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Colorado's Prospects for Interstate Commerce in Renewable Power

Prepared for the Colorado Governor's Energy Office, Renewable Energy Development Infrastructure (REDI)

David J. Hurlbut

Technical Report
NREL/TP-6A2-47179
December 2009

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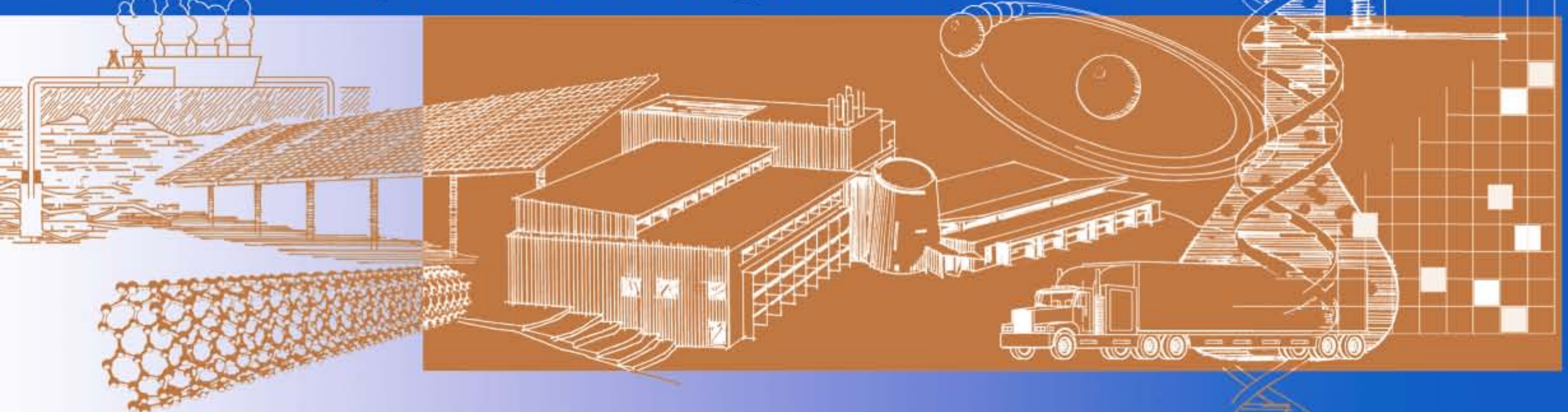

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Foreword

This report was prepared by the National Renewable Energy Laboratory (NREL) under a contract with the Colorado Governor's Energy Office (GEO). It supplements GEO's broader examination of transmission issues contained in its Renewable Energy Development Infrastructure (REDI) report.

During the preparation of the REDI report and its predecessor report—produced in 2007 by the Renewable Resource Generation Development Areas Task Force as directed by the Colorado State Assembly in Senate Bill 07-91—commenters frequently noted the fact that Colorado has more renewable resources than it needs for its own consumption. Many of these commenters concluded that such surplus could be sold to other states, thereby increasing the state's revenues from interstate commerce in energy. The purpose of this report is to provide analytical background for further discussion about interstate commerce in renewable energy development, drawing on current technical analysis being conducted by NREL and others.

The findings presented here do not constitute policy recommendations. Rather, they are intended to clarify the salient issues that would arise if Colorado policymakers choose to include interstate commerce in renewable energy development as part of the state's long-term goals for transmission investment.

Acknowledgments

As of this writing, several major studies are under way examining the technical challenges of large-scale regional renewable energy deployment. The author is grateful for the assistance provided by those involved in these efforts, particularly the Western Governors' Association (WGA) and WestConnect. Background research for the WGA's Western Renewable Energy Zone Initiative was crucial to the analysis presented in this report, as was data from the Western Wind and Solar Integration Study (WWSIS) being conducted by WestConnect and NREL. The consulting firm Black & Veatch conducted much of the analysis for WGA. NREL's Debra Lew and Michael Milligan provided crucial guidance on WWSIS, particularly with regard to navigating its massive data set and to understanding the study's preliminary findings. If this report errs in its use of information from either study, the responsibility lies with the author of this report and not with those who provided guidance.

Eric Lantz of NREL also provided important background on the renewable energy value chain and its implications for Colorado. Thanks also go to the REDI Advisory Committee for comments on early drafts of this study; and to Lori Bird, Matthew Brown, Jeff Hein, and Morey Wolfson for their review of the overall report.

Finally, the author gratefully acknowledges both the financial and intellectual support provided by the U.S. Department of Energy's Office of Electricity Delivery and Energy Reliability.

List of Acronyms

AC	alternating current
CAISO	California Independent System Operator
DC	direct current
DNI	direct normal insolation
GDA	generation development area
GEO	Governor's Energy Office (Colorado)
NERC	North American Electric Reliability Corporation
NREL	National Renewable Energy Laboratory
R&D	research and development
REDI	Renewable Energy Development Infrastructure
REZ	Renewable Energy Zone
RMPA	Rocky Mountain Power Area
RPS	renewable portfolio standard
WEEC	Western Electric Coordinating Council
WGA	Western Governors' Association
WREZ	Western Renewable Energy Zone
WWSIS	Western Wind and Solar Integration Study

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Executive Summary

Colorado has more renewable energy potential than it is ever likely to need for its own in-state electricity consumption. Such abundance may suggest an opportunity for the state to sell renewable power elsewhere, but Colorado faces considerable competition from other western states that may have better resources and easier access to key markets on the West Coast.

This report examines factors that will be important to the development of interstate commerce for electricity generated from renewable resources. It examines market fundamentals in a regional context, and then looks at the implications for Colorado.

The relevant market

- Colorado's relevant market for renewable power is the Western Interconnection, which includes all states west of the Great Plains.
- The greatest demand for renewable power within the Western Interconnection is on the West Coast, particularly California.
- Wind resources in Colorado's Eastern Plains constitute the state's most economically competitive, utility-scale renewable power (based on cost per unit of output), yet there is no viable transmission corridor by which these resources can reach West Coast demand centers. In-state transmission constraints limit the flow of power from the Eastern Plains to the Western Slope, and the two major high-voltage paths out of the state westward have little spare transfer capacity.
- States adjacent to Colorado do not constitute a large source of demand. Consequently, economies of scale may be difficult to achieve for projects in Colorado that are intended to serve load in adjacent states.

Competing resources

- Wyoming has significant amounts of wind resource potential that is rated higher than Colorado's wind potential (based on cost per unit of output). In addition, Wyoming has better transmission access to West Coast demand centers.
- New Mexico has solar resource potential with higher direct normal insolation factors than are found in Colorado, while New Mexico's wind potential is comparable to Colorado's.
- Lower-rated wind resources in California, Washington, and Oregon enjoy a competitive advantage because they are closer to that region's largest demand centers. Lower transmission costs reduce the delivered cost per unit of output, compensating for generally lower wind speeds.

Cost impact of regional operations

- Managing Colorado and Wyoming wind resources together may reduce costs and make both more competitive.
- Combining geographically diverse wind and solar resources into a single portfolio tends to reduce hourly and sub-hourly variations in real-time output. This would result in a more consistent level of output over a longer time frame, which could reduce the cost of wind integration.
- A larger and more geographically diverse portfolio of wind and solar resources requires less use of reserves from conventional generating units. Using less reserved conventional power can reduce the costs that a utility would need to recover in its rates, and could increase the interstate competitiveness of the portfolio as a whole.
- Wyoming wind power would tend to mitigate high wholesale electricity prices in California more so than Colorado wind power would, due to the hourly production profiles of wind power throughout the year and especially during the summer.
- Jointly managing wind resources from Colorado and Wyoming would largely preserve Wyoming wind power's downward pressure on California wholesale power prices.

The report concludes that a successful interstate commerce strategy for Colorado wind and solar power may need to include multi-state collaboration on the planning, approval, dispatch and operation of renewable resources and the transmission system. Colorado would have a dual stake in the success of such a regional effort: greater value-added for its own renewable energy production, and greater in-state economic development because of Colorado's position as a regional manufacturing center for renewable energy technologies.

Introduction

Interstate commerce in energy has fueled local economic booms for states rich in oil, natural gas, and coal throughout U.S. history. Similar opportunities are now arising for wind, solar, and other renewable energy resources as the New Energy Economy takes on national proportions. The economic value of the nation's least-cost, zero-carbon alternatives will almost certainly increase with the promulgation of public policies to reduce carbon emissions.

