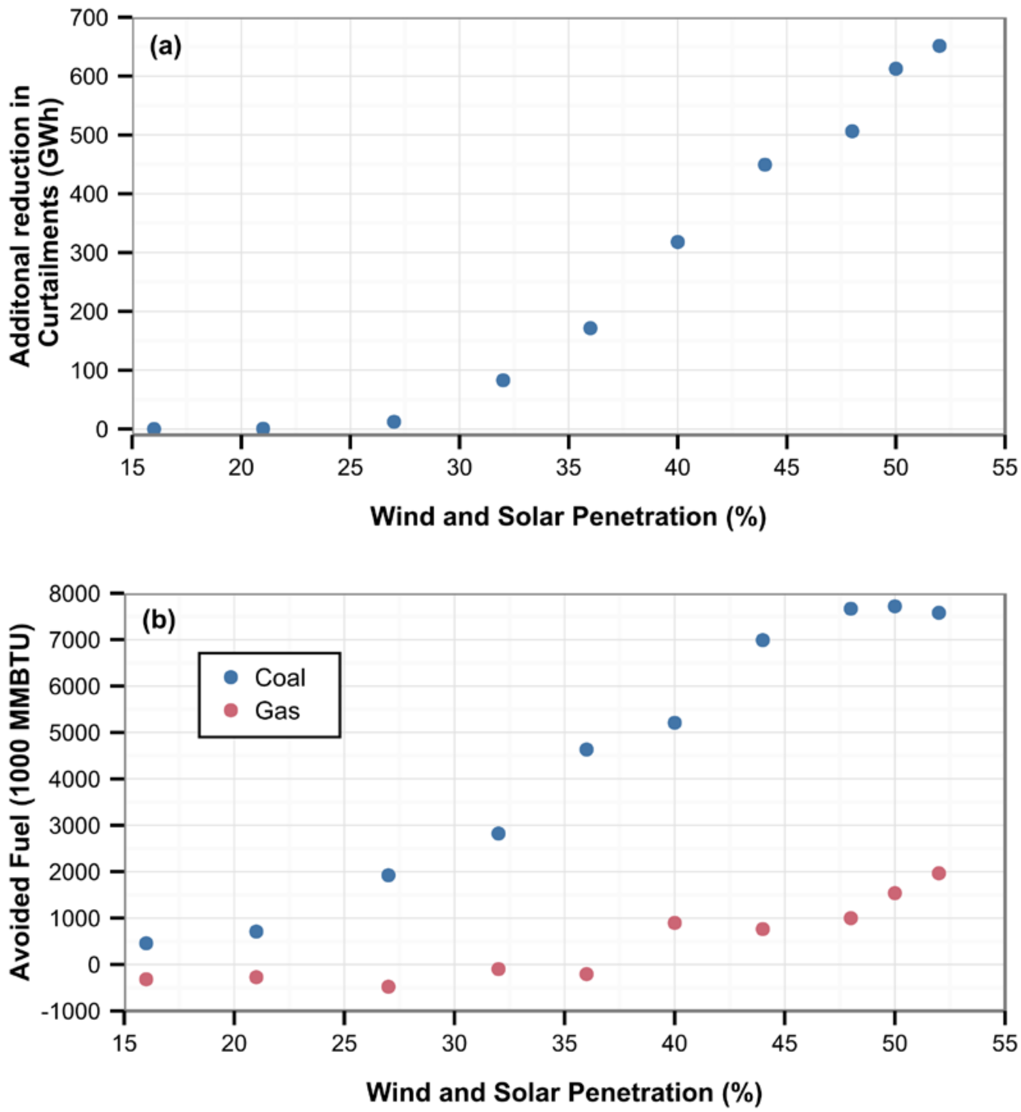

Figure 6. (a) Reduced curtailment rate and (b) reduced fuel use in each scenario resulting from increased coal plant flexibility

