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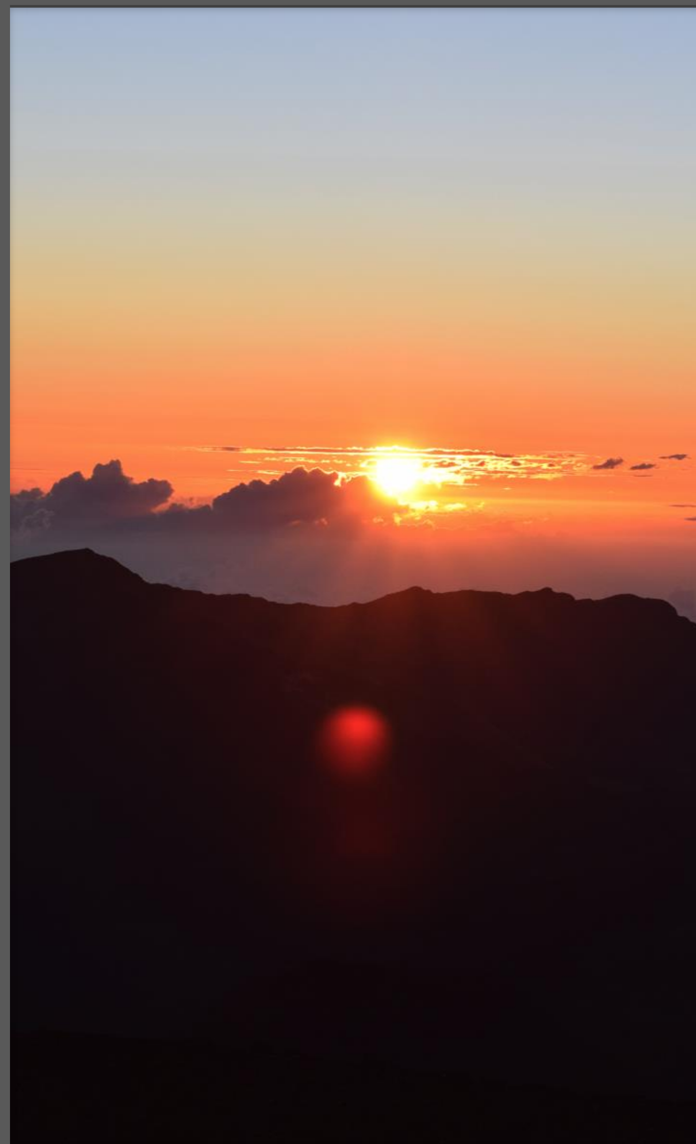

# *MISO high penetration renewable energy study for 2050*

*A study commissioned by the Midcontinent Independent System Operator*

January 2016

VIBRANT CLEAN ENERGY LLC

## Disclaimer

The present report has been prepared in good faith on the basis of information and study results available at the date of publication. The study results are produced using a Vibrant Clean Power, LLC co-optimization model. No guarantee or warranty of the results is applicable. The study intended to investigate the Midcontinent Independent System Operator (MISO) footprint only. It was not designed to be a full grid integration study. Neither Vibrant Clean Energy, LLC nor MISO will be liable for any loss, damage, or cost incurred by using or relying on the information in this report.

# Executive Summary

The co-optimization carried out by Vibrant Clean Energy, LLC assessed the difference between purely cost-optimized futures, where expansion of wind, solar, natural gas and transmission was considered, and futures where carbon dioxide emissions are constrained. The case studies had time horizons of 2016, 2030, 2036 and 2050. The demand was grown to keep up with increasing electricity consumption over the MISO footprint. No connections to other markets were considered.

For the carbon dioxide reduction cases, targets were set at each of the time horizons. There was no carbon reduction level for 2016, a 30% reduction by 2030, a 50% reduction by 2036 and an 80% reduction by 2050. The reductions were compared with the emissions level in 2005. The base cases without emissions constraints are used as a reference point to determine changes in the grid and the costs associated with those changes. The model initializes with the existing generation within the MISO footprint and solves for each of the ten Local Resource Zones (LRZs).

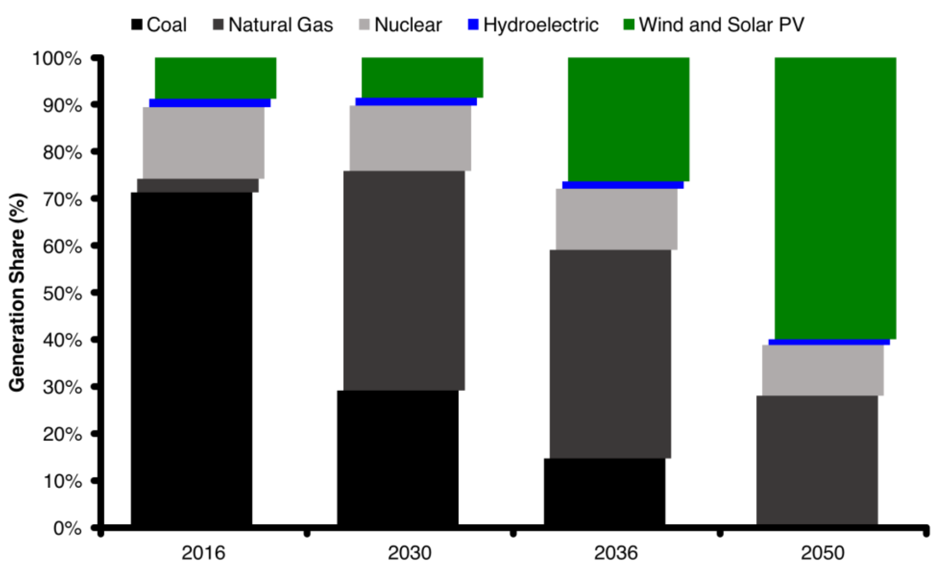


Figure 1: The share of generation for the most dominant sources within the MISO footprint over the four study time horizons. Carbon dioxide emissions are not constrained in 2016, are reduced by 30% by 2030, 50% by 2036 and by 80% by 2050. Transmission expansion is allowed in this co-optimized scenario. By 2050, over 60% of the electricity can be produced by weather-driven renewable sources.

In Fig. 1, we show the composition of the generation share from 2016 through 2050, when the emission targets are enforced. Between 2016 and 2030, the first emission reduction results in a decrease in coal use replaced with a significant increase in natural gas. The very small share of natural gas in 2016 is likely a consequence of relatively high natural gas fuel price within the model compared with the actual cost for 2016. As the carbon dioxide emission constraints tighten (between 2030 and 2036), more coal is displaced along with some natural gas; transitioning to wind and solar PV. In the final transition, the remaining coal is removed in favor of a combination of wind, solar PV and natural gas. In the scenario shown in Fig. 1, transmission is expanded extensively by 2050 between the LRZs to accommodate the variable generation of wind and solar PV.

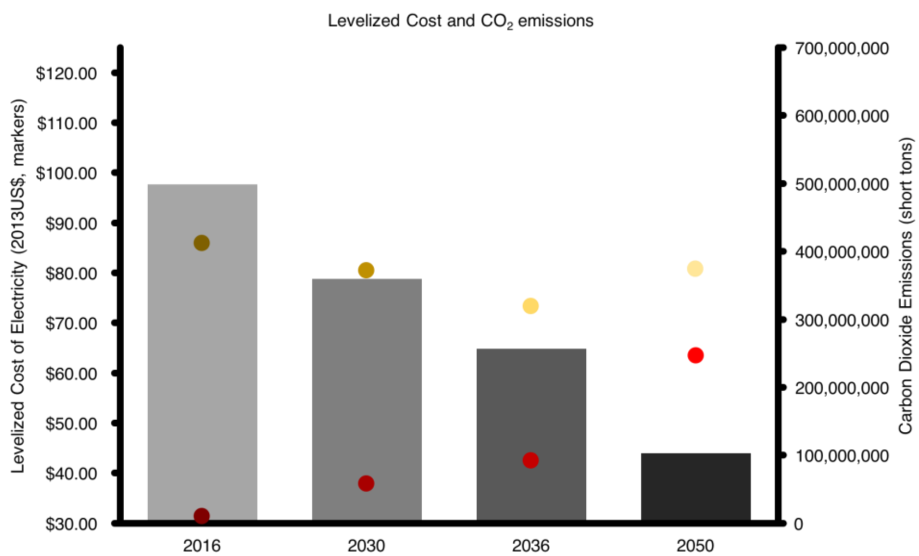


Figure 2: The levelized cost of electricity (LCOE) and the total carbon emissions from electricity production within the MISO footprint. The bars represent the $CO_2$ emissions (right axis). The red dots symbolize the LCOE when not considering the capital costs of existing generators on the MISO grid, while the yellow dots show the LCOE that includes these capital costs. The scenario is the same as in Figure 1.

The transition to a lower emissions MISO electric grid will involve many aspects. One significant aspect is cost of electricity. As can be seen in Fig. 2, the generation costs over time will increase, when existing generator sunk costs are not considered. If these costs are considered, for example to replace like-for-like generators, the cost of electricity actually decreases by 2050. In Fig. 2, the emission rates for each time horizon can be seen. It shows a significant reduction compared with 2005 levels and is related to emission constraints imposed on the reduction cases.

