Analysis of Cycling Costs in Western Wind and Solar Integration Study

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June 2012

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NREL
NATIONAL RENEWABLE ENERGY LABORATORY

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Executive Summary

The Western Wind and Solar Integration Study (WWSIS) examined the impact of up to 30% penetration of variable renewable generation on the Western Electricity Coordinating Council (WECC) system. While startup costs and higher operating costs due to part-load operation of thermal generators were included in the analysis, further investigation of additional costs associated with thermal unit cycling was deemed worthwhile. These additional cycling costs can be attributed to increases in capital, as well as operations and maintenance (O&M) costs, due to wear and tear associated with increased unit cycling. This analysis examined the additional cycling costs of the thermal fleet by leveraging the results of the WWSIS Phase 1 study.

Based on this analysis, the additional system-level cycling costs at the 30% renewable penetration level range from almost $150 million (at the lower bound) to over $450 million (at the upper bound) when compared to the case with no renewables. For reference, the system-level fuel, variable O&M and startup costs for the case with no renewables are approximately $33 billion, 1.5 billion and $123 million respectively. While the additional cycling costs are somewhat significant, they costs must be considered in relation to the large amount of renewable wind and solar energy that was added to the WECC region. When normalized to the amount of renewable energy, the additional cost of unit cycling reduces the value of the renewable energy to the system by about $0.06/MWh to almost $2.00/MWh, depending on the renewable penetration and on whether the lower or upper bounds for thermal plant cycling costs are selected. The overall system operating cost reductions due to wind and solar energy determined in WWSIS were roughly $85/MWh. Based on the lower-bound values provided by APTECH, the additional cycling costs would reduce the value of the renewable energy by 0.1% to 0.7%. If the upper-bound values are used, the reduction would be on the order of 0.6% to 2.4%. While the additional cycling costs are by no means trivial when viewed from the perspective of the individual impacted thermal units, they are relatively small from an overall system perspective. From the individual generator perspective, in general, the loss in net revenue due to reduced dispatch and reduced spot prices far outweighed the impact of the increased cycling costs.

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1 Introduction

The Western Wind and Solar Integration Study (WWSIS [1]) examined the impact of up to 30% penetration of variable renewable generation on the Western Electricity Coordinating Council (WECC) system. While startup costs and higher operating costs due to part-load operation of generators were considered in the analysis, further investigation of additional costs associated with cycling was deemed worthwhile. These additional cycling costs can be attributed to increases in capital, as well as operations and maintenance (O&M) costs, due to wear and tear associated with increased cycling.

This analysis examines the additional cycling costs of the thermal fleet by leveraging the results of the WWSIS Phase 1 study. The additional cycling cost for the system was determined by assigning a cycling cost to each thermal unit, and after-the-fact, using the hourly dispatch profiles obtained from the GE MAPS simulation output from the WWSIS Phase 1 study. Since the additional cycling cost for a unit was assumed to not change its dispatch, the overall cycling cost for the WECC system obtained this way represents the ceiling value. The actual cycling costs for the WECC system are likely to be lower if the additional cycling cost information is included in the commitment and dispatch optimization. A study to determine the impact of the additional cycling costs on the commitment and dispatch is currently underway.

For this analysis, the additional costs associated with turndown, hot, warm, and cold startup, by unit type, was obtained from the analysis performed by Intertek APTECH (APTECH analysis [2]). In their analysis, APTECH used two primary parallel approaches to analyzing cycling-related costs: (1) top-down analyses using unit composite damage accumulation models and statistical regression, and (2) modified bottom-up component-level studies using real-time monitoring data at key locations, prior engineering assessments of critical components, and a survey of plant personnel. The following cycling-related costs were developed by APTECH.

- Load following costs (minimum to maximum load)
- Hot, warm, and cold start costs
- Base-load variable O&M costs

The units were assigned to seven broad categories, as shown in Table 1. APTECH then developed the lower- and upper-bound values[1] for the cycling costs for each category. The lower-bound cycling costs are publicly available. The upper-bound costs are not publicly available and are covered by a non-disclosure agreement.

[1] APTECH fitted a lower-bound and an upper-bound cost curve for each cycling cost in each category. APTECH then determined the median, 25th percentile and 75th percentile values from the lower- and upper-bound cost curves. The lower- and upper-bound values referred to in the report are actually the median values from the lower- and upper-bound curves.

Table 1. Description of Seven Unit Types Used

Unit Type	Type Name
1	Coal - Small Sub-Critical
2	Coal - Large Sub-Critical
3	Coal - Super Critical
4	Gas – Combined Cycle
5	Gas – Large-Frame Combustion Turbine
6	Gas – Aero-Derivative Combustion Turbine
7	Gas - Steam

The analysis performed by APTECH also defined various operating characteristics for each category, including the number of offline hours that would constitute a cold, warm, or hot start. Also defined were the typical ranges for load following by category.

The operating characteristics, as well as the cycling cost data by unit category, were used along with the unit-specific GE MAPS dispatch to calculate the additional unit-level and system-level cycling costs. Both the upper- and lower-bound cost data were used in this analysis. While the upper-bound cost data by unit category is confidential, it was applied in this analysis, and the overall system results can be presented without divulging the confidential data.