Because increased generator flexibility results in reduced fossil fuel use, there will be an additional benefit of reduced CO_2 emissions. While we assume no cost or carbon constraints in this simulation, CO_2 reduction benefits can be calculated based on the fuel consumption values from Figure 6.[8] Figure 7 (a) provides the avoided total CO_2 emissions that result from the increased generator flexibility. This represents as much as a 2.5% reduction in total emissions in the highest renewable case. This data is also expressed per unit of renewable generation (b). The

[8] The emissions calculations only consider coal and gas, which are the primary fuels utilized in our test system. The assumed CO_2 intensity is 206.2 lb/MMBTU for coal and 117.0 lb/MMBTU for natural gas. (EIA 2013; EIA 1994).

slight decrease in emissions benefits at the highest penetrations in (b) is a result of the decreased marginal benefit of VG, as well as the inability of VG to provide more than 80% of the energy in this scenario. Therefore, the baseload coal is not changing much beyond 50% even though more VG is added.

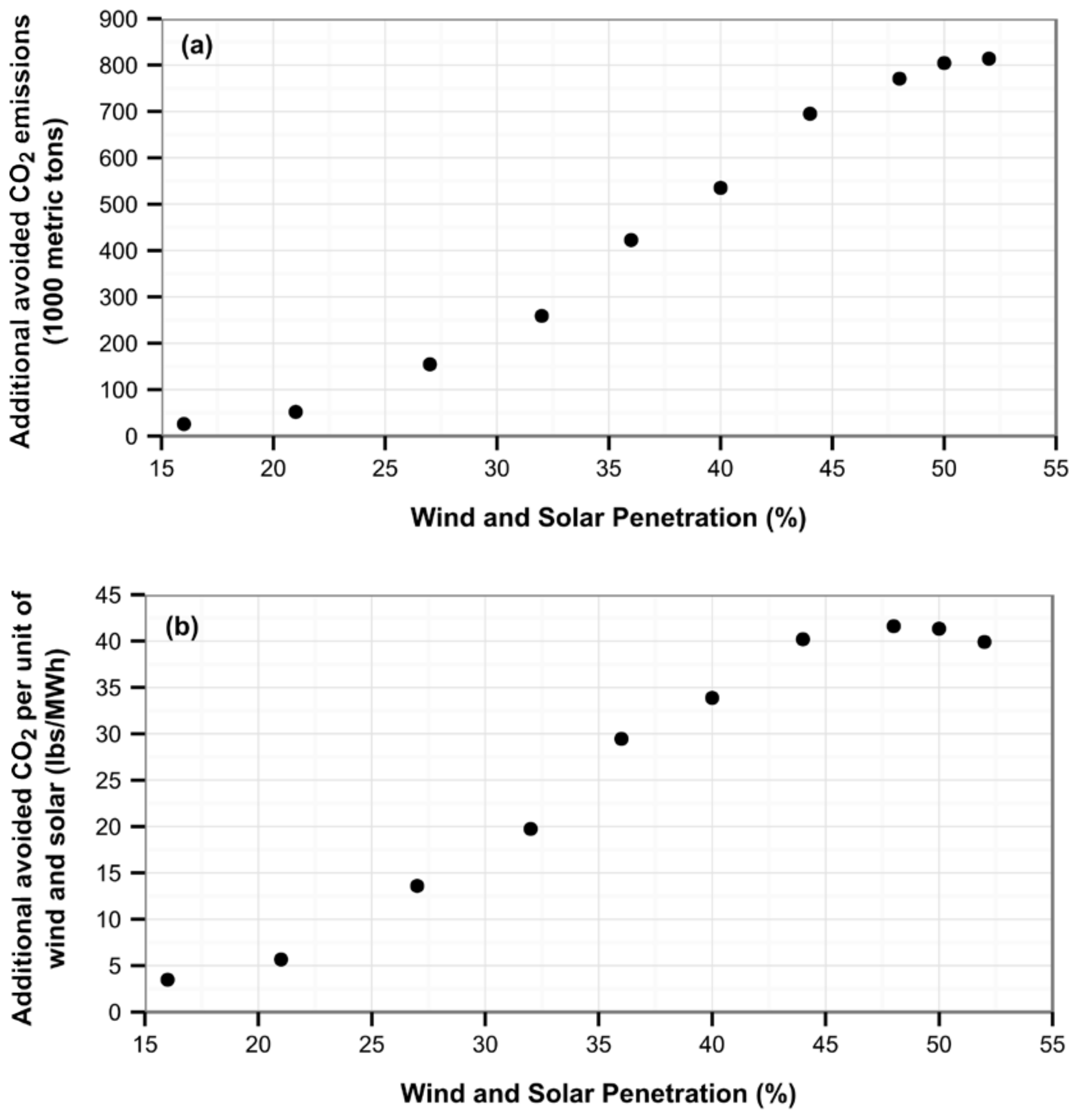

Figure 7. Additional avoided CO_2 emissions due to increased coal plant flexibility

While reduced fuel use is the dominant source of savings, an important secondary benefit is reduced plants starts. Figure 8 provides the total system start data for coal, combined-cycle and combustion turbines for each scenario. The data follows previous analysis by Lew et al. (2013) that indicates that the addition of wind and solar tends to decrease combined-cycle starts (because they are less often on the margin) while increasing coal unit starts. Overall, additional coal flexibility results in a substantial reduction in starts of all types.

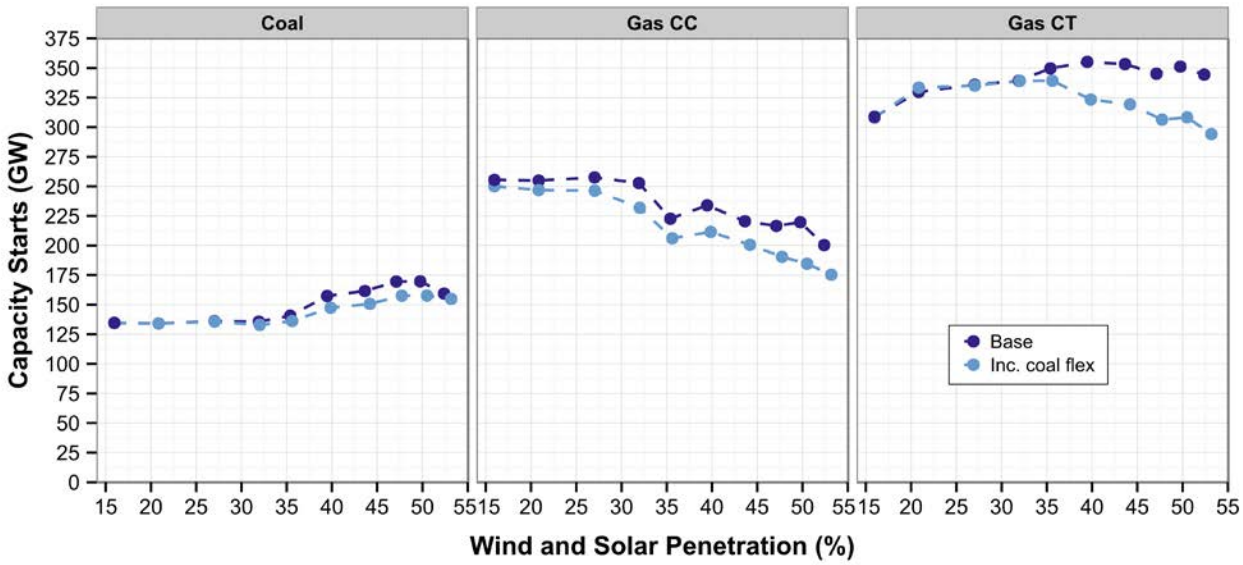

Figure 8. Capacity starts for the base case and Inc. coal flex case. Capacity starts are the number of starts multiplied by the rated capacity of the unit.