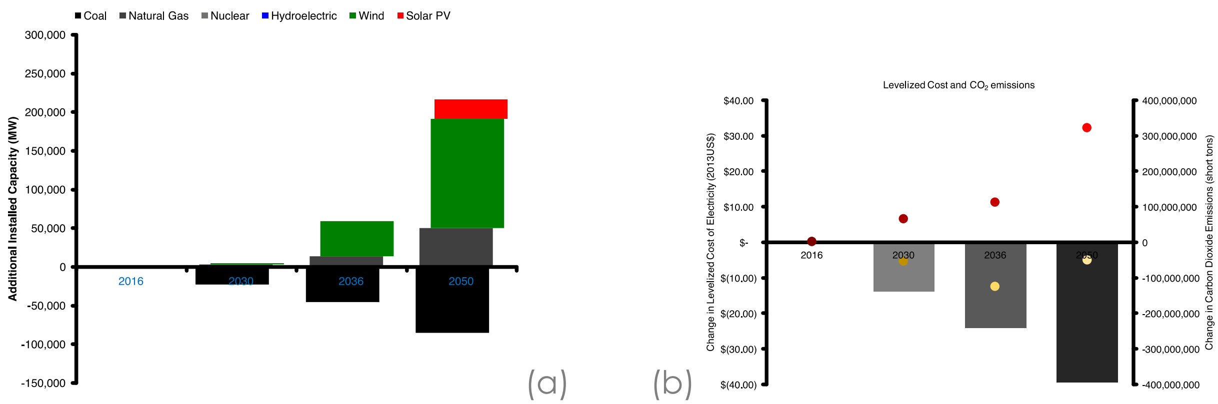


Figure 3: The incremental change of capacity (a), cost and $CO_2$ emissions (b) with each time horizon compare to the 2016 co-optimized solution. The capacity change is small in 2030, as transmission expansion and a perfectly efficient dispatch of the system reduce congestion and uneconomical capacity. By 2050, all coal is removed and is replaced with increased natural gas, along with significant amounts of wind and some solar PV. The difference in the changes when considering sunk costs is notable, and is shown in panel (b).

The transition to a lower carbon emissions electricity grid, while also incorporating increasing demand, will result in an increase in overall capacity. It is shown in the present study that when considering transmission expansion, fewer generators are necessary and lower costs are captured. The study further shows that without some type of dispatchable generation or a storage medium the MISO footprint alone cannot reduce emissions much lower than the 85-90% range. In Fig. 3, we show the change in capacity, costs and carbon emissions compared to the co-optimized 2016 model generated system. It shows how the capacity of the MISO footprint will grow in size, and how the costs vary between each model time horizon. If all costs are considered, the electric price falls over time. If sunk costs are not factored in the electric prices rises, as generators that are retired in the model are replaced with new ones; driving up the costs.

The MISO footprint has excellent wind and solar PV resources and can capitalize on these resources with strategic planning. The system can cope with a carbon emissions reduction target of 80% compared with 2005 levels. It may be possible to have the same reductions with lower costs, if MISO further connects with neighbors and takes advantage of geographic area smoothing of resource and demand. The present study shows significant possibilities for MISO to accomplish goals of emission reductions if deemed necessary.

# Contents

## Study Scope and Background

The Midcontinent Independent System Operator (MISO) commissioned Vibrant Clean Energy, LLC to perform a study that investigated high carbon emission reduction electric grid scenarios up to 2050. The study was limited in scope to four future time horizons, namely 2016, 2030, 2036 and 2050. This study informs MISO's analysis of potential fleet transitions in the future, including changes driven by environmental regulations such as the Clean Power Plan.

The study scope is defined in two separate categories:

1. Cost co-optimized scenarios over the entire MISO footprint evolving from 2016 through 2050.
    a. *The cost optimization has transmission constrained to existing transfer levels between the local resource zones (LRZs).*
    b. *Expansion of the transmission is allowed, but at costs to build the lines, if the model deems it economical.*
    c. *Each of a. and b. are further divided into a Base Case (BC) scenario and a Reduction Case (RC) scenario. The BC scenario is without carbon emission constraints, while the RC scenario constrains the carbon emissions.*
2. Load matching co-optimized scenarios over the entire MISO footprint evolving from 2016 through 2050.
    a. *The load matching optimization has transmission constrained to existing transfer levels between the local resource zones (LRZs).*
    b. *Expansion of the transmission is allowed, but at costs to build the lines, if the model deems it economical.*
    c. *Each of a. and b. are further divided into a Base Case (BC) scenario and a Reduction Case (RC) scenario. The BC scenario is without carbon emission constraints, while the RC scenario constrains the carbon emissions.*

Therefore, the study contains 32 separate optimized scenarios. The study created resource data for the wind and solar PV, along with associated land use datasets. MISO provided hourly load profiles for each of the LRZs for a standard year (2006). The weather and power data were produced for the same year.

The study scope is designed to determine the changes that occur between a 30% and 80% reduction in $CO_2$ for the MISO footprint. It provides a quantification of how transmission expansion transforms the optimized solutions. Further, it depicts the differences between a low-carbon electric grid and a baseline one. Finally, the load matching optimization facilitated determining an upper bound on carbon emission reductions when storage is not included.

The carbon emission constraints are given as:

A. *Entire MISO footprint without $CO_2$ emission constraints in 2016.*
B. *A 30% reduction in $CO_2$ emissions compared with 2005 levels by 2030.*
C. *A 50% reduction in $CO_2$ emissions compared with 2005 levels by 2036.*
D. *An 80% reduction of $CO_2$ emissions compared with 2005 levels by 2050.*

The final portion of the study is the production of this report to accompany the result files and graphics that are also produced. The intent of this report is to explain the major findings and to document the methods used.

# Methods

## Geographic Extent

The geographic extent of the study is contained within the MISO footprint. The model takes into account the ten LRZs, where LRZ 1-7 are defined as MISO north and LRZ 8-10 are defined as MISO south. These definitions are important when considering transmission planning within the model expansions. The LRZs are projected into the model space as shown in Fig. 4.

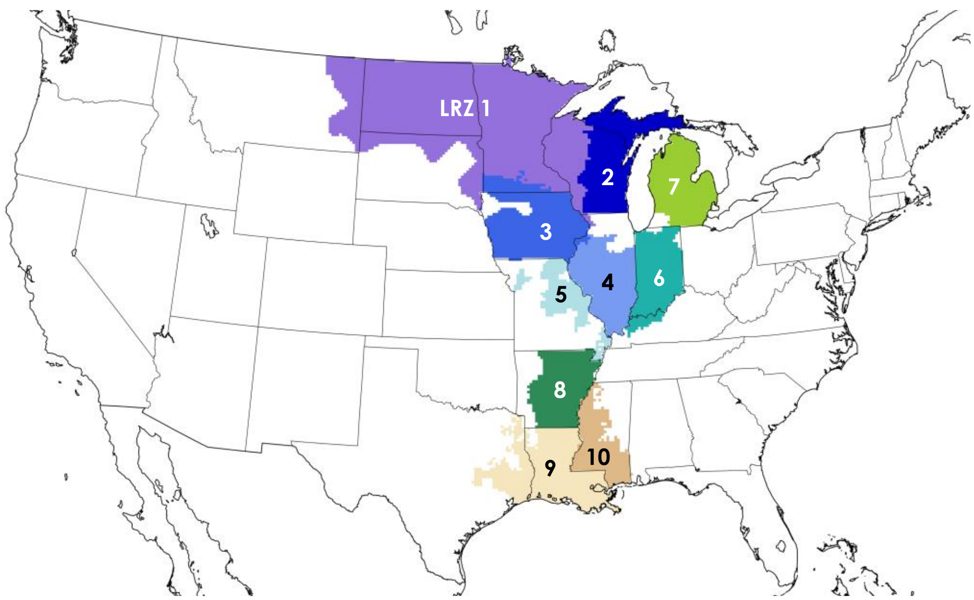


Figure 4: The geographic extent of the present study. Each of the LRZs has a separate color and is labeled. The model balances generation, transmission, and demand within each LRZ. The model does not consider transmission to or from outside MISO.

The LRZs shown in Fig. 4 are used to define the areas where generation, transmission and demand are balanced. Each LRZ has a separate load profile (see next section on how load is input). The LRZs are used from Fig 4. to assign the resource locations, transmission expansion, and cost inputs for generators.

## Load

The load profiles for each of the LRZs were provided by MISO from actual data. It was selected that 2006 would be the reference year. In Fig. 5, we show the normalized (to peak demand) aggregated load profile for MISO. It shows that the peak demand is 118,101 MW, with a mean normalized demand 60% of the peak value (70,917 MW). The total electric demand was estimated as 594,497,683 MWh.