Colorado has abundant renewable energy resources for generating electricity—much more potential for wind power and solar power than it needs for its own use. The best potential was documented and mapped in "Connecting Colorado's Renewable Resources to the Markets," a study authorized by the Colorado State Assembly under Senate Bill 07-091. Theoretically, the state's apparent surplus of renewable energy resources might suggest a new opportunity for state energy revenues. While it has policies in place to increase its internal use of renewable power, Colorado's activity with respect to interstate commerce has emphasized expanding the state's manufacturing base, not the sales of its renewable power to other states.

The ability to be a competitive player in a regional renewable energy market depends on more than just having spare resources, however. This study critically examines the factors that affect Colorado's position as a potential interstate supplier of renewable energy. The first section provides an overview of the likely geographic market, which is essentially defined by the transmission infrastructure along which power generated in Colorado can reach end users. Next, the paper examines the distribution and quality of wind and solar power throughout the region. This discussion will draw from recently completed regional analysis conducted for the Western Governors' Association (WGA). The third section discusses issues affecting the grid's ability to integrate larger amounts of wind and solar power. These technical issues are obstacles under existing grid management practices, but at the same time they point the way to changes that could open up the market considerably.

Robust interstate commerce presumes a regional market with willing buyers and sufficient transmission infrastructure. Colorado would not be the only player in this market. Other states may want a piece of the regional action, and some may be tough competitors. The greatest potential demand is on the West Coast, and some states have a competitive advantage over Colorado as potential suppliers to that market. Wyoming (which is already sending wind power to the West Coast) has world-class wind resources that tend to be more productive than Colorado's wind resources, and that also tend to follow hourly and daily load in a way that would provide more stability for wholesale power prices in California. Utility-scale solar resources in Arizona and Nevada are closer to demand on the Pacific Coast, and they are more productive and more consistent. New Mexico's wind resources are comparable to Colorado's, and its solar resource areas receive more sunshine and are closer to market.

A regional market, therefore, would provide no guarantee that a load-serving utility in any other state would want to buy Colorado renewable power if it were available. Colorado's best prospects for selling renewable power will depend on interstate partnerships and on eliminating outdated practices for operating the power grid—practices that prevent a regional market from operating efficiently. In any case, however, Colorado's head start as a manufacturing hub for renewable energy leaves it well positioned for significant job growth in the equipment supply chain, regardless of how a regional market may develop.

It is important to note that this analysis sets aside the question of "unbundling" renewable energy credits (RECs). Unbundling means that RECs and the physical energy they represent may be traded separately, as long as the latter is treated as generic electricity without any particular environmental attributes. In theory, a California utility could buy a Colorado wind farm's unbundled RECs and apply them towards its state-mandated renewable energy requirement even though the power generated by the Colorado wind farm may not actually flow to California.[1] Several state and regional authorities are looking at the pros and cons of unbundled RECs; this analysis makes no attempt to resolve those issues, as many of them are tangential to the questions at hand. Instead, this analysis presumes a physical flow of power from generation to demand, consistent with current transmission planning practice. This presumption enables a more in-depth analysis of Colorado's competitive position, as it includes value-added elements that would not be present in an unbundled REC scenario.[2] New rules allowing greater use of unbundled RECs would require re-examining the conclusions from this analysis.

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[1] Consequently, the Colorado wind farm's production would not count toward the Colorado state requirement, although the additional electricity would have to be accommodated locally.

[2] Two examples are a generator's capacity value, and the effect on wholesale prices. Both of these factors, which this analysis addresses in detail, depend on the real-time match between the generator's output level and the level of demand.

The Relevant Market

The configuration of the national electric grid dictates that the western United States is Colorado's main economic trading area for renewable power. Map 1 shows the region covered by the Western Electric Coordinating Council (WECC), the transmission reliability organization responsible for the synchronous grid to which Colorado is connected. Colorado already sends power to and takes power from other WECC states during the course of normal operations.

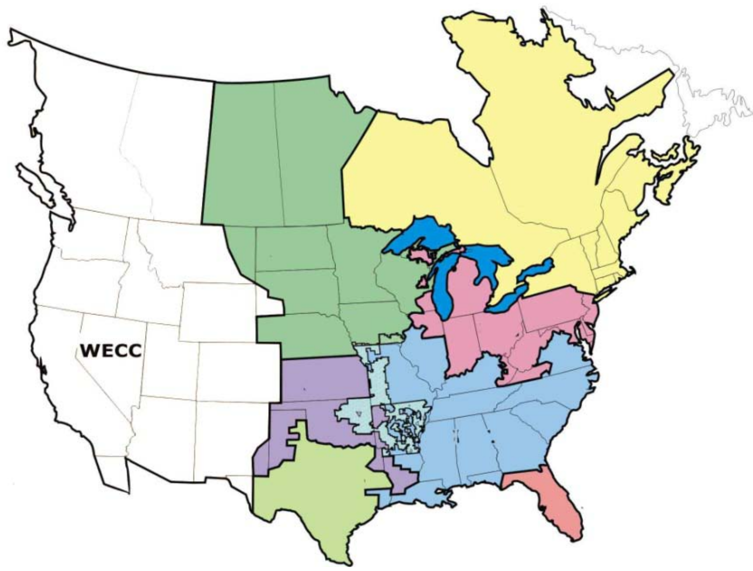
Very little power flows from WECC to the eastern grid because of technical differences in how the eastern and western grids operate. Consequently, bulk power movement from Colorado to Kansas would require a significant interstate investment in direct-current (DC) transmission lines that would both carry the power to eastern demand centers and enable it to mesh synchronously with the eastern grid. An alternative is to add tie stations at the interconnection seam near the Colorado-Kansas border that convert the alternating current (AC) from Colorado into DC, and then back to an AC current that is synchronized with the eastern grid. A tie would require sufficient transmission capability in western Kansas to move the power eastward through the local network. The network is currently transmission-limited, although current expansion plans would enable the development of more wind power in western Kansas.

Perhaps the greatest challenge, however, is that Colorado wind power may not be competitive economically. The eastern grid's own indigenous wind resources in the Dakotas, Kansas, and the Texas-Oklahoma Panhandle area are at least as productive as those in eastern Colorado. Thus, while DC options are conceivable and would theoretically expand Colorado's possible interstate commerce scenarios, they do not at this time represent the most likely near-term economic opportunities and therefore will not be addressed in depth.

Demand in the WECC region

Two factors currently affect a state's likely demand for renewable power: the size of total retail electricity sales, and whether the state has a renewable portfolio standard (RPS) in place. The economic influence of an RPS is not limited to the quantity of renewable power that is mandated. Of even greater importance is what an RPS signals to renewable energy developers and load-serving utilities: there will be a demand for renewable power inside these markets that is firm and certain. By contrast, a state with no RPS is an economically soft and highly uncertain source of demand.

New carbon reduction policies may stimulate even more demand in the near future, as may a future federal RPS. Assessing the shape and impact of these potential future policies is not the purpose of this analysis, however, so here they are set aside. Demand projections used in this analysis rely exclusively on state RPS policies as they exist in 2009. This analysis also sets aside any existing RPS eligibility requirement that may favor in-state resources—a simplifying assumption that is necessary if the aim is to assess the possible benefits of interstate commerce.



Map 1: Region Served by the Western Electric Coordinating Council (WECC)

Shading indicates North American Electric Reliability Corporation (NERC) reliability regions.

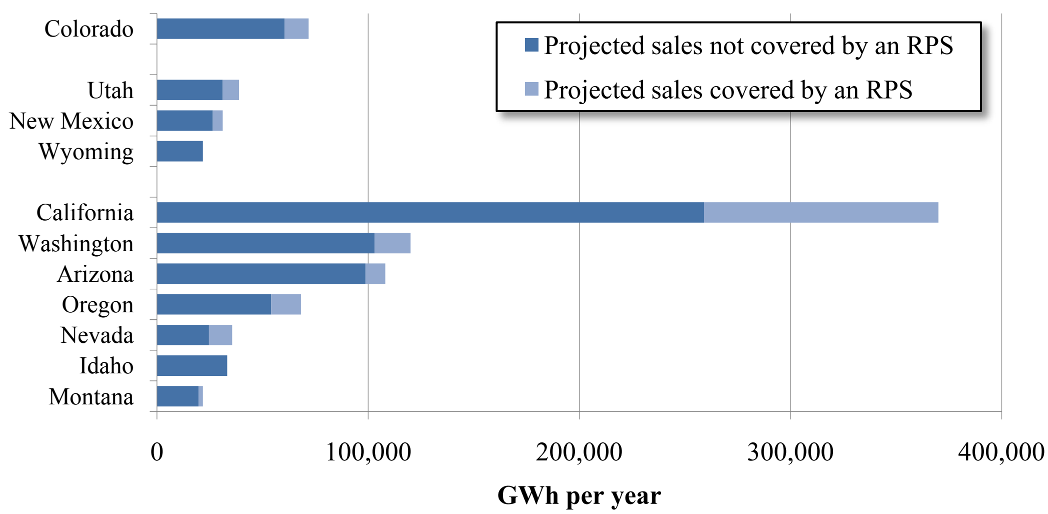


Figure 1: Retail Electricity Sales Projected for 2025, and Portions Covered by RPS Goals

Note: Changes in the rate of growth for electricity demand will change projected RPS requirements. Projections assume a simple 2% annual growth rate. State sales are allocated among provider categories (investor-owned utilities, municipally owned utilities, and rural electric cooperatives) based on distribution of 2007 retail sales. Sector-specific RPS goals for 2025 that were in effect as of 2009 are applied to each provider category. For a description of RPS goals by provider category, see Database of State Incentives for Renewables and Efficiency, at http://www.dsireusa.org/.