Finally, there is a small contribution from decreased operations and maintenance (O&M) costs. Of note is the increase in costs associated with providing regulation reserves. We model the non-steady-state costs associated with thermal generators, equivalent to a "bid" price for regulation in restructured markets. These costs are assumed to vary from $2/MW to $10/MW for thermal generators, with a more detailed discussion provided by Hummon et al. (2013a). Because we allow curtailed wind and solar to provide this service at no additional cost, when we increase coal flexibility and decrease curtailment, this slightly increases the system-wide cost of providing regulation. This small increase in cost is more than made up for by decrease in cost associated with generation from thermal generators.

There are two important implications of decreased production costs from the perspective of system wide benefits or benefits to individual plant operators. From the perspective of the system, (or a vertically integrated utility) the savings associated with increased coal flexibility must be compared to the cost of changing operational practices, plant retrofits, or potentially increased O&M requirements. The annual system-wide operational savings is about $24M in the highest renewable penetration case, or about $3,900/MW of coal capacity in the system. As noted previously, the mechanisms to change the minimum generation of coal generators could include both changes to operational practices as well as physical modifications. Further explanation of retrofits to individual generators is provided in Venkataraman et al. (2013), which found that benefits to the system are comparable to the costs of implementation. Cochran et al. (2013) addresses some of these physical modifications and also summarizes many of the implications and challenges of the operational changes that would be required to run coal plants at lower output.

From the perspective of a participant in a restructured market, flexibility can also have a positive impact. Overall, the introduction of zero marginal cost renewables will displace fossil generation, reducing their capacity factor and revenue. There is also a strong interaction between VG and prices which can be influenced by generator flexibility. Figure 9 shows the price duration curves for the 40% VG penetration scenario in the base case and the increased coal flexibility case. Prices are determined by the marginal generators on the system at a given time interval. Gas combined cycle units on the margin are represented by prices from about $25-$60/MWh. Coal is generally less expensive at about $18-$24/MWh. As VG penetration increases and gas is displaced, the number of hours with coal on the margin increases. However, there are also an increased numbers of hours where the inflexibility in the system produces hours of zero marginal prices. This is due to a higher number of hours with curtailment, which causes the locational marginal prices to be zero because there are free resources not being utilized.[9] We do not consider the impact of the production tax credit where wind generators bid negative costs. Including this effect would increase the benefits of increased coal flexibility on plant revenue. The impact of increased flexibility of coal units is to increase the number of hours of non-zero energy prices by reducing the hours with curtailment.

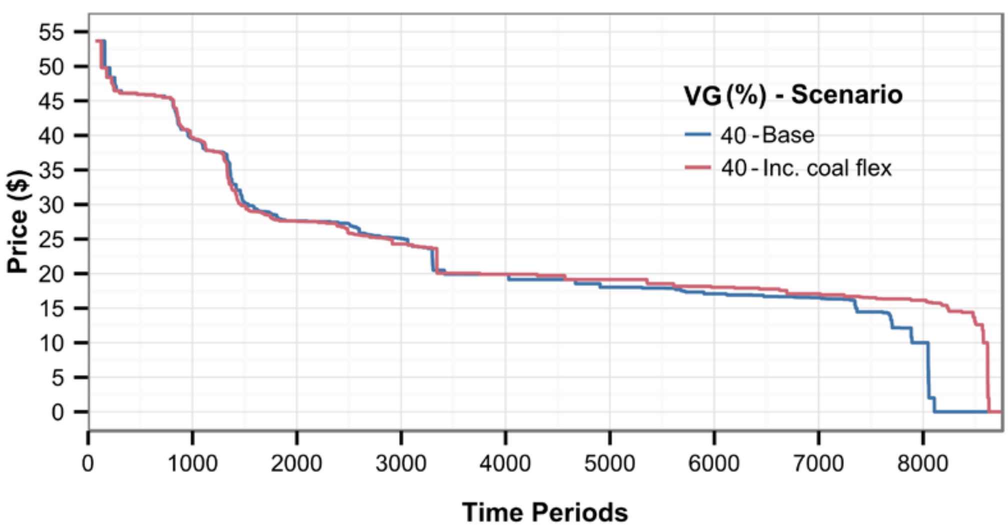

Figure 9. Price duration curves for both base case and Inc. Coal Flex case for 40% RE penetration

As a result, the increased generator flexibility results in higher revenues, despite reduction in output and the associated decrease in total generation costs. This leads to a somewhat counter-intuitive result that in some circumstances reducing output can actually increase revenues for fossil generators. The costs and revenues for coal generators are shown in Table 5.