2 Analysis

The hourly operation of the generators from the five WWSIS scenarios (No Wind, I10R, I20R, I2020R, and I30R) was examined to determine the number of hot, warm, and cold starts for the year, as well as the number of turndowns. The WWSIS scenarios represent system conditions with no wind, 10%, 20%, and 30% penetration in the WestConnect region with an additional half that amount of penetration in the rest of WECC and the I2020R scenario considered a 20% penetration across the entire WECC footprint. The hourly operation for each scenario was determined from an annual simulation of the entire WECC system using the GE MAPS program in the WWSIS Phase 1 study. The results of this analysis are shown in Figure 1. In this figure, the study scenarios are shown along the x-axis, and the count of starts and turndowns are shown in the y-axis.

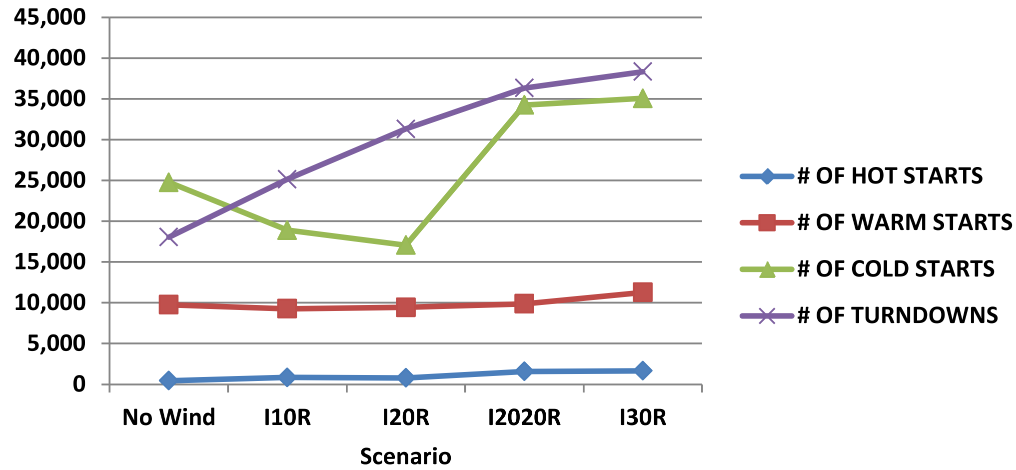

Figure 1. Total number of starts and turndowns by scenario

As might be expected, the number of turndowns increased with increasing renewable penetration. While the total number of hot and warm starts did not seem to vary significantly, the number of cold starts, while dropping initially, increased significantly with the higher renewable penetration. This is consistent with observations from the WWSIS Phase 1 study. Low to moderate penetrations of renewables generally displace existing generation without much of an operational burden. At higher penetrations, however, the forecast errors and variability exceed the operational capability of the online generators and result in more startups and shutdowns. Figure 2 shows the number of cold starts by unit type. The type 4 (combined cycle) units more than double their number of cold starts. The type 5 and 6 units, which are combustion turbines, initially decrease their number of starts due to displacement but then significantly increase their starts at higher penetrations due to forecast errors.

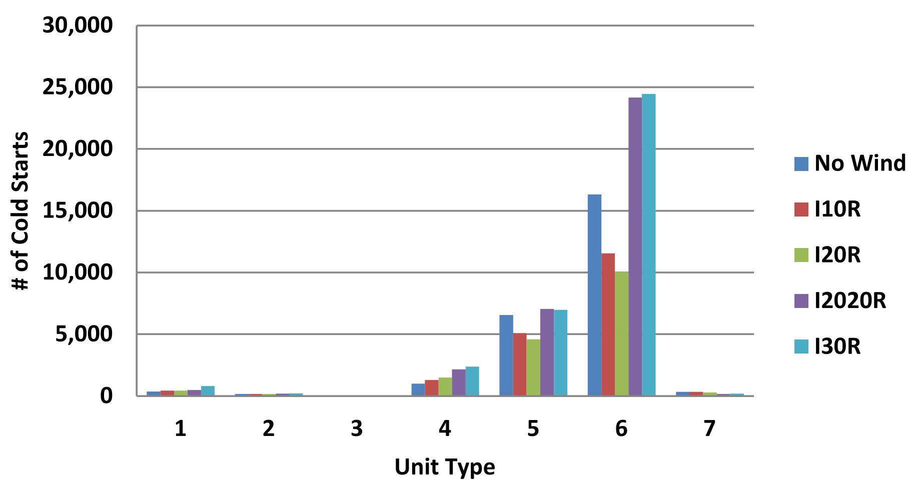

Figure 2. Number of cold starts by unit type

Figure 3 shows the number of turndowns by unit type for the various scenarios. The sub-critical coal units, types 1 and 2, had negligible turndowns at low penetrations of wind.