Source: Energy Information Administration (EIA), "Retail Sales of Electricity by State by Sector by Type of Provider" (Form EIA-861 database), http://www.eia.doe.gov/cneaf/electricity/epa/sales_state.xls.

California has by far the largest demand for renewable power in the West. As Figure 1 illustrates, California's total electricity demand is significantly higher than any other western state. In addition, California has the region's most ambitious RPS requirement − 33% of retail sales by 2020.[3] Washington, the state with the second-largest demand, has an RPS requirement of 15% by 2020.

The renewable energy goals in place as of 2009 are equivalent to approximately 28% of the WECC region's total projected demand for 2025. Assuming historical load growth, this amounts to about 188,000 GWh of generation from new renewable resources annually. Three-fourths of that demand will be in California, Washington, and Oregon, assuming no significant change in current trends or policies.

The three states that border Colorado in the WECC region—Utah, New Mexico, and Wyoming—are each much smaller than Colorado in terms of total electricity demand. In addition, Wyoming has no renewable portfolio standard and therefore no minimum demand level for renewable power. Utah has a non-binding renewable energy goal.

Fanning outward from Colorado, the overall demand for renewable power may be summarized as follows.

- *In-state*. Colorado's home market accounts for about 8% of total retail electricity sales in the WECC region. The state's 2020 RPS requirement—20% for investor-owned utilities and 10% for rural electric associations and large city-owned utilities—establishes a firm demand for renewable power in Colorado, but that required amount constitutes only 6% of the *region's* RPS-related demand projected for 2025.
- *Surrounding states*. Utah, New Mexico, and Wyoming together account for 10% of WECC retail sales—not much larger than Colorado's own internal demand. However, the market for renewable power in this surrounding area is less firm than within Colorado, because only New Mexico has an RPS requirement. Together, the three surrounding states account for only 6% of the projected RPS-related demand for 2025.
- *West Coast.* California, Washington, and Oregon account for about 54% of the projected electricity demand in the WECC region for 2025; they also account for three-fourths of the region's projected demand for renewable power. California is the largest demand center, where the projected need for renewable power is 59% of the region's projected demand. Like Colorado, all three of these states have RPS requirements in place, as do Arizona and Nevada.

Consequently, the largest potential demand for Colorado renewable power outside the state is on the West Coast. Moreover, the West Coast's already-large share of overall electricity demand is further weighted by the fact that all of these states have RPS requirements.

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[3] California's 33% goal is currently effected by an executive order from the governor. The statutory goal is 20%. See Database of State Incentives for Renewables and Efficiency, www.dsireusa.org.

To reach this relatively robust market, however, renewable power from Colorado would have to cross an area where demand for renewable energy is relatively small. While Colorado's surrounding states may contain niche markets for renewable power, those state's local resources would most likely enjoy a comparative advantage in their home markets. Because total demand in these neighboring markets would be small, a Colorado project with generation and transmission sized for these markets alone probably would not be large enough to achieve economies of scale.

Competitive Position of Colorado's Renewable Resources

Whether Colorado resources will be competitive on the West Coast will depend primarily on quantity and cost relative to other alternatives. This section examines both with respect to wind and solar potential, the two resources most easily developed in concentrations at utility scale in Colorado.

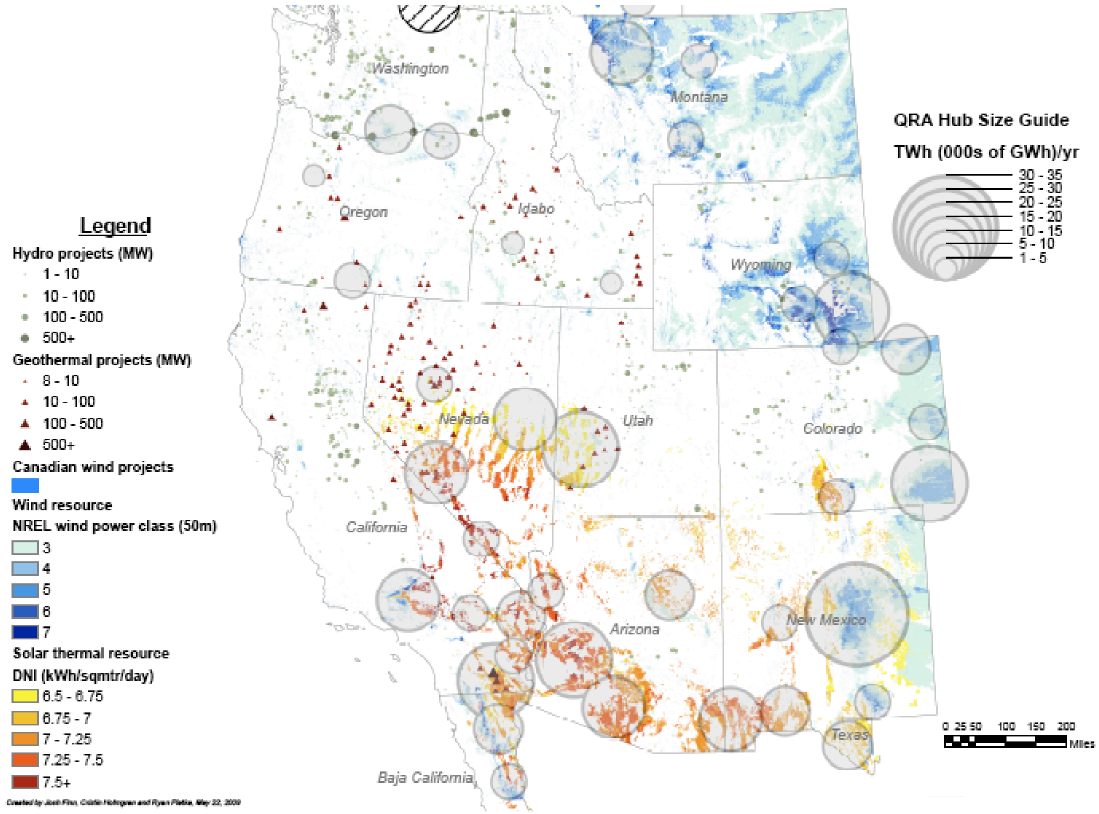
Concurrent with the preparation of the REDI report, the WGA conducted an assessment of renewable energy potential throughout the Western Interconnection. The objective of the Western Renewable Energy Zone (WREZ) Initiative was to "identify Renewable Energy Zones (REZ) in the Western Interconnection based on developable potential, development timeframes, common transmission needs, and cost of development."[4] Part of the WREZ effort was to identify the best renewable resources in each state, and from among those screened areas identify those with the greatest economic potential to meet regional demand for renewable power.

This section draws on the detailed assessments done in the WREZ initiative to examine the competitiveness of Colorado's best resources, both in terms of quantity and quality. The resources selected for comparison do not represent the entirety of the potential that exists in each state, only the amounts that passed various stages of WREZ screening for the anticipated purpose of large-scale, multi-state transmission.

Map 2 shows the geographic distribution of renewable energy resources identified in the WREZ initiative as being competitive regionally. Blue areas indicate the region's best wind resources based on the most recent validated data from NREL, with darker shades indicating the highest-class wind potential. Areas shaded orange to dark red indicate solar potential. In all cases, areas have been excluded if they are unavailable for development by law or by policy (e.g., national parks).

[4] The outcomes of the WREZ initiative are the product of stakeholder input and technical analysis conducted for the WGA by NREL and the Lawrence Berkeley National Laboratory, with assistance from the consulting firm Black & Veatch. Final products were recommended by a technical committee comprising industry experts and stakeholders, and reviewed and approved by a steering committee comprising governors' designees and other officials from states throughout the West. In June 2009, the WGA endorsed the report on the first phase of the initiative, including the map shown in Map 2. WGA, "Western Renewable Energy Zones Phase 1 Report," June 16, 2009 ("WREZ Phase 1") (available on-line at http://www.westgov.org).