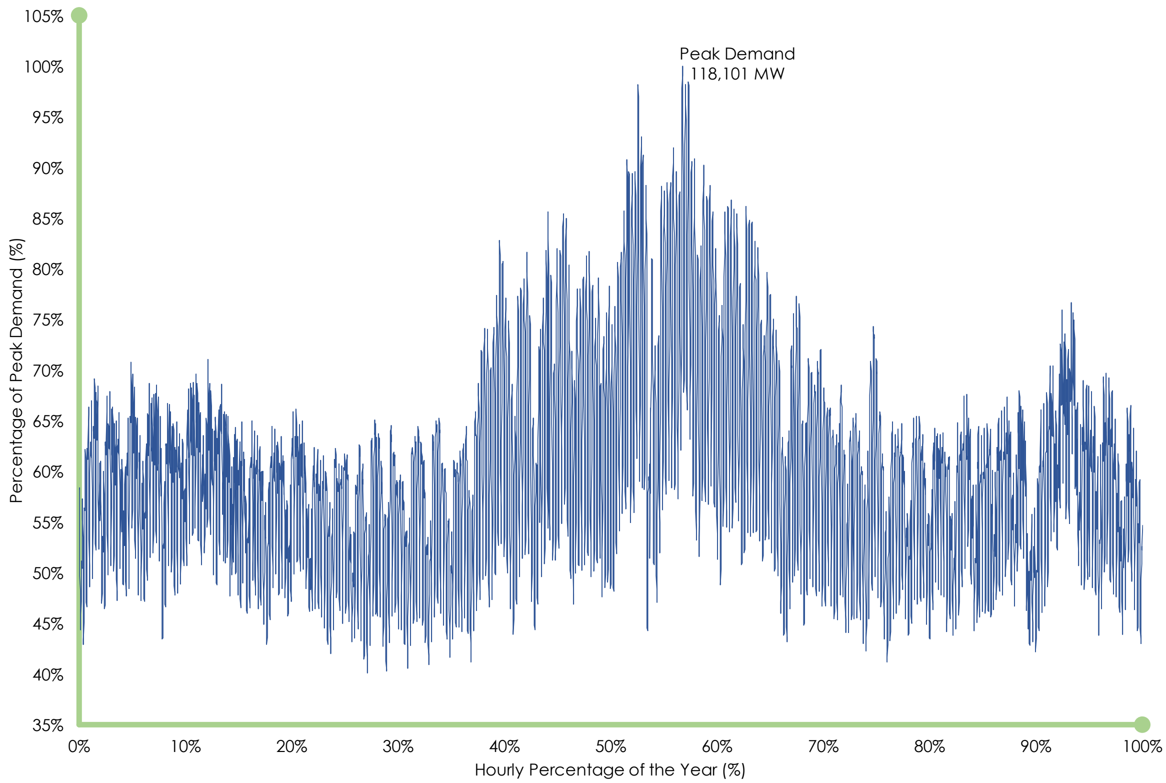


Figure 5: The peak-normalized aggregated demand profile for the entire US MISO footprint. The aggregated demand is the sum of the demand profiles in each of the LRZs. The year chosen as a reference was 2006. The peak demand was 118,101 MW. The demand profiles were time-aligned with the wind and solar power dataset.

The present study has time horizons ranging from 2016 to 2050. The demand profiles are for 2006. Therefore, assumptions need to be made with regards to the changes in the demand profiles through time. It was decided that a simplistic expansion constant would be applied to all of the demand profiles. The value of the expansion constant was +0.8% per year. That resulted in a modeled increase of electricity consumption of 12% by 2016, 21% by 2030, 27% by 2036, and 42% by 2050.

The increase in total electricity consumption is an important assumption because all of the LRZs demand profiles expand at the same rate (using our assumption). It may be that the electricity consumption growth is different in each of the LRZs, and the growth may be more complex than a simplistic expansion. For example, the demand may increase in summer and reduce in winter, altering the load profiles further. Another example would be the addition of electric vehicles, where charging will increase the electricity consumption; but the charging profiles may alter the overall demand profiles diurnally. However, the purpose of the present study is to look at the overall alteration in the structure of the electricity grid, while anticipating increases in total electricity demand.

Two final steps related to the demand profiles are the reserve requirements. The model assumes a 15% planning reserve capacity. The 15% is related to the peak demand over the entire US MISO footprint. The model must supply enough capacity to meet this constraint. The second reserve constraint is load-following. At each hour in the optimization procedure, the model must supply 7% of the load at that hour in reserve capacity. The reserve capacity in this case is either "spinning" reserves provided by thermal generation or down-dispatched wind and solar generation.

## Variable Generation Resource

An essential input for the co-optimization routines is the resource potential at sites across the MISO footprint. Since 2006 was selected as the reference year, the weather data for that period was critical. It was decided that the wind resource would be computed at 80m AGL and the solar PV resource would be created for flat panels, tilted at latitude (no tracking). The load profiles are at hourly resolution; thus the resource potential was calculated at the concurrent 60-minute intervals.

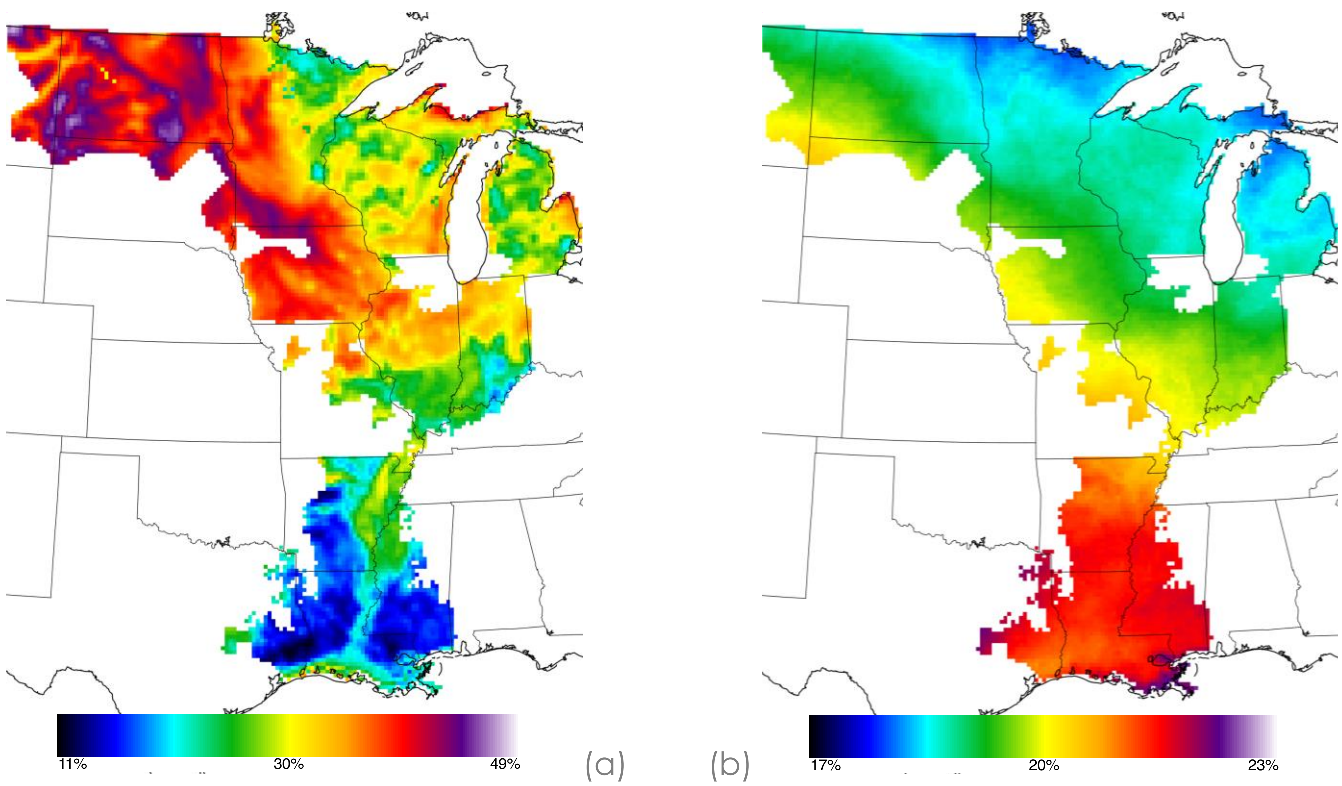


Figure 6: The wind (a) and solar PV (b) average resource for 2006. The average resource is defined as the annual capacity factor. It is clear from the panels that the best wind resources (in terms of capacity factors) are in the north and the best solar PV resources are in the south.

The atmospheric data is provided by a numerical weather prediction data assimilation model. The analysis fields from the operational Rapid Update Cycle (RUC) were downloaded from NOMADS (ftp://nomads.ncdc.noaa.gov/RUC/analysis_only/). To assist with the creation of the solar irradiance model data, GOES satellite reflectance were obtained from NOAAs CLASS database for each three-day periods for the entirety of 2006 (http://www.class.ncdc.noaa.gov/saa/products/search?datatype_family=GVAR_IMG) and images were also checked using the SSEC Data Center Archive (http://www.ssec.wisc.edu/datacenter/archive.html). Using the publicly available atmospheric data, proprietary algorithms were developed to mimic the behavior of wind turbines and solar PV panels. The wind power algorithms took into account shear, veer and turbulence across the rotor diameter (100 m) for turbines at 80 m above ground level (AGL). The solar PV power algorithms consider clouds, temperature, and the components of irradiance. Both algorithm suites incorporate reductions in final power output to account for downtimes, maintenance, and inverter/wiring inefficiencies.

The proprietary algorithms output power for each of the model resource locations at each hour for 2006. Each resource location was assigned to an LRZ, where it added to that regions potential portfolio. The resource is assumed to be "as is" by the co-optimization procedure. That means that the optimization has perfect foresight throughout each of the time horizons. However, the optimization does not have knowledge of future states. The resource is assumed the same for each time horizon. Some sensitivities in the future would be warranted to predict how the system changes under different weather and demand scenarios. However, since the present study is focused on the high-level adoptions on the electric grid as carbon dioxide reductions take hold, a single year's worth of data was utilized.