As the renewable penetration increases, however, the number of turndowns increases dramatically. The type 3 units, super-critical coal plants, do not cycle significantly even at the higher renewable penetrations. The bulk of the turndowns occur on the type 4 combined cycle units. This is consistent with the decreasing capacity factors observed on these units. The type 5 and 6 units, which are heavy-duty and aero-derivative combustion turbines, respectively, tend to either run at or near full load or else shutdown. Shutdowns were counted in the unit starts and were not considered in the turndowns. The type 7 gas steam units decreased their number of turndowns because they tend to be displaced at higher renewable penetration.

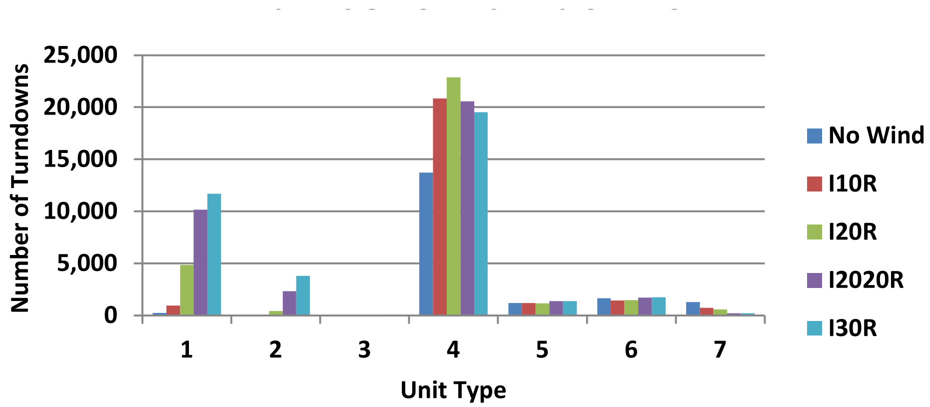

Figure 3. Number of turndowns by unit type

While the analysis of the operational data is illuminating, the important question is: How much more does this increased cycling cost?

To answer this question, the lower- and upper-bound unit-level costs developed by APTECH for turndown, hot, warm, and cold startup were used to calculate the annual cycling cost for WECC. The costs developed by APTECH were provided as a dollar-per-megawatt value so that larger units were correspondingly more expensive to start than the smaller units of the same type. Figure 4 shows the total WECC costs by cycling cost category based on the lower-bound values.

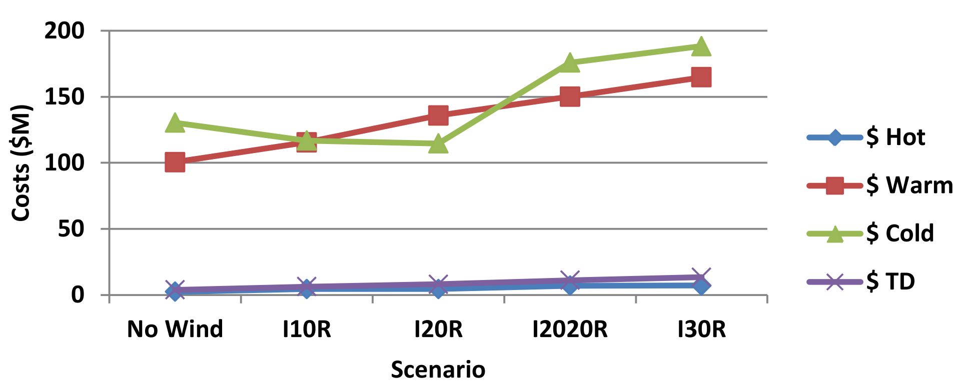

Figure 4. Total cost results by cycling cost category based on the lower-bound values

It can be observed from Figure 4 that the costs associated with turndown and cold starts are not that significant at the system level when compared with other cycling costs. This is not to say that these cycling costs may not be significant to an individual unit, but as these costs increase on some units they may be decreasing on others. The cost of the warm starts seemed to have one of the biggest impacts, which may be surprising considering the fact that the number of warm starts did not seem to change significantly in Figure 1. Figure 5 is a plot of the number of warm starts versus the unit's capacity for the No Wind and I30R scenarios. It can be seen that the number of starts decreased significantly for the smaller units but increased for the larger ones. Since the cost is proportional to the unit size, the overall costs increased.

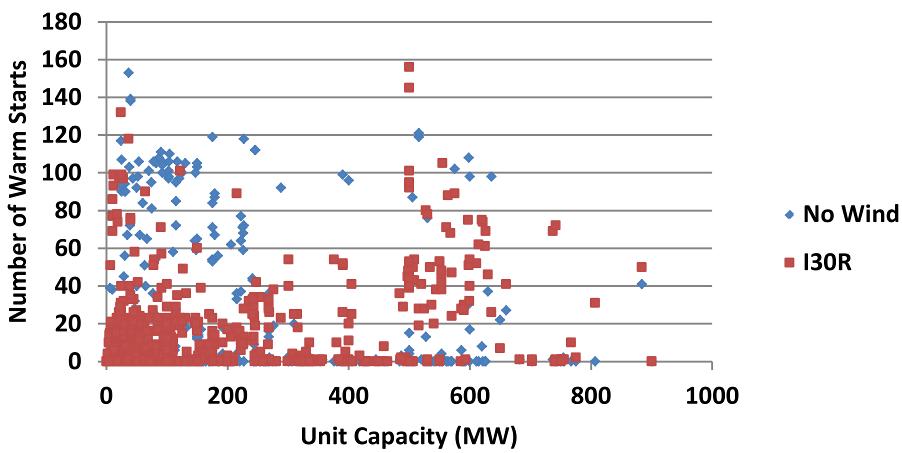

Figure 5. Number of warm starts versus unit size

Figure 6 shows the total WECC cycling costs using the upper-bound values. These results are similar to the case with lower-bound values but higher.