The results shown in Map 2 account for some reductions based on sensitive habitat areas. The adjustments vary from state to state, as determined by each state for the WGA analysis. There are currently no region-wide criteria for categorizing specific habitat issues in the context of renewable energy development.



Map 2: Potential Regional Hubs for Renewable Energy in the Western U.S.

Hubs represent concentrations of renewable energy potential in qualified resource areas (QRAs) identified in the WREZ stakeholder process. Renewable resources not part of a QRA are presumed to be available for in-state demand rather than for interstate commerce. Source: WREZ Phase 1.

The regional hubs represent approximately 577,000 GWh of generation from top-quality renewable energy resources annually. This includes about 123,000 GWh from areas in Canada and Mexico that are on the WECC system. The total generation potential in these regional zones is about three times what will be required under these states' current RPS programs by 2025.

Consequently, the pool of potential suppliers is likely to be very competitive if a regional market for utility-scale renewable energy develops in the West. A large part of any state's renewable energy needs will likely be met by in-state resources not represented in a WREZ hub, therefore the demand pool for *regional* renewable resources (power delivered from one state to another via long-distance transmission) will be smaller than the overall projected demand of 188,000 GWh. Transmission to support this regional market would be selective and would not be built everywhere, and if no regional high-voltage corridor connected Colorado to the West Coast, then Colorado would not be a player.

Expectations about the delivered cost of wind power and solar power would play significantly into criteria for selecting regional transmission corridors. The quality of an area's native climate with respect to wind and sunshine determine the delivered cost of wind or solar power from that area. The next sections examine Colorado's comparative position with regard to these two resources.

Wind

The Colorado wind resources that passed WREZ screening are largely the same as the wind generation development areas (GDAs) identified in the SB 91 report. Unlike that report, however, WREZ capacity estimates for each zone included a 25% "developability factor." This adjustment (applied uniformly to wind resources in each state) represents the amount of capacity that is likely to be developed in a zone, and is therefore a reasonable representation of the amount of transmission that may be needed. In other words, it was assumed that every 400 MW of technical potential for wind power would be competing for 100 MW of transmission access. This is the main reason that the 16 GW of wind potential that WREZ estimated for Colorado was a fraction of the 96 GW estimated by SB 91.[5]

WREZ also applied different wind class thresholds in each state. For Colorado and New Mexico, only class 4 wind areas or better were counted (as was the case for Colorado in the SB 91 report). In Wyoming, however, the amount of class 5 and better wind resources was so great that WREZ stakeholders judged the state's class 4 resources to be economically uninteresting from the standpoint of a regional market. Therefore, class 4 wind areas were not included in the regional capacity estimates for Wyoming.

[5] In addition, Wind GDAs 4 and 7 did not pass the WREZ screening. Wind GDA 1 was part of a zone shared by Colorado and Wyoming; as most of this zone was in Wyoming, it is not included in the Colorado total.

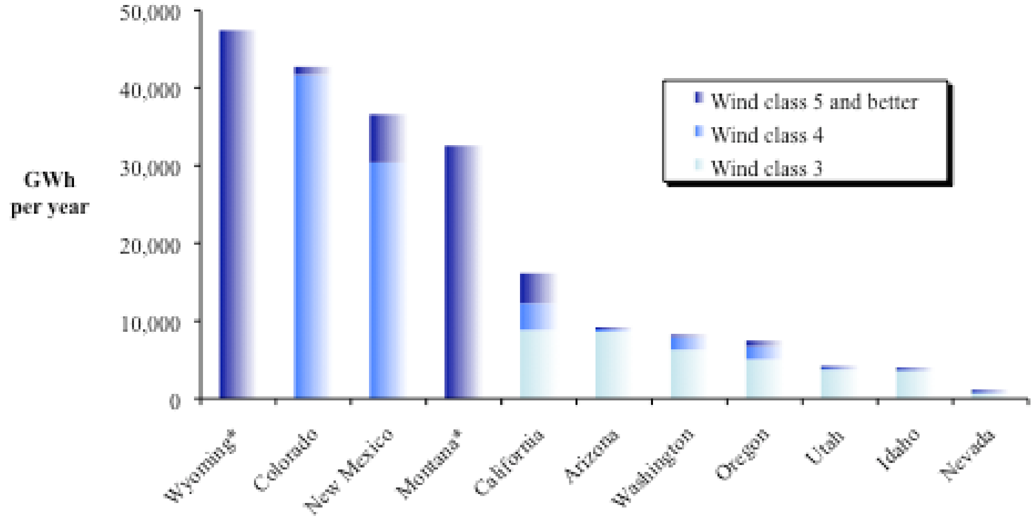


Figure 2: State Wind Resources that Passed WREZ Screening, by Class

*Wind class 4 and below not shown for Wyoming and Montana; wind class 3 and below not shown for Colorado and New Mexico. Wind resources outside a renewable energy zone are not included. Source: WREZ Phase 1.

Figure 2 shows the wind resources in each state that passed WREZ screens. These totals take into account the 25% developability factor, so the technical potential is four times the amounts shown in the figure. Figure 2 illustrates that:

- Wyoming has about as much commercially competitive wind power as Colorado, but the quality is higher
- New Mexico has almost as much regional-class wind power as Colorado, but has more that is class 5 or better.

Thus, while Colorado's wind potential is large enough to support its own RPS and a portion of the requirements on the West Coast, transmission that would take Colorado resources either northwest or southwest to that demand would pass through states with significant amounts of higher-class wind resources. Wyoming's advantage stems from its world-class wind potential; New Mexico's slight advantage with respect to wind is enhanced by a significant competitive advantage with respect to solar potential, as analyzed in the next section. While wind resources on the West Coast tend to be Class 3 or 4 and of limited quantity; as local resources, they have the cost advantage of being closer to demand.

Solar

The developability factor applied by WREZ to solar resources is 3.5%—much steeper than the factor used for wind power, because utility-scale solar plants are more concentrated geographically. (Wind turbines need to be far enough apart to ensure that downwind turbines suffer no degradation in production; solar collectors generally need to be as close as possible to minimize installation cost and maximize thermal efficiency.)

So whereas nearly all of Colorado's San Luis Valley has the technical potential for high-quality solar power development—240 GW in all, as estimated in SB 91—the solar developability factor imposes the operational assumption that only 3.5% of that potential would actually be developed, with the rest continuing to be farmland or some other existing use.

Colorado's best utility-scale solar potential as estimated by WREZ amounts to about 2.6 GW. Figure 3 shows the Colorado solar potential estimate alongside those for other western states.

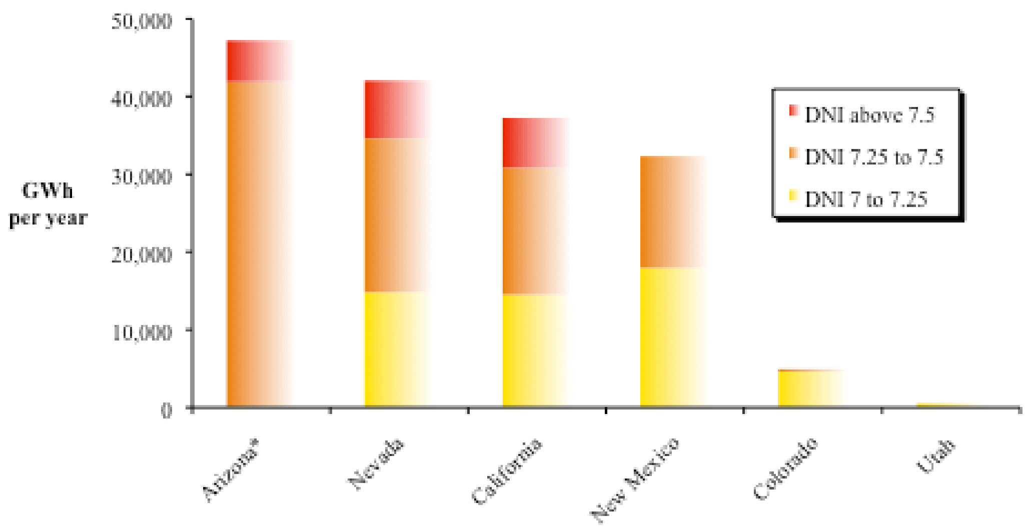


Figure 3: State Solar Resources that Passed WREZ Screening

*DNI below 7.25 not shown for Arizona. For all states, solar resources outside a renewable energy zone are not included. DNI (direct normal insolation) is the amount of sunlight hitting the ground on an average day, expressed as kilowatt-hours per square meter per day.
Source: WREZ Phase 1.