## Land Use

We began land use determination by gaining access to data that described the generators that exist on the MISO grid as of August 2015. The data was collected from the US Energy Information Administration (EIA) [http://www.eia.gov/maps/layer_info-m.cfm]. The data was obtained in GIS format and converted/re-gridded into the optimization model grid space. We only considered six generation technologies: Wind, Solar PV, Natural Gas, Coal, Nuclear, and Hydroelectric. The combined capacity of these generators is 223,648 MW.

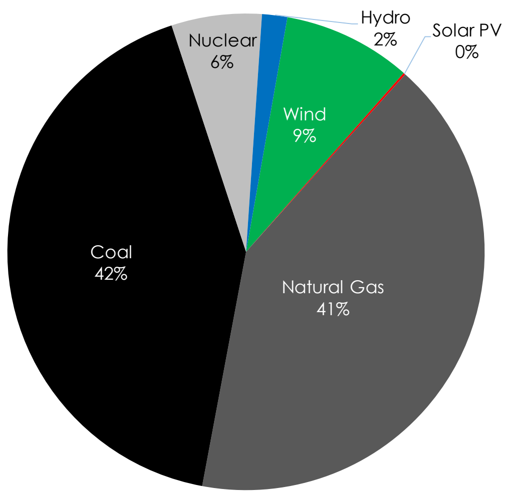


Figure 7: The share of estimated installed capacity on the MISO electric grid in August 2015. The chart shows the share of 223,648 MW of capacity available to the co-optimization procedure at its initialization; where costs are already sunk.

Figure 7 shows the share of total capacity that each generator type has at the outset of the co-optimization procedure. The model uses the actual locations and capacity of each of the different generators within the MISO footprint.

The only generator types that are allowed to increase in capacity are wind, solar PV, and natural gas. The model does not consider rooftop solar PV, concentrating solar power (CSP), or other type of generation. The co-optimization is capable of including these types in possible future studies, but for the sake of simplicity only three generator types are competing for expansion.

For natural gas, it is assumed that generators can be augmented at current facility locations or new locations for the same cost as an augmentation. For wind and solar PV, further analysis was required as the “fuel” for these generators cannot be transported as natural gas and coal can be.

For both wind and solar PV sorting algorithms were utilized to remove areas of population, protected lands and military facilities. Further, terrain was factored into the computation of available space for technologies. The maximum density of wind turbines within a model grid cell was restricted to no more than one per $km^2$ (< 2.5 MW / $km^2$). Solar PV was restricted to a maximum installed capacity of 15 MW per $km^2$. The resulting upper bounds for potential deployment were input into the co-optimization procedure to ensure that generation is not overbuilt in single grid cells.

Each resource site is assigned a distance from its LRZ demand center; which facilitates a cost and loss function to be applied within the co-optimization procedure if that resource site is chosen to be connected to the electric grid within that LRZ. The loss function then removes power from generator power output before it reaches the LRZ demand center.

## Generator Types and Costs

The type of generators is an important input, and in the previous sub-section it was noted that wind, solar PV, natural gas, coal, nuclear and hydroelectric were considered. Further, transmission is available between the LRZs and this was applicable for expansion in half of the co-optimizations. There are features of the generators that are important to note. All the information available to the co-optimization procedure is found in the accompanying excel spreadsheet (Cost_Matrices_ForInput_MISO.xlsx). That spreadsheet contains most of the cost and generator features that are utilized by the co-optimization.

| | Heat Rate Btu / kWh | Capital $ / kW | Fixed O/M $ / kW-yr | Variable O/M ¢ / kWh | Service Life Yr | Discount Rate % |
|---|---|---|---|---|---|---|
| Wind | N/A | 1,840 | 30 | 0.510 | 30 | 6.6 |
| Solar PV | N/A | 1,800 | 15 | 0.000 | 30 | 6.6 |
| Natural Gas | 6,430 | 1,000 | 15 | 0.276 | 30 | 6.6 |
| Coal | 9,250 | 2,890 | 29 | 0.409 | 30 | 6.6 |
| Nuclear | 10,700 | 4,130 | 92 | 0.063 | 30 | 6.6 |
| Hydroelectric | N/A | 3,230 | 14 | 0.275 | 30 | 6.6 |

Table 1: Some of the salient features of the generator types considered in the co-optimization. The model is capable of having unique quantities for each of the LRZs, but for the present study these values are ubiquitous over the MISO footprint.

Table 1 shows some of the most important inputs for the generator types considered by the co-optimization. The model has the capability to assign unique values for each of the quantities in Tab. 1 for each LRZ. However, in the present study the values are ubiquitous across the MISO footprint for the sake of simplicity.

| | Fuel Costs $ / mm Btu | Gen limit up. % capacity | Gen limit lo. % capacity | Ramp limit up. % capacity | Ramp limit lo. % capacity |
|---|---|---|---|---|---|
| Natural Gas | 5.19 | 100 | 25 | 50 | 50 |
| Coal | 2.26 | 100 | 50 | 10 | 10 |
| Nuclear | 0.50 | 100 | 95 | 5 | 5 |
| Hydroelectric | N/A | 100 | 0 | 100 | 100 |

Table 2: Thermal and hydroelectric generation features available to the model. Natural gas has the greatest ability to ramp of all the thermal generators; nuclear has the least.

Table 2 shows the dynamic range of the possible dispatchable generation. These numbers are only used when the generators are available to the grid. The wind and solar PV can also be down ramped by the co-optimization to help with grid stability. It should be noted that the cost of fuel (and all other costs) are constant throughout the optimizations. Even though the costs are in real US dollars, there would likely be learning curve cost reductions. In addition, the cost of natural gas fuel is known to be lower currently (2016); however, in the longer term its value is less predictable. The model can vary costs between time horizons, based upon learning curves or predicted changes in costs. For the present study, the costs were held constant to determine what the outcome would be without too many varying factors. Further work would be warranted to assess the impacts of evolving costs and pricing as the system transform under different scenarios.

The generator types are limited in scope for the present study, but the co-optimization procedure can include many more generators. Indeed, it can even incorporate variations of specific generators. For example, taller wind turbines, more efficient solar PV panels, CSP, distributed rooftop PV, storage, or geothermal. The present study focused on the most abundant generators on the MISO grid to calculate the broad changes that would occur with carbon reduction targets. The future MISO grid under high carbon dioxide emission reductions will likely include wind and solar PV in higher capacities than today; thus a consideration of how these resources are developed is of significant importance.

The cost of transmission is assumed to be the same for each LRZ. Transmission lines are priced at $701.36 / MW-mile. There is a further capital charge of $182,856.11 / MW for the transmission built between the LRZs and the Hubs. The charge is assumed to be for either HVDC stations (if transmission is direct-current) or the cost of Alternating Current (AC) connections. Within the LRZs the cost is simply assumed to be just for the transmission lines. The discount rate and service life are 6.6% and 30 years, respectively.

## C-OEM Application

The Vibrant Clean Energy, LLC co-optimization procedure: the Co-Optimized Energy Model (C-OEM) is a mathematical optimization software package that determines the capacity expansion of a pre-defined geographic electric grid while simultaneously dispatching generation and transmission at the temporal resolution of the demand profiles. C-OEM can be run in Linear Programming (LP) or Mixed Integer Programming (MIP) modes. When using the LP mode, the unit commitment is more simplistic than in the MIP version. The LP version is much more computationally efficient, and since C-OEM is provided with true weather and demand data, unit commitment is less important – the C-OEM has knowledge of the entire range of load and weather conditions for the entire year period, thus units are committed perfectly for the entire time horizon. In other words, the electricity system is dispatched in the most economically efficient way, and as such can be considered as an upper bound for the dispatch available.

The C-OEM solves the objective function for each time horizon, when considering a full year of dispatch requirements. The two objective functions for the present study are:

1. The total electric system costs; including capital for new generators, Operations and Maintenance, fuel for thermal generators, transmission expansions, reserve costs, and the cost of connecting new generators to the grid.
2. The total divergence of variable generation from the demand profiles. Simply, the sum of the curtailments and fossil thermal generation over the model time horizon.

The objective functions are minimized to find the smallest non-trivial solution, while providing the services of an electric grid. The services that the C-OEM must provide for an electricity grid include:

A. The demand profiles must be satisfied in each of the ten LRZs each hour for the entire time horizon, without fail.
B. To satisfy the demand profiles, transmission may be utilized. The transmission capacity must always be greater than the power flowing along the lines.
C. The C-OEM contains a transmission power flow matrix that computes the network flows within the transmission. It further calculates and updates itself with the losses associated with the power flowing between end points.

D. The possible generation reaching each LRZ must include a load-following reserve.
E. Over the time horizon the C-OEM must provide the electric grid with planning reserve for each of the LRZs.
F. The combined area of generators deployed by C-OEM in each model grid cell cannot exceed the area available for energy production.
G. Each generator must perform within its tolerance levels provided to it. In particular ramp rates and minimum/maximum operating levels are adhered to.
H. Retired generation cannot be brought back online at a later time horizon.
I. New capacity must be maintained within the grid through the final time horizon (2050).
J. The hydroelectric can only be dispatch up to the levels that it reached in that meteorological year (2006). That level is ~41% of the nameplate capacity.
K. The maintenance schedule for the nuclear power plants must be upheld.
L. The load is expanded between each time horizon.