[9] As noted previously, a large portion of the curtailed VG resource is held as reserve provision, especially at the lower wind and solar penetrations. When all of the energy curtailed can be used as reserves, the energy price does not go to zero. This leads to two mechanisms for the increased flexibility of coal to reduce the number of hours that there is a zero marginal energy price: (1) reducing the curtailed energy to zero, or (2) allowing VG to hold more reserve provision through changes in thermal dispatch.

Table 5. Total Revenue and Total Production Costs for all Coal Units in the RE Scenarios for the Base and Increased Flexibility Cases

VG Penetration	Total Generation Cost		Revenue		Net Revenue		Change in Net Revenue Due to Increased Flexibility
	Base	Inc. Coal Flex	Base	Inc. Coal Flex	Base	Inc. Coal Flex	
(%)	$M						
16	858	857	1459	1454	601	597	-4
21	845	844	1355	1358	510	514	4
27	821	818	1236	1239	415	421	6
32	786	782	1110	1130	324	349	25
36	760	753	1026	1048	266	296	29
40	721	713	932	960	211	248	37
44	676	664	835	866	159	202	43
48	640	627	750	788	110	161	51
50	608	596	700	746	92	151	59
52	579	567	645	680	66	113	47

3.3 Unconstrained Instantaneous Renewable Energy Penetration

The benefits of increased coal plant flexibility appear to largely saturate at the highest renewable penetration levels. This is partially due to the instantaneous penetration limit imposed in the base case. In the highest renewable scenarios, an increasing fraction of the curtailed energy is due to this limit, and increased generator flexibility does little to accommodate further renewable penetration. We imposed this limit because the impacts of large scale deployment of non-synchronous generators on inertia and primary frequency control have yet to be studied in great detail. However, relaxing our constraint can provide additional insights into the benefits of increased penetration potentially enabled via provision of synthetic inertia, and active power control (Ela et al. 2014; Ruttledge et al. 2012).

We consider a case where VG can provide up to 100% of instantaneous demand.[10] All other system constraints from the base case are enforced. Two cases were simulated: one with the base coal plant flexibility, and one with the increased coal flexibility, which effectively combines two system flexibility cases.

Table 6 summarizes the savings in production cost for all flexibility scenarios examined in this report. The first two values are the base case total production cost and savings from the increased coal flexibility case, repeated from Table 4. This is followed by the savings from the 100 Max RE case and also the case with 100% allowable renewable penetration and increased coal flexibility.

[10] To achieve 100% penetration of wind and solar would actually require greater than what is needed to meet 100% of demand because of the operating reserve requirements, which would need to be derived from curtailed wind and solar.

Table 6. Total Production Costs for Base and 100 Max RE Cases, as Well as Both Inc. Coal Flex Scenarios

VG Penetration	Base Case	Savings in Each Flexibility Scenario		
		Inc. Coal Flex	100 Max RE	100 Max RE + Inc. Coal Flex
(%)	($M)			
16	1423.6	0.0	-0.1	-0.1
21	1306.4	0.6	-0.2	0.5
27	1169.8	2.0	0.0	2.1
32	1072.5	6.1	0.1	5.9
36	1006.4	8.8	0.3	9.3
40	943.0	16.0	0.8	17.2
44	874.3	18.2	1.7	20.9
48	817.0	21.0	1.3	28.1
50	776.0	24.1	7.2	37.1
52	725.9	24.1	10.3	42.4

Savings from the 100% penetration cases do not appear significantly different than the base case until much higher penetration, simply from the fact that renewables do not exceed 80% instantaneous penetration until annual penetration levels reach about 40%. Also of note is the small negative value associated with the low renewable cases. Because the model finds a near-optimal solution, but not necessarily the optimal solution, there can be small differences between runs with nearly identical parameters.[3] This is apparent in the lowest penetrations of the 100% Max RE case. While allowing 100% instantaneous penetration does not affect any hours in these lowest RE scenarios, the presence of that constraint in the objective function causes a different local solution to be found.