Unlike wind resources, the West's best solar resources are located relatively close to demand. In fact, the California resources shown n Figure 3 are more than enough for its own requirements. Adding the potential in Arizona and Nevada, the near-by solar potential available to the combined West Coast markets is relatively rich.

Disparities in quality, quantity, and proximity to market pose significant challenges to the ability of Colorado's solar potential to compete in the West Coast market. The amount of premium solar resources—direct normal insolation (DNI) of 7.5 or higher—in Arizona, Nevada, and California each are more than the *total* WREZ-identified solar resources for

Colorado, where nearly all of the solar potential is less than 7.25.[6] New Mexico also has solar potential of higher DNI and greater quantity than that normally found in Colorado.

In short, Colorado wind and solar resources enjoy a home-market advantage for the largest renewable energy demand in the eastern portion of the WECC system. The West Coast, on the other hand, will fundamentally be a very challenging market for the state. Wyoming wind power is generally more productive and therefore less expensive (more output per dollar of capital investment) than Colorado wind power.

If Colorado aims to compete outside its home market, it will need a policy strategy that leverages the state's regional position so that developers can deliver the greatest value from Colorado resources to West Coast customers. One possible strategy is to combine grid operations over a larger area that includes Colorado, Wyoming, New Mexico and other states. If geographic diversity reduces the cost and increases the value of wind and solar power, Colorado could still be a viable player in a regional renewable energy market. The next section takes a close look at some of the technical issues that, if addressed, could increase Colorado's competitiveness.

[6] DNI (direct normal insolation) is the amount of sunlight hitting the ground on an average day, expressed as kilowatt-hours per square meter per day.

Regional Management of Renewable Energy Resources

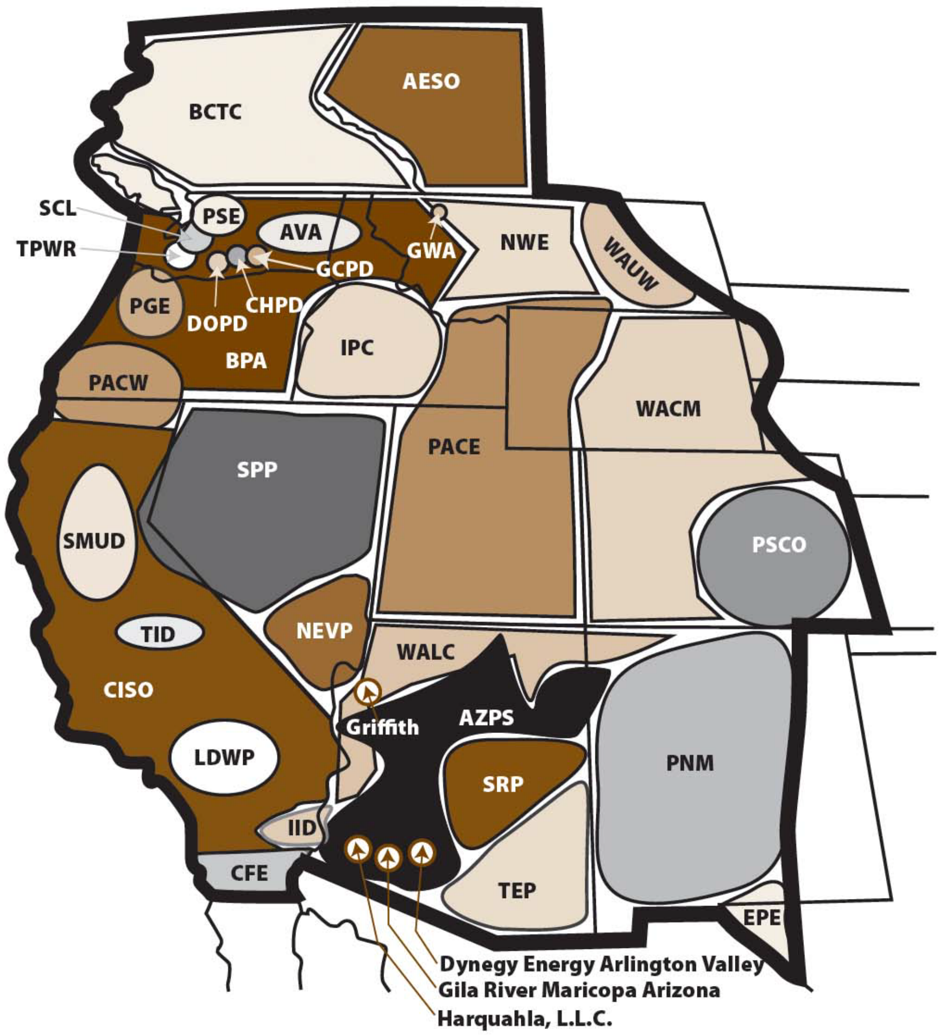
A 2009 study by the North American Electric Reliability Corporation (NERC) concludes that effective, efficient integration of wind and solar resources would require changes in the traditional ways that operators manage the grid.[7] One of the changes it recommends is to consolidate daily operations of small transmission systems into larger balancing authority areas. NERC found that a larger pool of generation resources and demand-side management capability would make reliability problems easier and less costly to manage. These findings agree with the analysis conducted in this study, and they could have significant material implications for the regional competitiveness of Colorado's renewable resources.[8]

A balancing authority area is the geographic unit within which generation and demand are kept in balance every moment of the operating day.[9] The entire Western Interconnection comprises 37 balancing authority areas, as shown on Map 3.

[7] North American Electric Reliability Corp., "Accommodating High Levels of Variable Generation," April 2009 [http://www.nerc.com/files/IVGTF_Report_041609.pdf].

[8] The findings would still be applicable in the event that California decides to allow unbundled renewable energy credits (RECs) to count toward RPS compliance. "Unbundled" means that RECs issued for renewable energy production could be traded as commodities independent of how the corresponding power physically flowed on the grid. Greater use of unbundled RECs would reduce the need for interstate transmission from Colorado to California, but would increase the amount of renewable power that would have to be accommodated in Colorado.

[9] The net between generation and load also includes the flow of power to or from neighboring balancing authority areas.



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PUD No. 1 of Douglas County (DOPD)
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Puget Sound Energy (PSE)
Sacramento Municipal Utility District (SMUD)
Salt River Project (SRP)
Seattle City Light (SCL)
Sierra Pacific Power Company (SPP)
Tacoma Power (TPWR)
Tucson Electric Power Company (TEP)
Turlock Irrigation District (TID)
Western Area Power Administration, Colorado-Missouri Region (WACM)
Western Area Power Administration, Lower Colorado Region (WALC)
Western Area Power Administration, Upper Upper Great Plains West (WAUW)

Generation-only, controls no load

Map 3: Thirty-seven Balancing Authorities in the Western Interconnection

Source: Western Electricity Coordinating Council (available on-line at http://www.wecc.biz/).

Wind and solar resources are by nature variable and uncontrollable. This poses two challenges for routine grid operations.

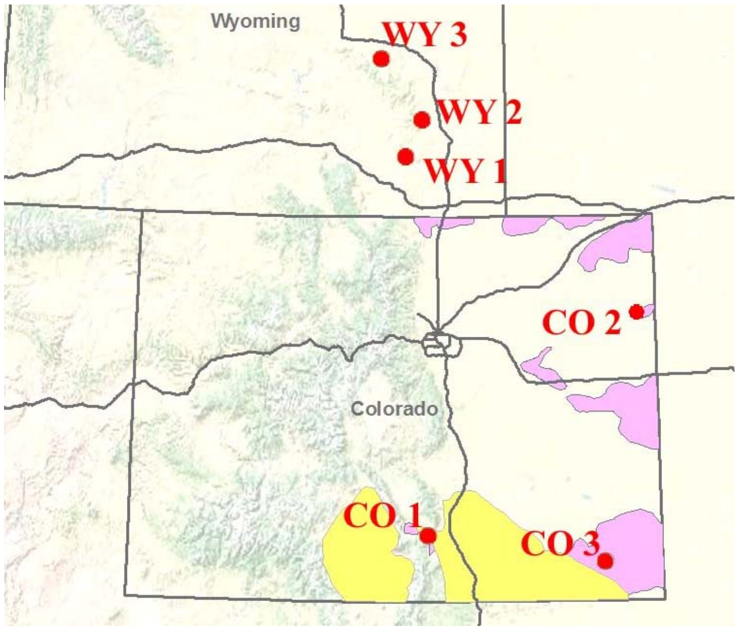
- *Moment-to-moment changes in wind or sunshine and, consequently, the amount of instantaneous power produced by the equipment*. Random changes in actual wind or solar output have to be balanced in real-time with flexible generation resources (usually natural gas), so that total system generation matches total system load at all times throughout the day. Load itself is variable and largely uncontrollable, and system operators rely on flexible reserves to manage the changes. Wind and solar generation introduce an additional source of uncontrollable variation.
- *Typical daily production profiles that differ from typical load profiles*. Even when the real-time variations are averaged into typical daily production profiles, the shape of those profiles may require grid operators to change how they schedule flexible resources, such as natural gas, a day in advance.