The C-OEM is not currently built to be a full and complete grid integration model, rather an estimation of grid operation while conducting capacity and transmission expansion. Additional features can always augment the ability of C-OEM to represent realistic operations of the electric grid. Nevertheless, the C-OEM satisfies all of the constraints A.-L. above, for each hour of a standard year for each of the time horizons within the model.

For the present study there are four time horizons. The C-OEM solves at each time horizon. All information is passed between the previous time horizon to the one being solved. Thus, C-OEM does not have knowledge of how the resource, load profiles, or emission constraints may change pushing forward in time. Once C-OEM solves a time horizon it outputs all of the variables that have been computed. The process was repeated for each of the scenarios.

Once C-OEM has produced the outputs and completes the optimizations a further suite of algorithms and scripts are used to compile the information together. This data is then input into report spreadsheets. There are numerous outputs and many files to deal with. The results section below will delve into what these files contain.

# Results

## Cost Optimization (CO)

The cost optimizations have four separate scenarios: Base Case (BC) with and without transmission expansion (NCT [Non Constrained Transmission] and CT [Constrained Transmission], respectively); Reduction Case (RC) with and without transmission expansion (NCT and CT, respectively). The CO BC NCT scenario is the most efficient for the electric power grid contained within MISO. It reduces the capacity needed, increases transmission flows (and capacity), and has lower costs than all the other scenarios. The CO RC NCT scenario produces an electric grid that emits 80% less carbon dioxide than 2005 levels in a manner that is most cost effective of all scenarios.

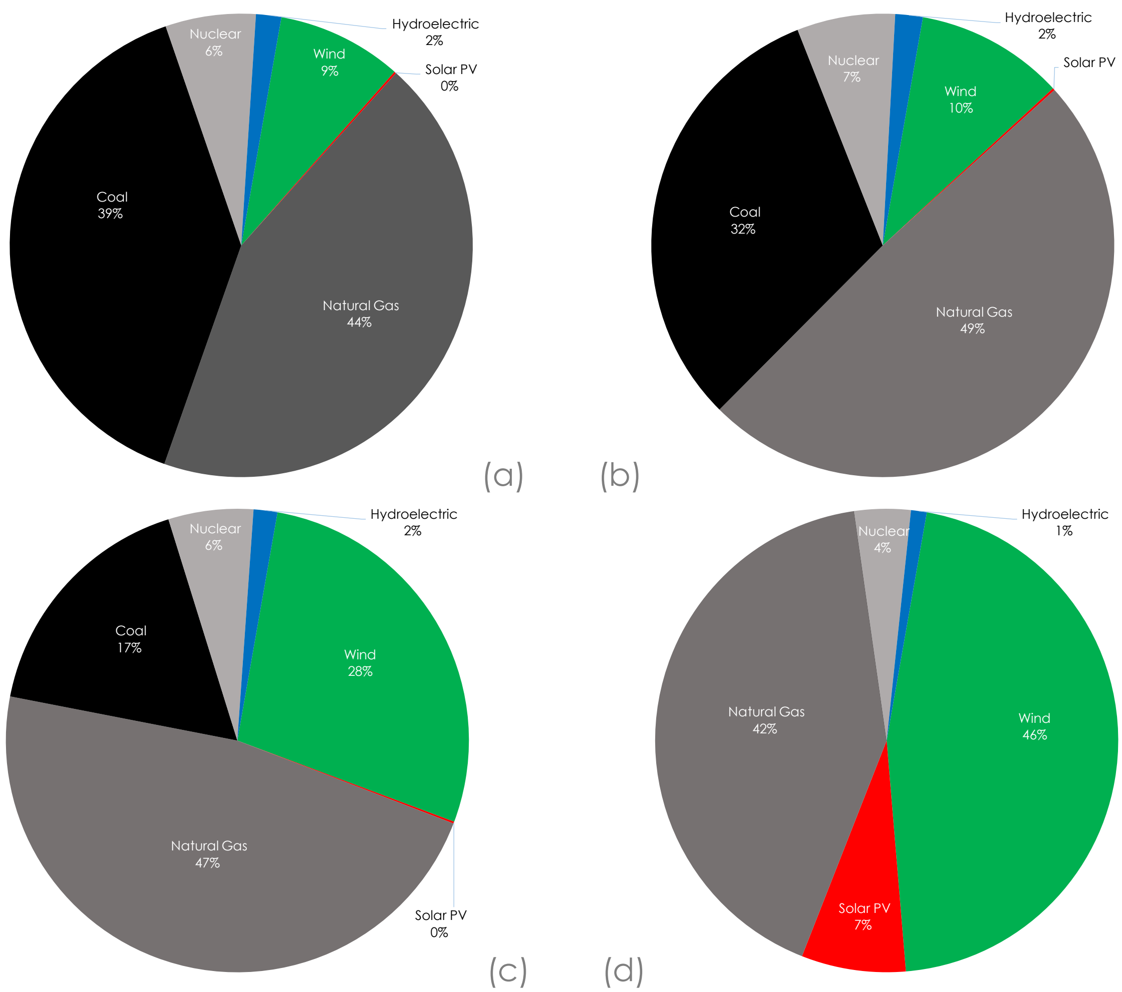


Figure 8: The share of capacity for the four time horizons for the CO RC NCT scenario; (a) 2016, (b) 2030, (c) 2036, (d) 2050. By 2050, with an 80% CO2 reduction, most electricity comes from wind and solar PV.

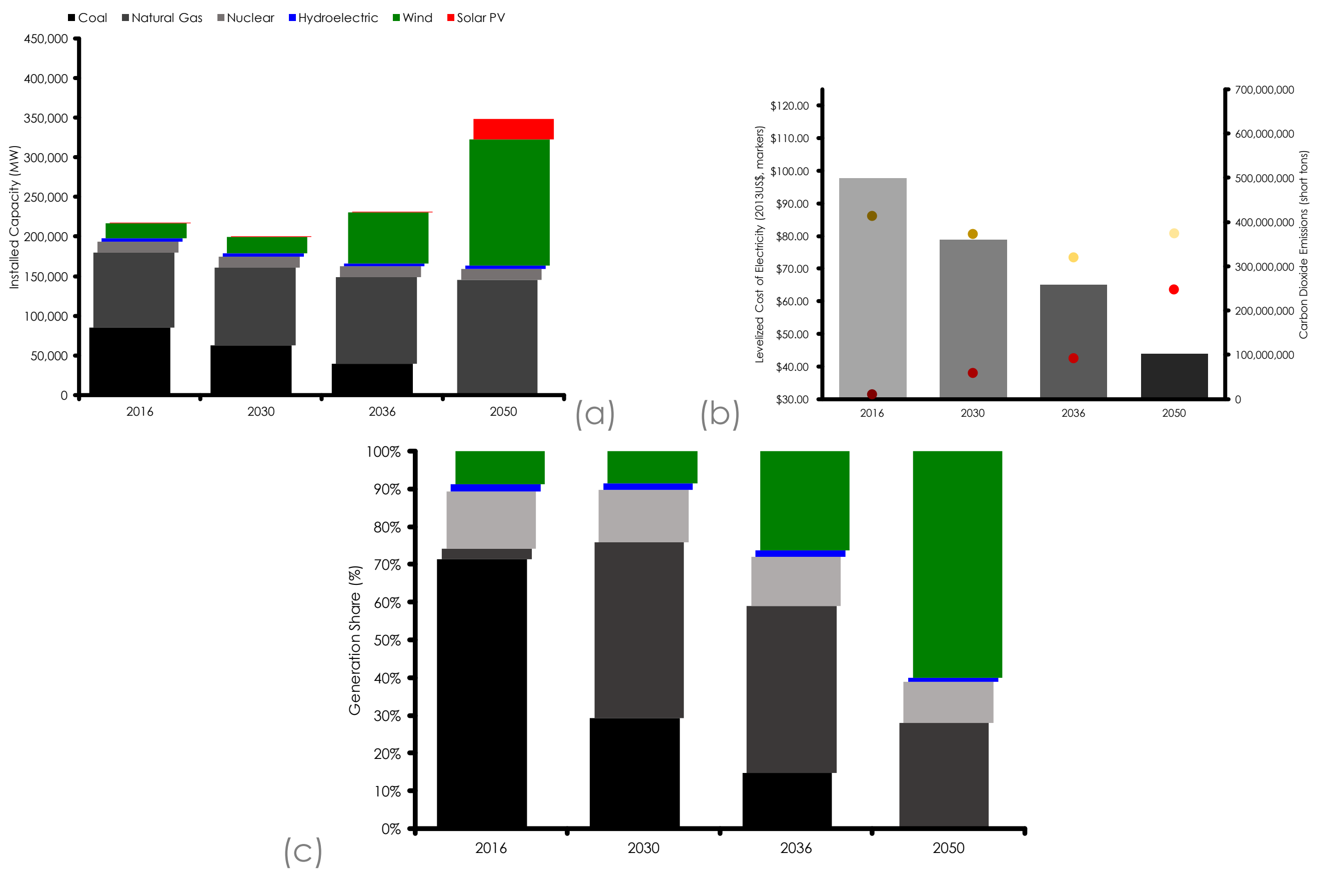


Figure 9: The overall features of the CO RC NCT scenario. (a) The capacity stack for each time horizon, (b) the levelized cost of electricity and carbon dioxide emissions, (c) the generation share by technology (green is wind and solar PV combined).