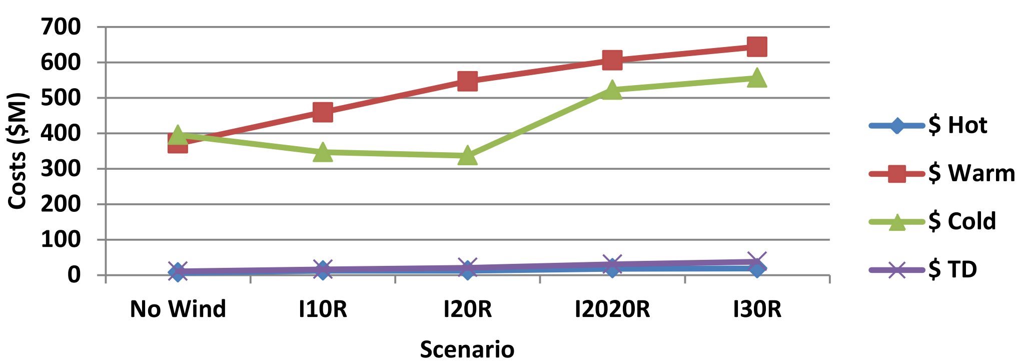

Figure 6. Total cost results by cycling cost category based on the upper-bound values

Figure 7 shows the total cycling cost increases over the No Wind scenario for both the lower- and upper-bound values. At the highest penetrations the additional system-level cycling costs range from almost $150 million (at the lower bound) to over $450 million (at the upper bound). This is a significant increase in overall WECC operating costs due to cycling. However, these costs must be considered in relation to the large amount of renewable wind and solar energy that was added to the WECC region.

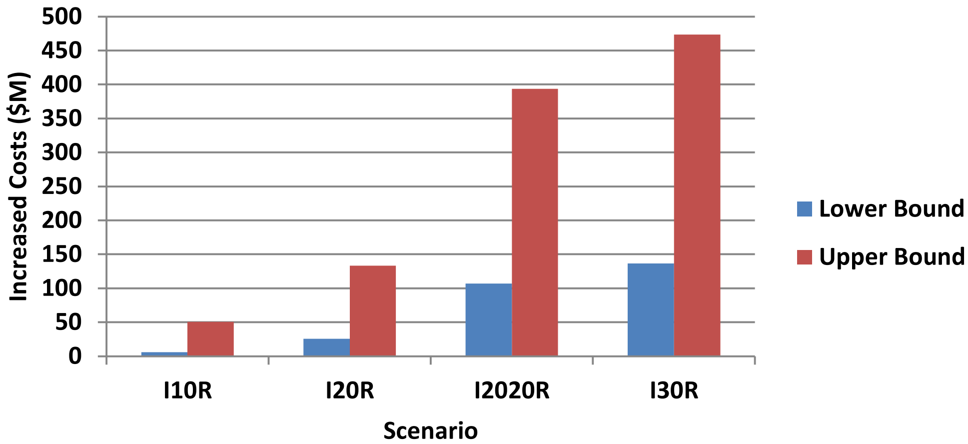

Figure 7. Increased cycling costs over No Wind scenario ($million)

Figure 8 has normalized the total WECC operating cost increases due to cycling with respect to the amount of renewable energy. Based on this figure the increased cost of unit cycling reduces the value of the renewable energy to the system by about $0.06/MWh to almost $2.00/MWh, depending on the renewable penetration and whether the lower or upper bounds for thermal plant cycling costs are selected. The overall system operating cost reductions due to wind and solar energy determined in WWSIS were roughly $85/MWh. Based on the lower-bound values provided by APTECH, the increased cycling costs would reduce the value of the renewable energy by 0.1% to 0.7%. If the upper-bound values are used, the reduction would be on the order of 0.6% to 2.4%.