In theory, geographic diversity should make the first problem easier to manage as the amount of wind and solar power on the system becomes large. The farther apart two points are, the greater likelihood that random changes happening at the same time at each point will cancel each other out. If diversity creates greater predictability, operators should also find it easier to schedule flexible resources in the normal day-ahead schedule so that the renewable resources and the flexible resources, when combined, fit the hourly profile of the load forecast.

These challenges, as well as other operational benefits of regional diversity of wind and solar power, are among the questions addressed in the Western Wind and Solar Integration Study (WWSIS). A partnership between NREL and WestConnect, WWSIS uses mesoscale-modeled wind production potential for wind turbines at a hub height of 100 meters, which is the height of many new wind installations. Site-specific production potential is calculated by a computerized model that combines wind turbine technical specifications and topographic data with detailed meteorological data for 2004, 2005, and 2006. The results are estimates of wind speed at a height of 100 meters at 10-minute intervals throughout the year. Data for more than 32,000 sites across the WestConnect footprint were selected for detailed analysis.

This report uses six selected data points from the WWSIS study to examine the question of diversity between Colorado and Wyoming, because these are the two primary states that constitute the Rocky Mountain Power Area (RMPA). Two balancing authority areas make up most of RMPA, one operated by Xcel Energy and the other operated by the Western Area Power Administration.

The locations of the sites are shown on Map 4. Site selection was not random, as the goal was to select sites indicative of each state’s best wind resources. The Colorado sites are in Wind GDAs 4, 6, and 8 identified in the SB 91 report. The selected sites are those with the highest capacity factor within the bounds of the GDAs, as estimated by the WWSIS mesoscale modeling. A similar selection method was used for the Wyoming sites, using the north, east, and central resource hubs identified in the WREZ initiative, selected so as to avoid sensitive wildlife areas identified by the state. All six sites represent relatively high annual capacity factors ranging from 33% to 46%.



Map 4: Six Sample Sites Used in Geographic Diversity Analysis

Real-time Variation in Wind Output

Does managing wind power over a more expansive balancing authority area make Colorado wind power more valuable? A key determinant is the potential savings in balancing costs if the larger pool of wind resources deviates less from its scheduled output. This analysis used the following approach.

1. Using the modeled data for 2005, standardize the estimated 10-minute output levels of each individual sample site, as well as the same-time sum of output combining the sites.
2. Calculate the changes in standardized output over each 10-minute interval, and from hour to hour.
3. Compare the average differences to determine whether combining sites results in smaller differences.

For context, the measures of average variation (in standard deviations from the mean) were converted into an equivalent amount of megawatts, assuming one gigawatt of nameplate wind capacity.

Table 1: Geographic Diversity and Variation in Output

Sample Site	10-minute variation		One-hour variation	
	σ	MW equivalent**	σ *	MW equivalent**
Colorado sample site 1	0.24	96	0.48	193
Colorado sample site 2	0.23	75	0.47	153
Colorado sample site 3	0.24	81	0.48	162
Simultaneous output at three Colorado sites	0.18	45	0.40	102
Wyoming sample site 1	0.19	72	0.38	148
Wyoming sample site 2	0.20	73	0.48	172
Wyoming sample site 3	0.18	69	0.38	143
Simultaneous output at three Wyoming sites	0.13	42	0.29	95
Simultaneous output at all six sample sites	**0.12**	**31**	**0.28**	**71**

*Standard deviations from mean annual output.
** Converted to megawatt equivalent for one gigawatt of nameplate wind capacity.

Source: Author's analysis using mesoscale-modeled data from the Western Wind and Solar Integration Study (http://www.nrel.gov/wind/integrationdatasets/western/methodology.html). Wyoming sample site were Nos. 16338, 19065, and 22193; Colorado sample sites were Nos. 9099, 31139, and 30940. Production data for all sites were based on meteorological data for 2005.

Table 1 shows the average for the sites over a typical 10-minute interval and in the span of an hour. The changes labeled "σ" (sigma) are statistical standard deviations from the mean output for the year; this makes the results comparable for any given amount of wind capacity, regardless of whether it is placed entirely at one site or spread equally among the group of sites.

The combined output exhibits smaller 10-minute changes than any of the individual sites. Moreover, the net change becomes relatively smaller as the analytical footprint becomes larger. For each state, the σ values for the combined output at all three sites are lower than for any of the individual sites. The reduction in variation was even greater when all six sites were examined. In fact, the 10-minute change for the combined sites is less than the change at any individual site.

What this means is that less flexible reserve capacity would be deployed over the course of a typical year if 1 GW of wind power were spread out between Colorado and Wyoming in a larger balancing authority area, instead of being all in Wyoming or all in Colorado.

Precisely estimating the value resulting from less use of flexible reserves is beyond the scope of this report, as it would involve detailed simulations of economic dispatch system-wide. By applying a number of simplifying assumptions, however, it is possible to provide a very rough indication of the relative degree to which the use of flexible reserves would be reduced by managing wind resources over a larger and more geographically diverse control area. To roughly estimate the value of such savings, the study calculated the amount of flexible reserves that would have been needed in 2005 to balance wind output on a daily basis, as follows.

1. Assume that a wind farm's set point (the output at which it would be scheduled to operate the next day, based on wind forecasts) is the average of its output estimated for that *day*.
2. Calculate *hourly* average output, and calculate the reserves that would need to be deployed up or down in order to make up the difference between the hourly average and the daily set point. (Positive differences would represent up-deployments.)
3. Sum the estimated up-deployments for the year (in megawatt-hours), calculate the wind farm's electricity production for the year (also in megawatt-hours), and calculate the amount of up-deployment required for each megawatt-hour of production.

Using this very rough methodology, a set point based on the same-time output of all six sites would require about 120 MWh of up-deployment from flexible resources for one gigawatt of nameplate capacity. Applying the same methodology to the three Colorado wind sites individually, the up-deployment requirement increases to between 240 MWh and 260 MWh. Assuming that the output is typical of a good site, and natural gas prices of $7 per mcf, the difference in up-deployment costs would be between $20 million and $30 million annually.

The net cost of up-deployments and down deployments together would be smaller than the value of up-deployments alone. This is because down-deployments would involve over-production at the wind farm, and a corresponding *reduction* in the output of a flexible natural gas generator. Typically, up-deployments involve increasing production on units that are more expensive than any of the units running at the time. Down-deployments tend to be the opposite, as they remove the most expensive units running at the time. In other words, what may be saved by *reducing* output by 10 MW would tend to be less than the additional cost of *increasing* output by 10 MW; even if the quantities are equal in either direction, the economic value is not. An accurate estimation of the true net savings would require modeling the landscape of variable costs at different levels of production, which is beyond the scope of this report.

What the foregoing analysis suggests is that management across a larger balancing authority area would increase the value—and, therefore, the regional competitiveness—of wind resources in both Colorado and Wyoming. The additional competitive value is attributed to reduced operational costs, particularly the use of flexible reserves to balance real-time errors from scheduled output levels.

Matching Production to Load throughout the Day

If combining wind resources across a larger area makes the net wind schedule less variable and more stable, operators can incorporate the shape of wind power's hourly production profile into the next day's operating schedule with greater confidence in its consistency. This raises another analytical question, however: assuming that wind power's production profile is stable enough for day-ahead scheduling, how does the wind profile match the daily load profile?

The *diurnal* pattern of load or generation is how either one changes during the course of an average day. The diurnal load profile is low in the early morning hours and gradually increases through the rest of the morning and early afternoon. In Colorado, load tends to peak in the late afternoon during the summer, and in the evening during a typical winter day.

Operational issues can arise from how the diurnal profile of wind production differs from the load profile. If the two patterns are counter-cyclical (i.e., one tends to be up when the other tends to be down), then it may reduce the amount of baseload generation needed from coal-fired plants, and require more reliance on generation from natural gas units. Coal plants are expensive to start up and difficult to adjust once they are operating, and for these reasons operators prefer to operate coal-fired units at the same level around the clock. Consequently, coal plant generation is often scheduled based on the system's minimum load level.

When wind production peaks at night, the net effect is to reduce the effective minimum load. This, in turn, would reduce the amount of baseload production needed from coal plants but would also increase the use of flexible generation from natural gas throughout the day. A counter-cyclical pattern between load and wind, therefore, usually reduces electricity-related carbon emissions, but it also increases exposure to potentially extreme changes in natural gas prices.