Figures 8 and 9 show the overall results from the Cost Optimized, Reduction Case, Non-Constrained Transmission (CO RC NCT) scenario. In Fig. 8, the transition under a tightening $CO_2$ emission constraint is evident. The 2016 capacity share is similar (but not identical) to that of Fig. 7. The difference can be attributed to the cost of natural gas being higher in the model than in reality and the fact that Fig. 7 is not the total capacity of the MISO grid, therefore to meet the load profile more capacity is needed than available from Fig. 7. To meet the 30% reduction by 2030, the C-OEM choses a path that increases dependency on natural gas and reduces the amount of coal. By 2036, the $CO_2$ emission reduction increases to 50%. Natural gas cannot accomplish that alone, so the C-OEM selects more wind, more natural gas, and a further reduction of coal. Finally, in 2050, under an 80% $CO_2$ emission target coal is removed entirely from the MISO footprint. Natural gas, wind and solar PV now dominate. Natural gas supplies a small amount of base load and peaking capability. Wind and solar PV provide the majority of the electricity needs over the MISO footprint.

In Fig. 9, we look a little closer at the changes over the model time horizons. In panel (a) it becomes clear that by 2050 there is a significant increase in capacity. The increase is driven by the lower capacity factors of wind and solar PV compared with thermal generation. The generation capacity is not significantly altered until the $CO_2$ reduction constraint exceeds 50%. Transmission, natural gas, along with wind in the best resource locations successfully mitigates 50% of the carbon emissions.  Panel (b) displays the carbon dioxide emissions and the levelized cost of electricity. The cost of electricity is shown twice. The red circles denote the cost of electricity when the cost of existing generators is not accounted for. That is, capacity payments are not considered for replacing like-for-like. The yellow circles take those costs into account. Necessarily, the costs shown by the red circles rise over time, as new generators are needed to meet the growing demand and carbon constraints. However, the costs shown by the yellow circles show a slight decrease over time. This is because these costs include existing generator capital payments. Finally, panel (c) shows the generation share by technology. The green in this panel combines wind and solar PV. It depicts the transition to wind and solar as the major electricity producers by 2050, when carbon reductions are necessary.

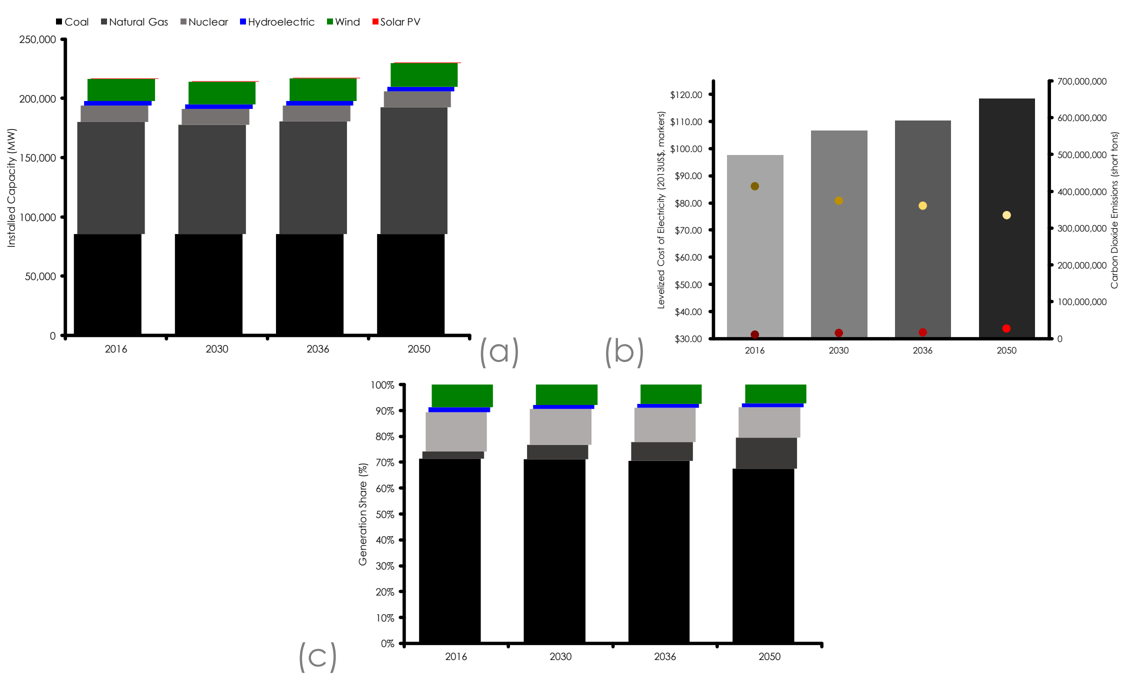


Figure 10: The overall features of the CO BC NCT scenario. (a) The capacity stack for each time horizon, (b) the levelized cost of electricity and carbon dioxide emissions, (c) the generation share by technology (green is wind and solar PV combined).

When we considered the CO BC (Base Case) NCT there are no emission constraints. Figure 10 shows the overall results. Panel (a) displays how capacity must grow to keep up with the increasing demand. In panel (b) it can be seen that carbon dioxide emissions increase by around 30% by 2050. This illustrates the transition that may be needed for a low carbon electric grid. It must reduce future emissions, while (likely) increasing generation to keep pace with demand growth. In panel (b), the cost of electricity is also displayed. Again, the red circles show an increase, although much smaller than for the CO RC NCT scenario. The yellow circles also have a downward trend as in the CO RC NCT scenario. Finally, panel (c) depicts the generation share by technology. In the CO BC NCT scenario, the fossil fuel thermal generation dominates. Primarily, because coal is not retired within the model, and the model coal fuel cost is substantially cheaper than natural gas.

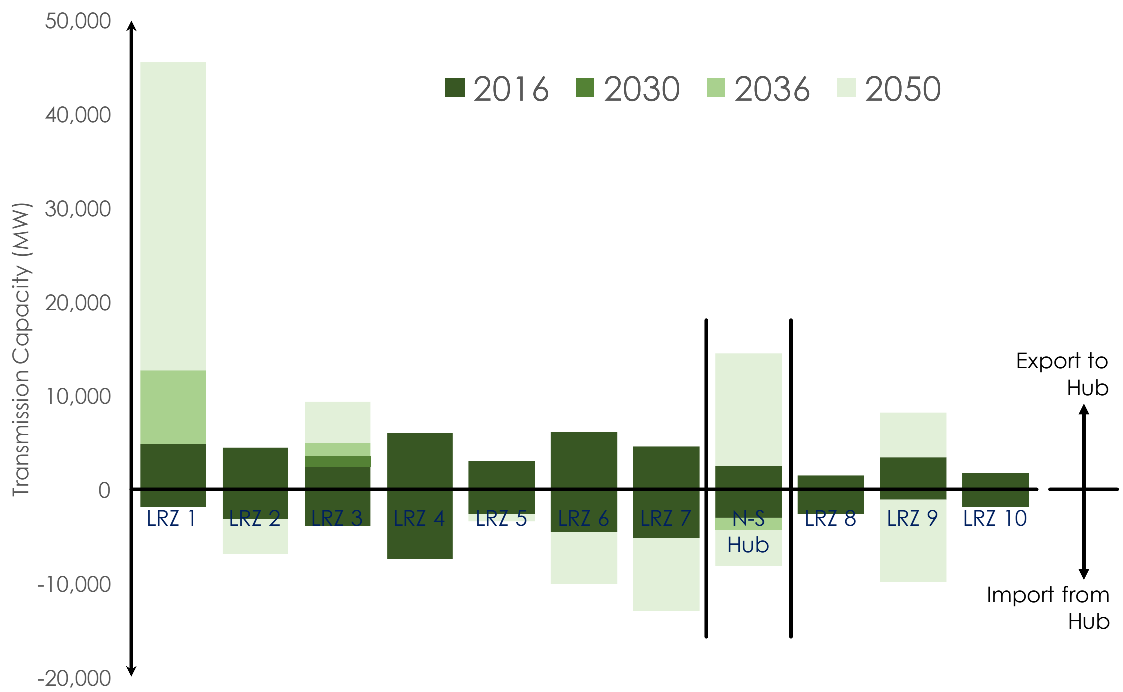


Figure 11: The transmission capacity at each time horizon of the CO RC NCT scenario. The exploitation of higher quality wind resource in LRZ 1 is facilitated by significant transmission capacity. The dark green is the existing transmission capacity. Where lower amounts of wind and solar PV are deployed, transmission expansion is not as critical.

Allowing transmission expansion results in a marginal increase in annual costs by 2050 for the CO BC NCT compared with the CT scenario. The increase is within the noise of the model (+$68.3 million; +0.1% annual costs). Whereas, the transmission expansion, as depicted in Fig. 11, for the CO RC NCT scenario reduces annual costs by $3.8 billion compared with the CT scenario. That is an annual reduction of 5.3%. The savings could be even larger if weather forecasting and dispatching were imperfect. The reduction in costs could also be further enhanced by transmission connections to MISO neighbors. That would facilitate deeper diversification of the weather-driven resource.

In Fig. 11 the transmission capacity expansion for the CO RC NCT scenario is displayed. It shows that for high levels of added wind power in the north MISO footprint, particularly LRZ 1, transmission needs to be significantly enhanced. The level of transmission capacity for 2016 is shown in dark green; as the shades lighten time moves forward. The large expansion to the northern most portions of the MISO footprint helps diversify the weather-driven resource and results in cost savings. When transmission expansion is not allowed, more solar PV is deployed by C-OEM to help reduce carbon emissions. Since solar PV has a lower capacity factor than wind, and power drops to zero at night, more fossil fuel thermal generation is required.