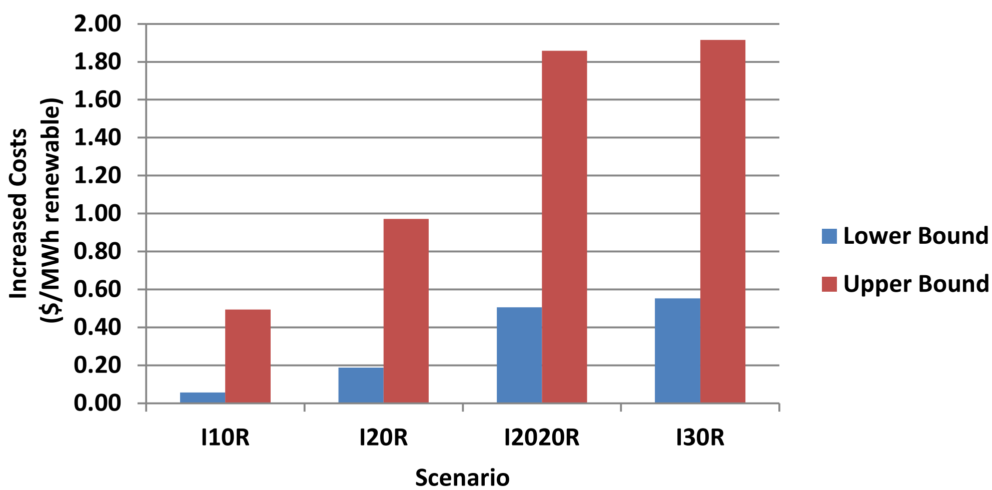

Figure 8. Increased cycling costs over No Wind scenario ($/MWh of renewable energy)

While the analysis described earlier focused on the incremental cycling costs only, Table 2 shows the incremental cycling costs obtained using the lower-bound APTECH costs in relation to other variable costs. It should be pointed out the base case figures were already included in the GE MAPS simulation performed in the WWSIS Phase 1 study. The incremental cycling costs were determined in the analysis described earlier. Although the startup costs, incremental startup wear and tear costs, and incremental turndown costs increase with increasing renewables, these costs do not offset the much more significant decrease in fuel and O&M costs. Figure 9 plots these values, highlighting their relative impact. Figure 10 shows just the non-fuel components.

Table 3, Figure 11, and Figure 12 show similar results using the upper-bound values from APTECH.

Table 2. Costs Versus Scenario (Lower-Bound Values)

Scenario	Base Fuel Cost ($M)	Base Variable O&M ($M)	Base Startup ($M)	Incremental Startup Wear & Tear ($M)	Incremental Turndown ($M)	Total Costs ($M)
No Wind	33,167	1,525	123	233	4	35,053
I 10R	25,777	1,360	125	237	6	27,505
I 20R	23,603	1,312	138	255	8	25,316
I2020R	18,867	1,214	142	333	11	20,566
I 30R	17,239	1,162	163	360	13	18,937

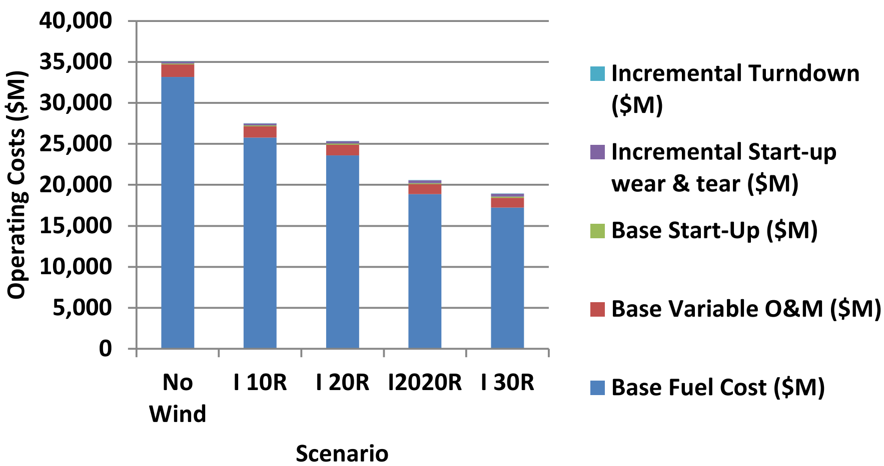

Figure 9. Costs versus scenario (lower-bound values)

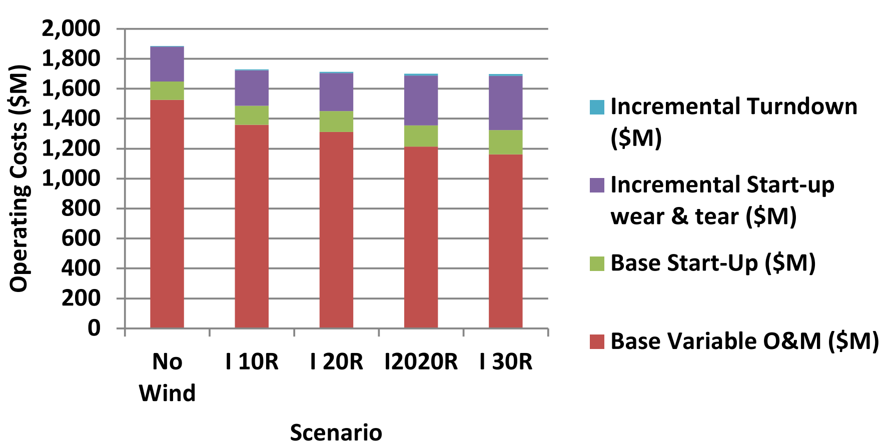

Figure 10. Non-fuel operating costs versus scenario (lower-bound values)