The more renewable generation tends to peak during the day, the flatter the combination load and renewable generation tends to be. The use of coal baseload may change little, while daytime use of natural gas resources would decrease. This pattern provides more price stability, but carbon emissions would not fall as much. (Coal produces about twice the amount of carbon dioxide that natural gas does per unit of electricity generated.)

For the purposes of this analysis, *net load* is the difference between electricity demand and the level of wind output, or mathematically,

$$\text{net load MW}_t = \text{load MW}_t - \text{wind MW}_t,$$

where *t* designates the operating hour, and all three quantities are expressed in megawatts. The analytical metric used in this analysis is *the difference between a diurnal profile's extrema*, that is, the difference between the maximum and minimum megawatt levels over the course of a typical operating day. The analysis examines what happens to the extrema differences when taking into account wind power that is distributed among the six sample sites in Colorado and Wyoming shown on Map 4. Table 2 provides a simplified thumbnail sketch of what the changes in the extrema differences mean.

First, the analysis examined *Colorado as an energy importer*, using 2005 load data for PSCo. The scenarios tested were based on 2.5 GW of wind power. This amount of capacity would have produced about 20% of PSCo's annual demand, based on 2005 data for load and meteorological conditions. (Colorado's renewable energy standard calls for PSCo to obtain at least 20% of its power from renewable resources by 2020.) More precisely, 2.5 GW at the three Colorado sites would have produced 19.6% of PSCo's demand in 2005, while 2.5 GW distributed among all six sites would have produced 20.8% of the utility's 2005 demand.

Table 2: Implications of Extrema Differences in Diurnal Net Load

	Consequence:	***Why:***	***Assumption:***
Bigger difference	Better for reducing carbon emissions	Minimum demand is lower, reducing the amount of baseload generation needed.	Baseload generation reduced is coal-fired.
Smaller difference	Better for price stability	Peak demand is lower, reducing the amount of intermediate and peak generation needed.	Intermediate and peak generation reduced is from natural gas.

Table 3: Estimated Wind Power Deliveries to Destination Markets

	To Colorado (2.5 GW of wind power to PSCo)		**To California** (15 GW of wind power to CAISO)	
	Est. GWh	*% of 2005 demand*	*Est. GWh*	*% of 2005 demand*
From Colorado	7,843	19.6%	47,061	20.0%
From Wyoming	*Not estimated**		52,777	22.4%
From both states	8,320	20.8%	49,919	21.2%

*A Wyoming-only scenario is not realistic for Colorado, as nearly all of the wind power already serving Colorado customers is from in-state resources.

Figure 4 shows the hypothetical reductions in demand for the Colorado import analysis. Each month's segment along the x-axis shows the typical 24-hour profile for that month, calculated as the average load (or net load) at a given hour for each day of that month. The two net load profiles differ little during the summer months. Each yields the greatest net load reductions during the winter and spring months, although in most cases (but not all) the two-state distribution of wind power reduces net load more than the Colorado-only distribution does.

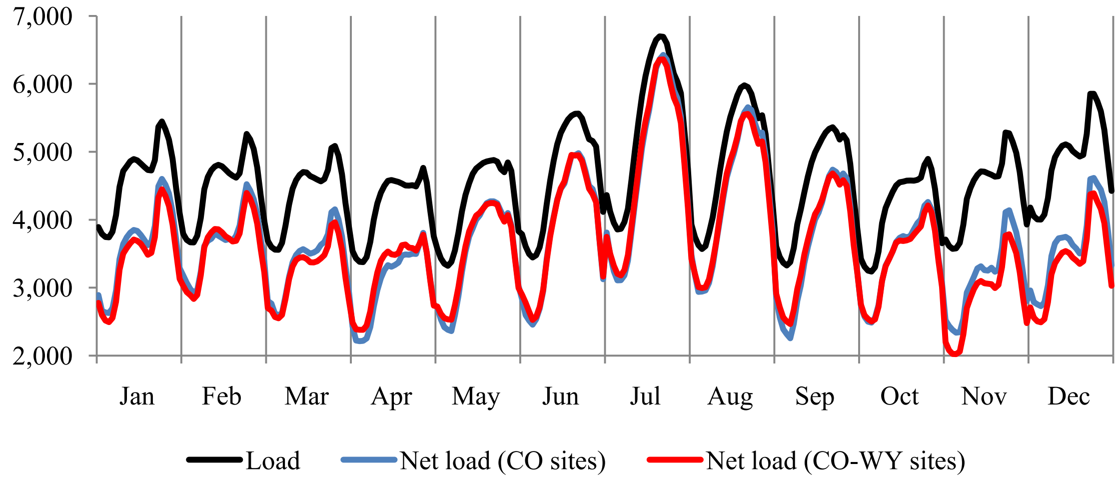


Figure 4: Diurnal Load Profiles for PSCo, Averaged by Month

Net load for PSCo calculated based on 2.5 gigawatts of wind capacity.
Sources: SNL Financial (load data); WWSIS (wind site production estimates).

Table 4 compares the magnitude of the extrema differences. For every month except November, the two-state net load profile showed smaller differences between the daily high and the daily low than did the Colorado-only profile. In February and March, the two-state net load actually *reduced* the gap between daily high and daily low as compared with gross load.

Table 4: Diurnal Extrema Differences for PSCo, 2005

	Difference between average daily maximum and minimum load			Magnitude of net load difference relative to load-only	
	Load-only	Net load (CO sites)	Net load (CO-WY sites)	Net load (CO sites)	Net load (CO-WY sites)
Jan	1,705	1,973	1,956	16%	15%
Feb	1,595	1,597	1,560	0%	-2%
Mar	1,527	1,560	1,413	2%	-7%
Apr	1,387	1,593	1,398	15%	1%
May	1,556	1,912	1,719	23%	10%
Jun	2,115	2,524	2,428	19%	15%
Jul	2,843	3,317	3,179	17%	12%
Aug	2,409	2,718	2,563	13%	6%
Sep	2,035	2,483	2,215	22%	9%
Oct	1,658	1,774	1,708	7%	3%
Dec	1,852	1,886	1,900	2%	3%
Nov	1,710	1,802	1,764	5%	3%

Sources: SNL Financial (load data); WWSIS (wind site production estimates).

Generally, then, combining wind power supplies from Colorado and Wyoming tends to increase the stability of electricity costs more than obtaining wind power only from Colorado. Conversely, using only Colorado wind would tend toward less use of coal and a greater reduction in carbon emissions from coal plants serving Colorado load.

The next part of the analysis examined *Colorado as an energy exporter*, using 2005 load data for the California Independent System Operator (CAISO). As earlier sections of this report demonstrate, California constitutes the largest demand for regional renewable energy. This part of the analysis uses 15 GW of wind power, which would have produced about 20% of CAISO's 2005 demand. (The three Colorado sites would yield 20%, while the three Wyoming sites would yield 22.4%. The same capacity distributed among the six Colorado and Wyoming sites would yield 21.2%.)

Figure 5 shows—and Table 5 quantifies—what would happen to CAISO's net load with Colorado competing head-to-head with Wyoming via separate transmission lines, and with Colorado and Wyoming sharing a single line to California.[10] For every month except December, California's net load profile with Colorado wind exhibits larger differences between the daily highs and lows than is the case with Wyoming wind. Moreover, the net load profile with Wyoming wind is actually flatter than the *unadjusted* daily load profile for four months out of the year.

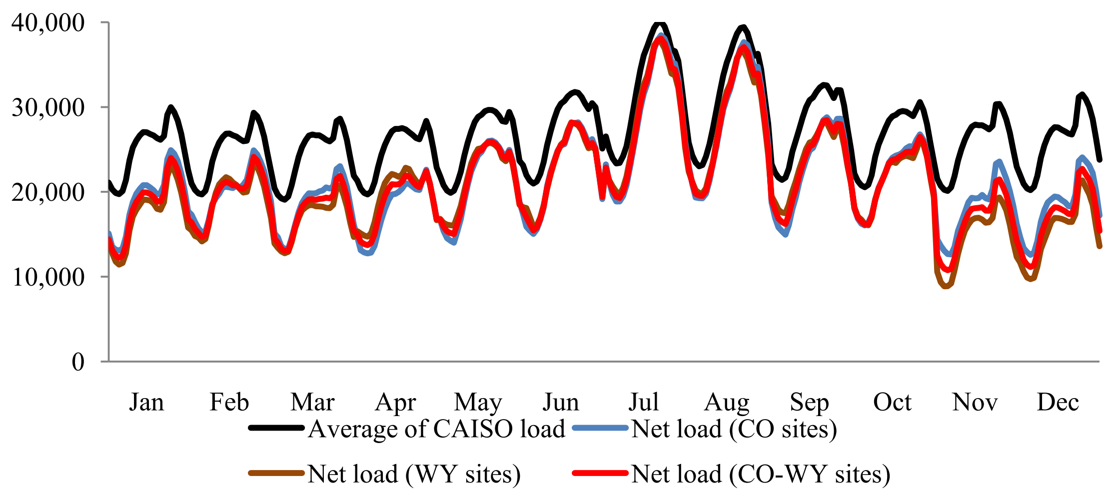


Figure 5: Diurnal Load Profiles for California ISO, Averaged by Month

Net load for California ISO calculated based on 15 gigawatts of wind capacity.
Sources: SNL Financial (load data); WWSIS (wind site production estimates).