The 100% RE penetration cases have a lower savings than the Inc. coal flex cases in all scenarios at all VG penetrations. However in the highest penetration scenarios the combination scenario has savings that exceed the sum of the two individual cases in isolation. This is because of the increased number of hours that coal is at or near minimum generation when higher levels of RE are allowed. This combined effect is observed in both curtailment reduction and CO_2 emissions reductions.

Figure 10 shows the curtailment rates for all four scenarios, demonstrating a significant reduction at the higher levels of curtailment. It shows both the reduced curtailment as a function of flexibility (shift downward), and also the corresponding increase in renewable penetration (shift rightward). In the highest penetration scenario, the same amount of installed wind and solar renewable capacity produces an annual energy penetration of 52.4% in the base case, and 55.4% in the combined flexibility case due to reduced curtailment.

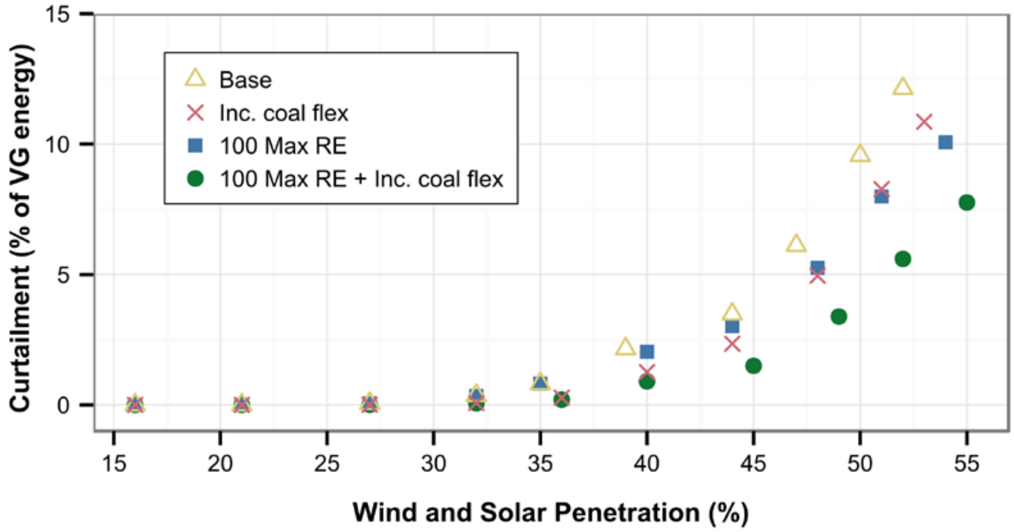

Figure 10. Curtailment for all flexibility scenarios

This analysis demonstrates that increased generator flexibility can be a very effective option to reduce curtailment. Below 45% penetration, the combined flexibility cases reduced curtailments by greater than 50%. This reduction (on a percentage basis) falls as the supply/demand mismatch of load and renewable generation increases at higher penetration, because there is simply not enough load at the correct time (particularly during the spring) to absorb the times when the largest amounts of renewable energy are available. At these higher penetrations additional flexibility options, such as demand response or storage, may be needed for further curtailment reduction.[11]

The improved dispatch efficiency and lower curtailment in the combined flexibility cases results in a significant CO_2 emissions reduction potential, illustrated in Figure 11. Overall, up to a 7% reduction in CO_2 emissions is created, which again indicates the potential importance of grid flexibility in high renewable, low carbon grid scenarios.