Table 3. Costs Versus Scenario (Upper-Bound Values)

Scenario	Base Fuel Cost ($M)	Base Variable O&M ($M)	Base Startup ($M)	Incremental Startup Wear & Tear ($M)	Incremental Turndown ($M)	Total Costs ($M)
No Wind	33,167	1,525	123	773	10	35,598
I 10R	25,777	1,360	125	818	16	28,095
I 20R	23,603	1,312	138	895	20	25,968
I2020R	18,867	1,214	142	1,146	30	21,399
I 30R	17,239	1,162	163	1,219	37	19,820

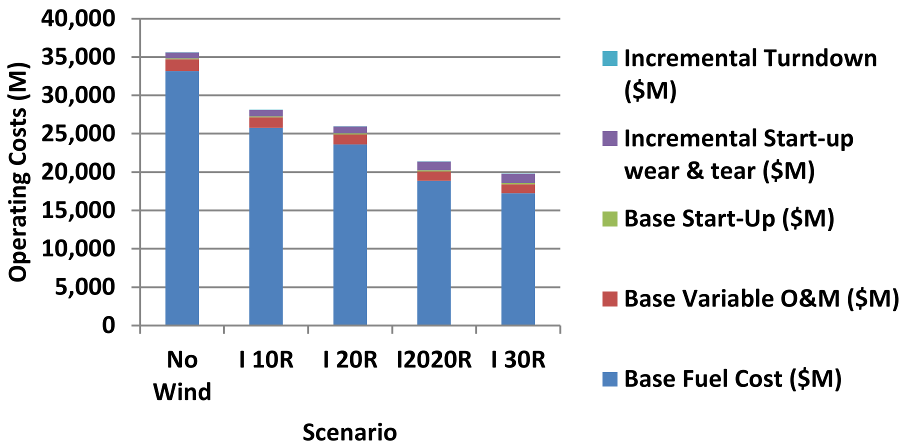

Figure 11. Costs versus scenario (upper-bound values)

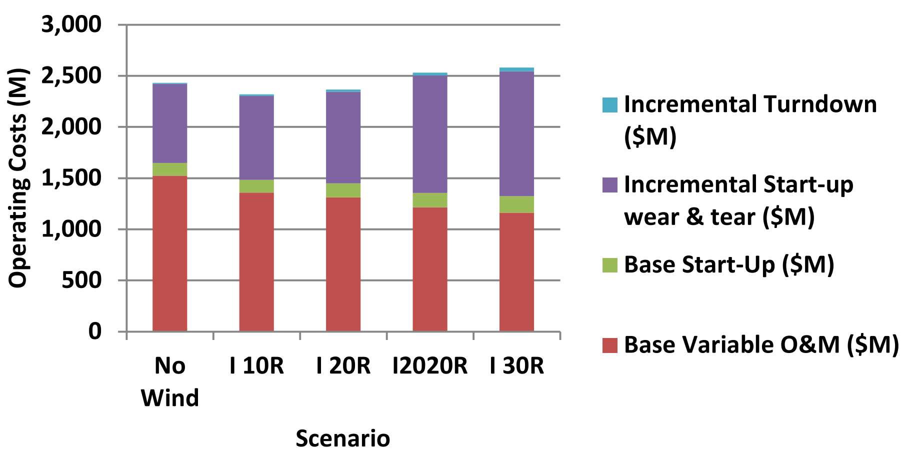

Figure 12. Non-fuel operating costs versus scenario (upper-bound values)

The next set of charts show the additional cycling costs by unit type. Figure 13 and Figure 14 show the total cycling cost by unit type for the various scenarios using both the lower- and upper-bound values. The largest impact by far is from the type 4 (combined cycle) units followed by type 5 and 6 (combustion turbines). Although it may be significant to the individual units, the cycling cost on the coal units had almost no impact on the overall system costs.