One of the main factors as to why more costs savings are not achieved over the MISO footprint is that at 80% carbon emission reduction levels, the diversification of the wind resource is already approaching saturation. The next section will discuss the maximum reductions possible on the MISO grid without storage or interconnection with neighboring power systems.

The cost optimized C-OEM solutions indicate that MISO has the potential to remove 80% of its annual carbon emissions, while continuing to see demand growth by 2050. Further, it shows that MISO has sufficient diversification that transmission expansion within the footprint will decrease annual costs by 5.3% when reduction targets are pursued. The base case scenarios further indicate that retirements may become important as time progresses. Since the C-OEM variant used for the present study did not capture the retirement that must happen in the future, the base case allowed all existing generators continue to run, for free, through 2050. If retirements had been taken into account (which C-OEM is now capable of) the retirements would impact cost differences over the coming decades.

## Load Matching Optimization (LMO)

The Load Matching Optimization (LMO) seeks to find the best mix of generation and transmission that minimizes the difference between the demand profile and the curtailed energy plus the dispatched electricity. It does not take economics into account. However, it defines an upper bound on the carbon free variable generation that the MISO grid can incorporate.

As the LMO does not account for economics, the metric for comparison will be carbon dioxide emissions. The lower the emissions the fewer dispatches of fossil fuel generation there is. Since the C-OEM LMO is not considering costs, the Base Case (BC) and Reduction Case (RC) result in almost the same solutions. This is explained by the fact that the $CO_2$ emissions reductions are smaller than the reductions caused by the LMO solution.

To explain more on what we mean by the LMO finding an upper bound on the variable generation within MISO: the MISO grid has enough variable generation to supply the entire load profile. However, the diversity of the potential generation has its limits. To supply 100% of the demand by wind and solar PV alone, every hour will over generate; with one exception, the minimum generation period. At that time, the load and generation will be exactly equal. The LMO finds the optimal solution to minimize both the curtailment and the fossil fuel generation; that is how closely can the variable generation track the varying demand profiles? Thus, it finds the maximum variable generation possible that does not produce overly excessive curtailment or dispatched electricity.

Not surprisingly, the LMO produces solutions that are more expensive than the CO scenarios. Further, the LMO scenarios result in much deeper carbon emission reductions. The LMO RC CT and the LMO RC NCT scenarios carbon emissions are shown in Fig. 12. The emissions from the NCT scenario are greater than those of the CT scenario in 2016, but are reduced by half for the outgoing years. Both the CT and NCT scenarios have lower carbon emissions at all time horizons than the deepest emission targets. These results are more theoretical than the CO scenarios, and depict the upper limit to variable generation carbon emission mitigation within the MISO footprint.

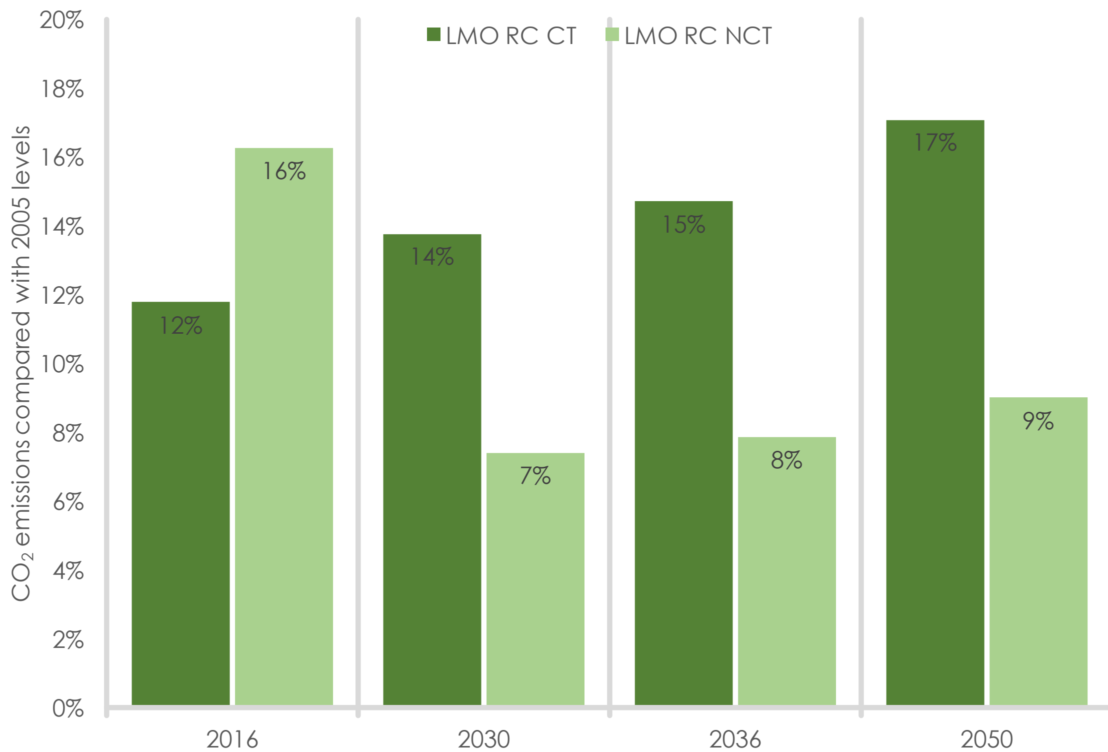


Figure 12: The carbon emission rates for the Load Matching Optimization Reduction Case Constrained and Non Constrained Transmission (LMO RC CT and LMO RC NCT) scenarios. The carbon emission rates are normalized to the 2005 levels from MISO.

To provide such carbon emission reductions for the LMO RC NCT scenario, substantial deployment of transmission is modeled. Figure 13 shows the expansion required to fulfill the needs of the non-constrained transmission version. Dramatic placement of wind in LRZ 1 dominates, and this power must be transported to the North Hub, and as can be seen in Fig. 13 a large portion is then moved to the South Hub. Development of solar PV is significant in the LMO scenarios, as it provides peaking capacity and is generally anti-correlated with wind. The expansion of the transmission shown in Fig. 13 for LRZ 1 is nearly tripled and from the North Hub to the South Hub is six times the capacity. This is evidence of the C-OEM LMO procedure trying to maximize the diversification of the weather-driven resource.

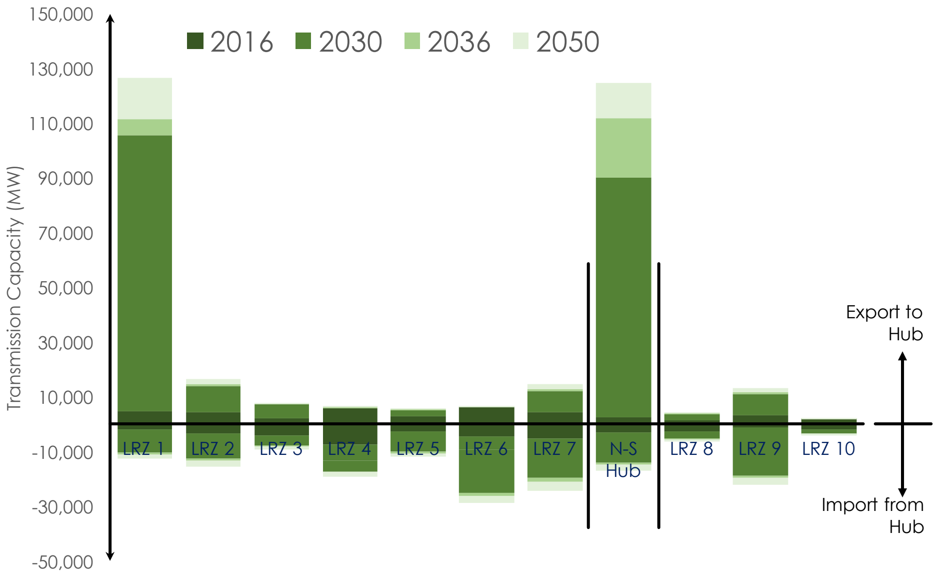


Figure 13: The transmission capacity at each time horizon of the LMO RC NCT scenario. The dramatic exploitation of higher quality wind resource in LRZ 1 is facilitated by significant transmission capacity. The dark green is the existing transmission capacity. The trend is the same as in Fig. 11 for the CO RC NCT scenario, but here it is extended much further.