[10] For simplicity, this analysis assumes a direct DC line to CAISO from Colorado fed by Colorado resources only, from Wyoming fed by Wyoming resources only, or a single line fed by wind resources from both states. On an upgraded AC network path, the diurnal effect of Wyoming or Colorado wind on California's net load would be affected by the diurnal profiles of other loads on the network path.

Table 5: Diurnal Extrema Differences for California ISO, 2005

	Difference between average daily maximum and minimum load				Magnitude of net load difference relative to load-only		
	Load-only	Net load (CO sites)	Net load (WY sites)	Net load (CO-WY sites)	Net load (CO sites)	Net load (WY sites)	Net load (CO-WY sites)
Jan	10,256	11,860	11,656	11,758	16%	14%	15%
Feb	9,629	9,640	9,192	9,416	0%	-5%	-2%
Mar	9,544	9,763	7,985	8,863	2%	-16%	-7%
Apr	8,658	9,874	8,134	8,722	14%	-6%	1%
May	9,776	12,039	9,740	10,881	23%	0%	11%
Jun	10,800	13,168	12,326	12,685	22%	14%	17%
Jul	16,710	19,594	18,129	18,776	17%	8%	12%
Aug	16,416	18,408	16,703	17,527	12%	2%	7%
Sep	11,203	13,850	10,748	12,243	24%	-4%	9%
Oct	10,047	10,744	10,119	10,347	7%	1%	3%
Nov	10,262	10,943	10,489	10,688	7%	2%	4%
Dec	11,287	11,493	11,656	11,574	2%	3%	3%

Sources: SNL Financial (load data); WWSIS (wind site production estimates).

Significantly, during the peak load months of July and August, 15 GW of Wyoming wind would have flattened CAISO's net load profile by 1,500 MW to 1,700 MW more than the same amount of Colorado wind would have. This means that Wyoming wind (relative to the same amount of Colorado wind capacity) would have required more baseload during the early-morning hours, and less natural gas generation during the peak hours. The effect would be more relief from high wholesale prices in the entire CAISO market during the peak summer hours.

A two-state supply, however, would preserve much of the summertime price relief effects in California. Over the entire year, the price effect (as represented by changes in the difference between daily extrema) would be midway between that of Colorado and Wyoming separately.

In summary, 2005 empirical data from the six sample wind sites, CAISO load, and PSCo suggest the following.

- Wind farms in Wyoming can typically deliver more electricity to the market on an annual basis than can the same quantity of wind capacity located in Colorado.
- A common transmission system with a balancing authority area spanning both Colorado and Wyoming would yield price stability benefits and emission-reduction benefits midway between what wind resources from either state would provide individually.

- The daily profile of Wyoming wind power is such that it would be more likely to help mitigate high wholesale prices in the CAISO market than would Colorado wind power.

Implications for energy storage

Energy storage, operating reserves, and curtailing spikes in wind output are three tools for addressing the same task of managing naturally variable renewable resources. Each tool poses its own challenges, but if a larger balancing area improves renewable energy's intra-hour variability and load-following characteristics, the challenges may be less problematic.

For storage, the challenges are regulatory (e.g., permits for adding pumped storage capability to existing reservoirs), technological (e.g., large-scale use of underground compressed air storage, batteries or flywheels), as well as economic (particularly how costs are recovered). The details of these challenges are beyond the scope of this analysis and are being addressed in several studies by NREL and others. Nevertheless, the present analysis does suggest that, if a storage facility supports a geographically larger balancing area rather than a smaller one, then

- the real-time production changes that storage would need to offset would tend to be smaller, and
- the risk and financial burden of the project could be spread out over a larger economic base.

Conclusion

Colorado could benefit from selling renewable power to other states, but doing so would most likely require multistate policy partnerships. Interstate commerce in almost any commodity requires some conveyance infrastructure as well as common rules ensuring fair and open access to the market. Colorado cannot by itself plan or authorize the transmission that would be necessary for more robust interstate commerce in renewable power to happen. Even if Colorado were to try to get ahead of other states by accelerating its environmental and siting reviews[11], there would still be the issue of whether the power could get to market via the existing regional transmission network.[12]

With respect to the renewable energy supply chain, Colorado is already a major regional presence. Its emergence as a center for manufacturing and production of renewable energy equipment effectively makes Colorado the commercial hub of a regional New Energy Economy. Vestas, the world's largest manufacturer of wind turbines, builds components in Colorado. Likewise the Solar Energy Industries Association estimates there are nineteen companies currently in Colorado that produce equipment that directly serve the solar energy technologies supply chain.

Expanding its existing manufacturing base for renewable energy would allow Colorado to take advantage of renewable energy development across the region wherever it occurs. For the most part, doing so would involve expanding and promoting advantages the state already has, particularly:

- *The value of existing manufacturers and institutions engaged in R&D.* Colorado's existing manufacturing base and R&D facilities at its research universities, NREL, and in private industry provide a unique advantage for Colorado. By leveraging the benefits that result from having a strong R&D and manufacturing base, Colorado can use these assets to attract component suppliers, entrepreneurs, and new manufacturing firms to the state.
- *Continued development of the state's renewable energy markets.* A proven market demand for renewable energy increases investor confidence, and therefore helps attract new manufacturing investment. State policymakers may not be able to have a direct influence on national market conditions, but ensuring a robust state market for emerging renewable energy technologies can help draw manufacturers, especially for emerging technologies.
- *State and local infrastructure development.* A well-functioning and efficient transportation system is critical for the movement of renewable energy components between suppliers and assemblers as well as the movement of product to the site of final installation. Research has shown that local infrastructure is important for the support of large-scale equipment producers;

[11] Wyoming and Utah are already ahead of Colorado in providing wind power to the West Coast, however.
[12] The use of unbundled RECs would make this problem moot, but at the same time Colorado would face higher reliability costs due to the larger amount of renewable power it would have to accommodate locally.

infrastructure can also reflect on broad trends in governance. Furthermore, investments in fundamental economic assets can enhance economic productivity throughout the state.

- *Education and workforce training*. Workforce development becomes easier and gathers its own momentum when a sector becomes large and active enough to reach critical mass in the economic sense. As such, Colorado's renewable energy workforce is likely to grow simply based on existing assets. To keep its advantage over other states, however, Colorado will need to continue maintaining and expanding its renewable energy workforce.

This analysis shows that some empirical reason exists for believing multistate collaboration could yield efficiency gains that may augment the regional competitiveness of Colorado's wind resources. Consolidating operations across larger balancing authority areas would likely make wind power easier and less costly to manage. Geographic diversity would reduce moment-to-moment variability in wind power output, which would reduce the amount of reserves required to keep load and generation in balance and to manage reliability. Less moment-to-moment variability in wind and solar resources would help day-ahead scheduling of coal- and gas-fired generators. The forecasted net load profile would be more consistent, providing clearer benchmarks for the amount of baseload, intermediate, and peaking generation that would be required from conventional resources during the operating day.

Additional WWSIS analysis will indicate whether the findings of the present study (limited to Colorado and Wyoming) also hold across the entire West. If so, it could indicate greater value-added for renewable energy overall if a larger and more robust regional market were to develop. Colorado could, therefore, have a dual stake in a regional transmission strategy: greater opportunities to sell its own wind power, and greater manufacturing output as renewable energy suppliers in Colorado increase their production.

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14. ABSTRACT *(Maximum 200 Words)*
Colorado has more renewable energy potential than it is ever likely to need for its own in-state electricity consumption. Such abundance may suggest an opportunity for the state to sell renewable power elsewhere, but Colorado faces considerable competition from other western states that may have better resources and easier access to key markets on the West Coast. This report examines factors that will be important to the development of interstate commerce for electricity generated from renewable resources. It examines market fundamentals in a regional context, and then looks at the implications for Colorado.

15. SUBJECT TERMS
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