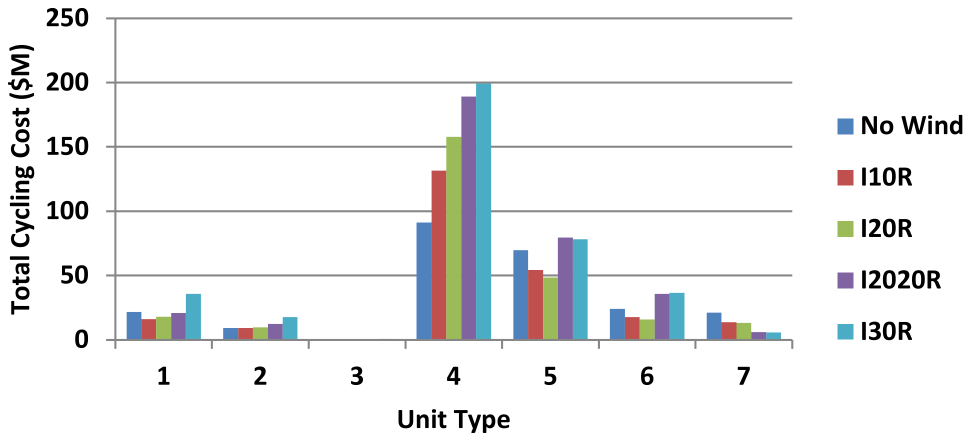

Figure 13. Total cycling cost by unit type with lower-bound values

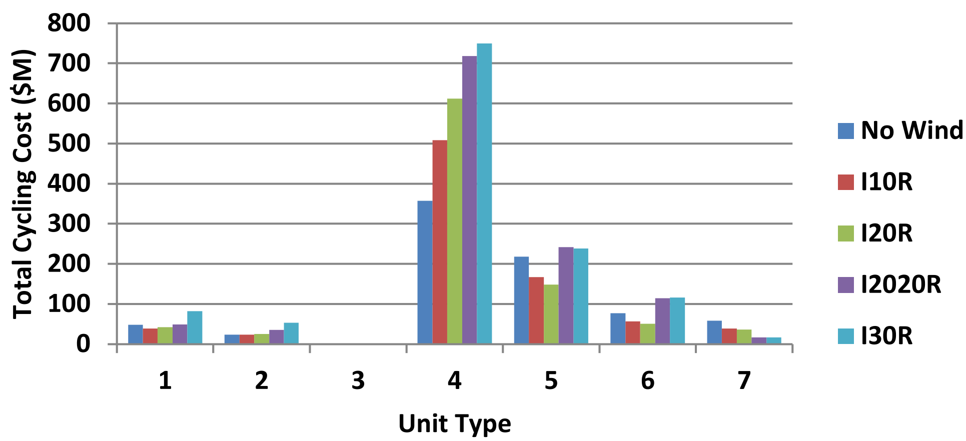

Figure 14. Total cycling cost by unit type with upper-bound values

Figure 15 shows the change in cycling costs for all of the units by unit type using the upper-bound values from APTECH. These values are the scenario I30R total cycling cost values minus the corresponding values from the No Wind scenario. The combined cycle units, type 4, increase their cycling costs by as much as $20 million. Figure 16 puts these cycling cost changes in perspective with the changes in the base operating costs (fuel + O&M + startup). The dot to the farthest right in the lower right quadrant increased its cycling costs by almost $20 million, but what is far more significant for the unit is that its base operating costs decreased by over $100 million. In general, the scale of the operating cost impact is an order of magnitude larger than the cycling cost impact.

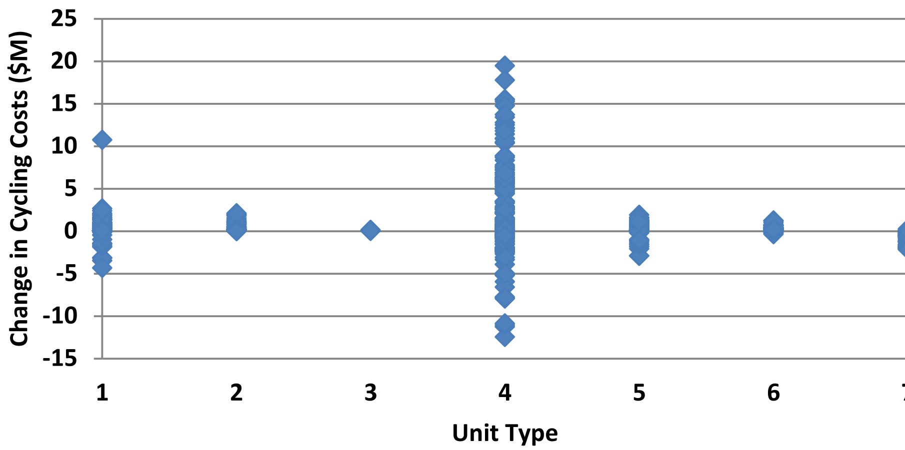

Figure 15. Change in unit cycling costs—Scenario I30R minus No Wind scenario (upper-bound values)

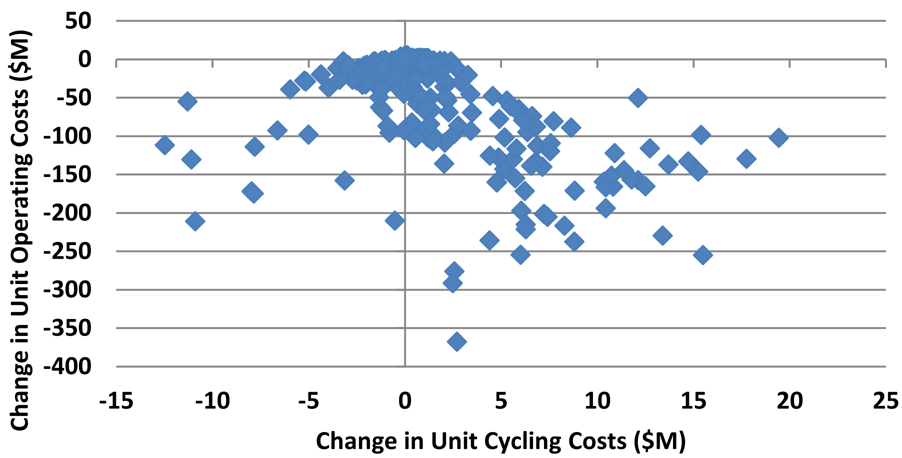

Figure 16. Change in base operating costs (fuel + O&M + startup) versus change in cycling costs—Scenario I30R minus No Wind scenario (upper-bound values)