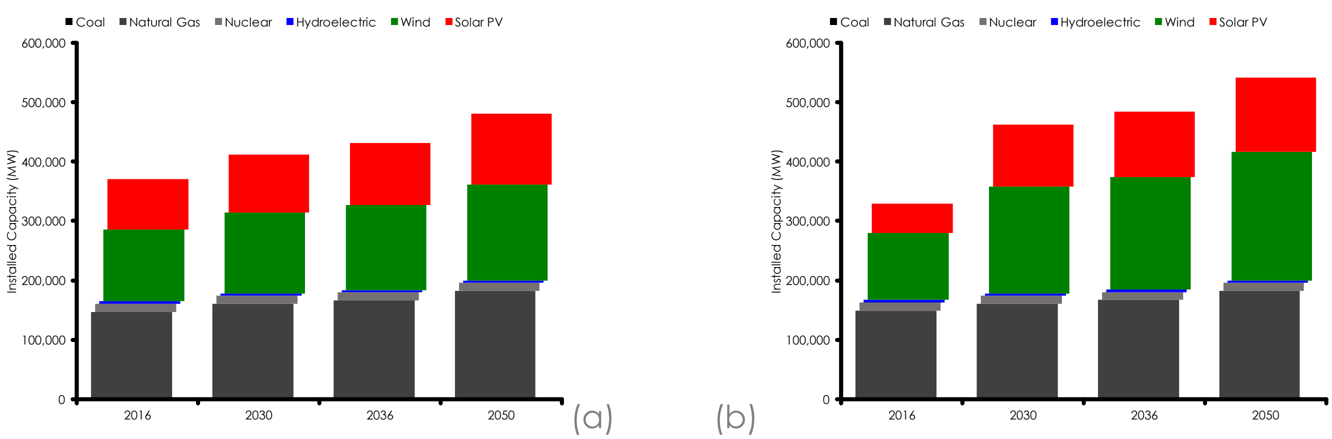


Figure 14: The capacity of generators on the MISO grid for the LMO RC CT (a) and LMO RC NCT (b) scenarios. The expanded transmission facilitates further deployment of wind and solar PV. The transmission does not significantly alter the amount of natural gas developed, although it is slightly decreased.

The generator development is driven by the need within the LMO procedure to find variable generation that is diversified with respect to other generators chosen within the model. Figure 14 shows the capacities for both the transmission constrained and non-constrained scenarios. It can be seen that natural gas deployments are not significantly altered by transmission, although there is a slight decrease. The total capacity far exceeds that of the CO scenarios. Indeed, it is approaching a doubling of capacity. This is a result of the MISO grid reaching saturation point for diversification of the wind and solar resource for the carbon reductions met in the CO scenario. Capacity reductions would occur if MISO connected to neighbors, as the weather-driven resource is more diverse in the zonal direction on the Earth compared with the meridional direction. MISO has vast extent North-South, but is more confined in the East-West.

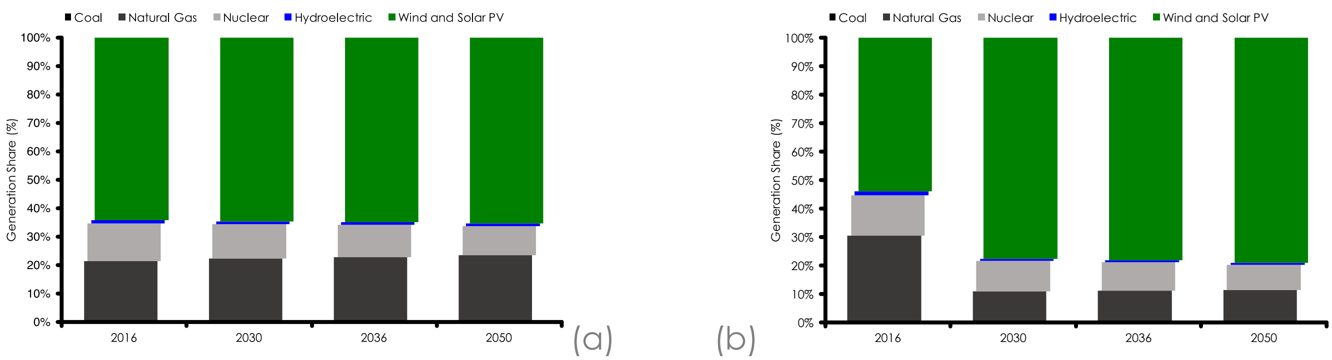


Figure 15: The generation share by technology for the LMO RC CT (a) and LMO RC NCT (b) scenarios. Panel (b) clearly shows the effect of transmission expansion in 2030, when the wind and solar PV generation jumps from ~50% to ~80%. In panel (a), the generation share remains fairly constant, but as the demand is growing, new generators are added to provide the generation in the same proportions between fossil fuel (natural gas) and variable generation (wind and solar PV).

The LMO procedure seeks the highest amount of variable generation such that dispatched generation and curtailment are minimized. Figure 15 displays the generation share by technology. In panel (b) it is clear when transmission expansion is allowed (2030). There is a shift to more wind and solar PV, and a reduction in natural gas. Note that in Fig. 14, there was not a dramatic reduction in natural gas capacity. This is because the model must keep generators built in the previous time horizon optimizations. The generation share in panel (a) appears to show generation share essentially unchanged between the time horizons. This is because the demand is grown between time horizons and the C-OEM LMO finds equal mixes of wind, solar PV and natural gas to satisfy that. Even so, the diversity of MISO supports 60% wind and solar PV generation, without transmission expansion (at significant cost).

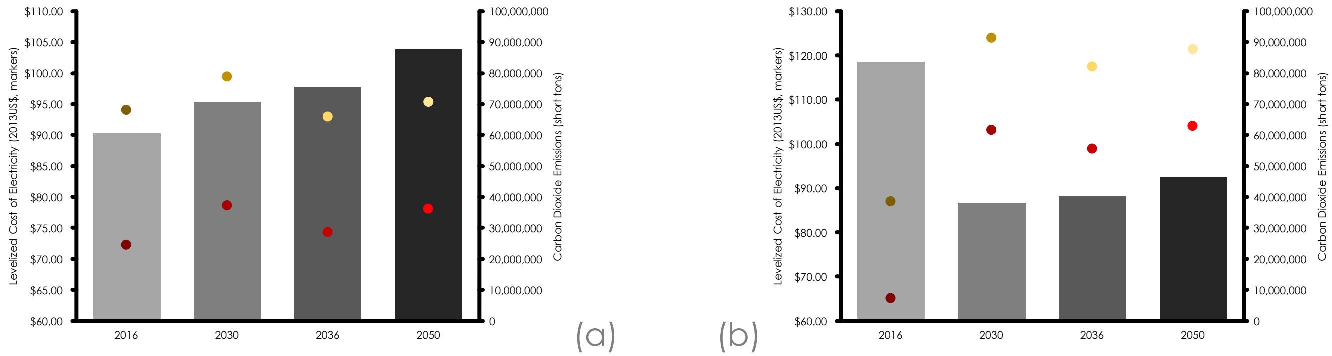


Figure 16: The cost of electricity and total carbon emissions for the LMO RC CT (a) and LMO RC NCT (b) scenarios. Both scenarios remain under 100 million short tons (~80% reduction compared with 2005). The cost increase due to transmission expansion is evident in panel (b).

The costs of the LMO are of interest with respect to how far the MISO system could be pushed to meet carbon emission reductions. It is evident from Fig. 16; that ~90% carbon emission reductions are theoretically possible for MISO. The deep cut of ~90% would require substantial transmission and capacity expansion; in the absence of cheap, abundant storage or connection to MISO neighbors.

The costs for the deepest cuts in $CO_2$ range from $100 to $125 / MWh, depending on how to account for all the costs in the system. By necessity, the LMO solutions are more expensive than the CO solutions. The LMO RC NCT is approximately 50% more expensive than the CO RC NCT, while the LMO RC CT is roughly 19% more costly than the CO RC CT scenario. These cost increases result in ~10% further carbon dioxide emission reduction. If greater reductions were necessary, costs would rise at an ever increasing rate as more curtailments would be necessary; without storage or connections to more distant resources.

# Conclusions

The present study was commissioned by MISO to investigate how the electric system under MISO would be altered with deep carbon emission reductions. The study used two different techniques; a cost optimization (CO) and a load matching optimization (LMO). The CO used economics to drive the carbon emission reduction, while the LMO used diversity to drive the emission reductions. Essentially, the CO provides an estimate of costs for an economic transition and the LMO provides an estimate of the upper bound of variable generation with MISO (when storage is not considered).

It is found that MISO has the resources within its borders to reduce carbon dioxide emissions by 80% compared with 2005 levels by 2050. It will require the retirement of the entire coal fleet, significant expansion of wind, a somewhat smaller expansion of solar PV. Further, it is more cost effective to perform this transition concurrently with transmission. If transmission is expanded with variable generation, approximately $3.8 billion annually is saved by 2050, while achieving the emission reduction target of 80% compared with 2005 levels. The cost of electricity is relatively unchanged when considering the capital costs for replacing existing generators like-for-like. When not considered, costs necessarily increase, as older generators are retired and new ones replace them.

The LMO scenarios indicate that the MISO footprint can reach 90% carbon emission reductions with resources from within its boundaries. The deeper emission reduction comes with further expansion of capacity for wind and solar PV. The costs increase with this methodology because economics are not accounted for. These results also suggest that the MISO footprint would benefit from storage, connection to neighbors, or other new technologies in order to meet carbon reduction objectives. The MISO footprint has the majority of its load-correlated wind resource in LRZ 1. This generation is distant from major population centers and transmission would be needed to move the power to the demand centers.

The C-OEM suggests that incorporating more variable generation within MISO will require a shift in the deployment procedures. The highest value variable generation is not always the cheapest electricity, nor the most abundant. Diversification is also an important factor. Correlation to the demand and/or de-correlation to other generators becomes increasingly important as penetration levels of wind and solar PV increase.

The C-OEM model runs provide a solid initialization of pathways to lower emission electric grids within MISO. The model is capable of incorporating retirement schedules, multiple meteorological years, storage capabilities, connections to MISO neighbors, and more. The current study was confined in scope to define areas of interest for further study and development. The current version of the C-OEM supplied valuable insight into the high level evolution of the MISO grid when carbon dioxide emission targets are set.