[11] The availability of wind is often highest during nighttime hours, when load is at its lowest over the course of a day (GE Energy 2010). Another possible alternative to enabling technologies is a more balanced mix of wind and solar, which are often complimentary in their production profiles.

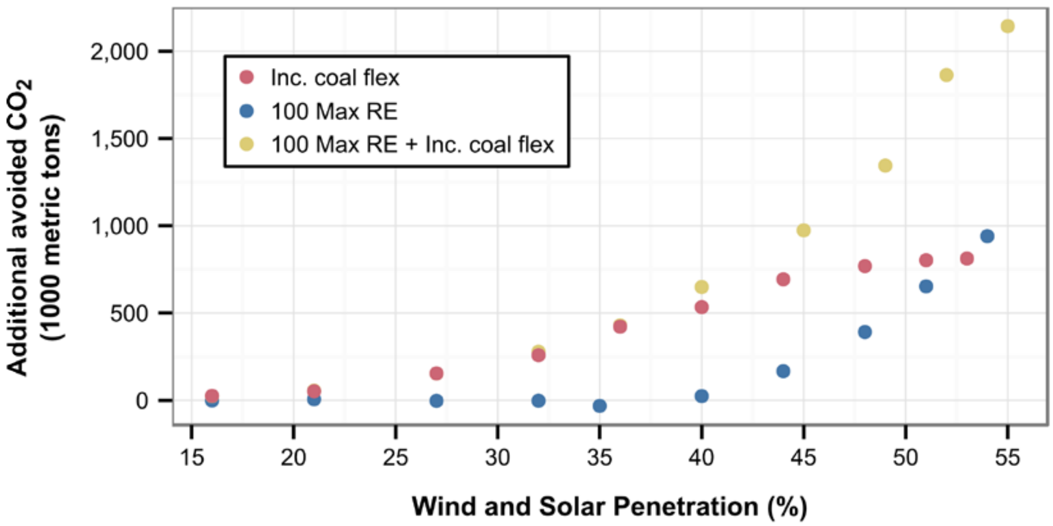

Figure 11. Avoided CO_2 emissions due to increased flexibility

4 Conclusions

This analysis finds that increasing the flexibility of the electric power system will lead to decreased operation costs, especially as VG becomes a larger part of the generation fleet. This study looked specifically at changing the minimum generation levels of coal plants. At low penetration of renewables, there is little savings from increased flexibility; however, at increased penetration, additional flexibility allows increased use of VG and decreased curtailments.

The study also examined the impact of instantaneous penetration limits of VG. Penetration limits can exist due to concerns of system stability and limited ability of some wind and solar technologies to provide primary frequency response and inertia. Cases comparing 80% and 100% instantaneous penetration limits find reduced curtailment in the 100% case, implying further examination of the benefits of wind and solar providing active power control and synthetic inertia are warranted.

Finally, the study examined the possible revenue implications for coal plants in a market setting. While introduction of zero-cost generation will always decrease revenue in general, changing flexibility can impact the decreased revenues. We found that in some cases increased flexibility, while decreasing actual generation from the coal fleet, can actually increase revenue. This is largely due to reducing curtailment and the number of hours of zero marginal prices.

While this analysis is focused on a coal-dominated generation mix, we would expect similar trends in systems with greater contribution from gas generation. This is because much of the avoided curtailment is during short periods with small levels of curtailment. Units with shorter minimum run times, such as gas generators, would likely remain committed during many of these periods and still be able to accommodate VG more effectively with lower minimum generation levels. Further analysis is needed on the actual impact of other generation mixes, as well as altering other generator parameters, such as ramp rate or minimum up and down times. Insight could also be gained by changing the parameters of a subset of generators, rather than altering the whole fleet as we did in this case study. Also, it is important to understand how these changes in either operational practice or enabling upgrades compare to the economic benefit of establishing them. This is especially important when comparing different methods for adding flexibility to the electric power system.

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