Figure 17 is a similar plot that compares the change in cycling costs to the change in generator net revenue. In this instance the revenue is determined by the hourly generation times the hourly spot price at the generator. Although this is more typical of California (which has an energy market) than all of WECC, this provides a good indication of the generator's income potential. The net revenue subtracts the fuel costs, startup costs, variable O&M, and emission trading costs from the gross revenue. The unit with the $20 million increase in cycling cost only had an $11 million decrease in net revenue, so in this instance the change in cycling costs were more important. However, several of the units with a $15 million increase in cycling costs saw their net revenues decrease by $60 million to $90 million. In general, the reduction in net revenue far exceeds the increase in cycling costs.

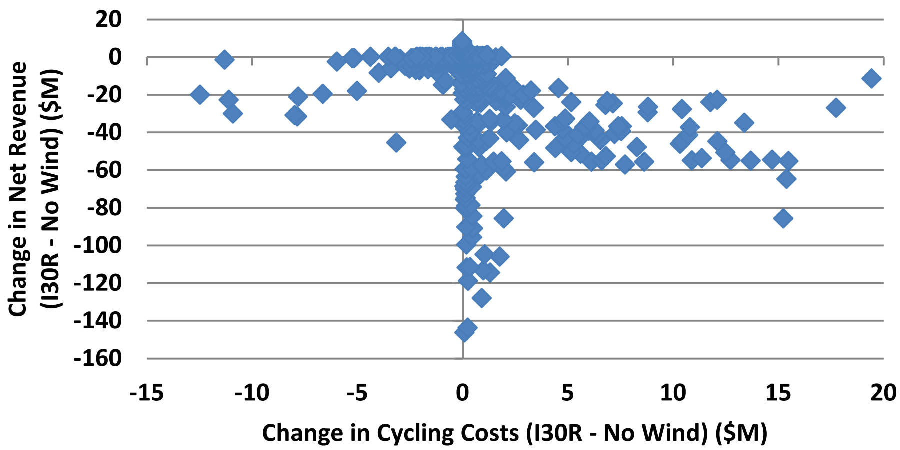

Figure 17. Change in net generator revenue versus change in cycling costs—Scenario I30R minus No Wind scenario (upper-bound values)

The forced outage rate changes due to increased cycling were not factored into this analysis. Per the APTECH analysis, the average increase in forced outage rate due to cycling was 0.12% for small sub-critical coal units and 0.02% for large sub-critical coal units. The super critical coal units did not increase their starts enough to affect their forced outage rates. While increased outages will require replacement by higher cost generation, these average changes did not seem to be overly significant.

3 Conclusion

This analysis examined the additional wear and tear costs associated with increased unit cycling due to renewables. The additional cycling cost for the system was determined by assigning a cycling cost to each thermal unit, and after-the-fact, using the hourly dispatch profiles obtained from the GE MAPS simulation output from the WWSIS Phase 1 study. Since the additional cycling cost for a unit was assumed to not change its dispatch, the overall cycling cost for the WECC system obtained this way represents the ceiling value. The actual cycling costs for the WECC system are likely to be lower if the additional cycling cost information is included in the commitment and dispatch optimization.

At the highest penetration level, the additional system-level cycling costs range from almost $150 million (at the lower bound) to over $450 million (at the upper bound) when compared to the case with no wind. This is a significant increase in overall WECC operating costs due to cycling. However, these costs must be considered in relation to the large amount of renewable wind and solar energy that was added to the WECC region. When normalized to the amount of renewable energy, the additional cost of unit cycling reduces the value of the renewable energy to the system by about $0.06/MWh to almost $2.00/MWh, depending on the renewable penetration and on whether the lower or upper bounds for thermal plant cycling costs are selected. The overall system operating cost reductions due to wind and solar energy determined in the WWSIS Phase 1 study were roughly $85/MWh. Based on the lower-bound values provided by APTECH, the additional cycling costs would reduce the value of the renewable energy by 0.1% to

0.7%. If the upper-bound values are used, the reduction would be on the order of 0.6% to 2.4%. While the impacts are by no means trivial when viewed from the perspective of the individual impacted thermal unit, they have a relatively small impact from an overall system perspective. From the individual generator perspective, in general, the loss in net revenue due to reduced dispatch and reduced spot prices far outweighed the impact of the increased cycling costs.

4 References

1. GE Energy, "Western Wind and Solar Integration Study", prepared for NREL, May 2010.

2. Intertek APTECH, "Power Plant Cycling Costs", prepared for NREL, April 2012.