The Value of Diversifying Uncertain Renewable Generation through the Transmission System

COST SAVINGS ASSOCIATED WITH INTERCONNECTING SYSTEMS WITH HIGH RENEWABLES PENETRATION

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BU Institute for Sustainable Energy Webinar Series

OCT 14, 2020

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Boston University Institute for Sustainable Energy

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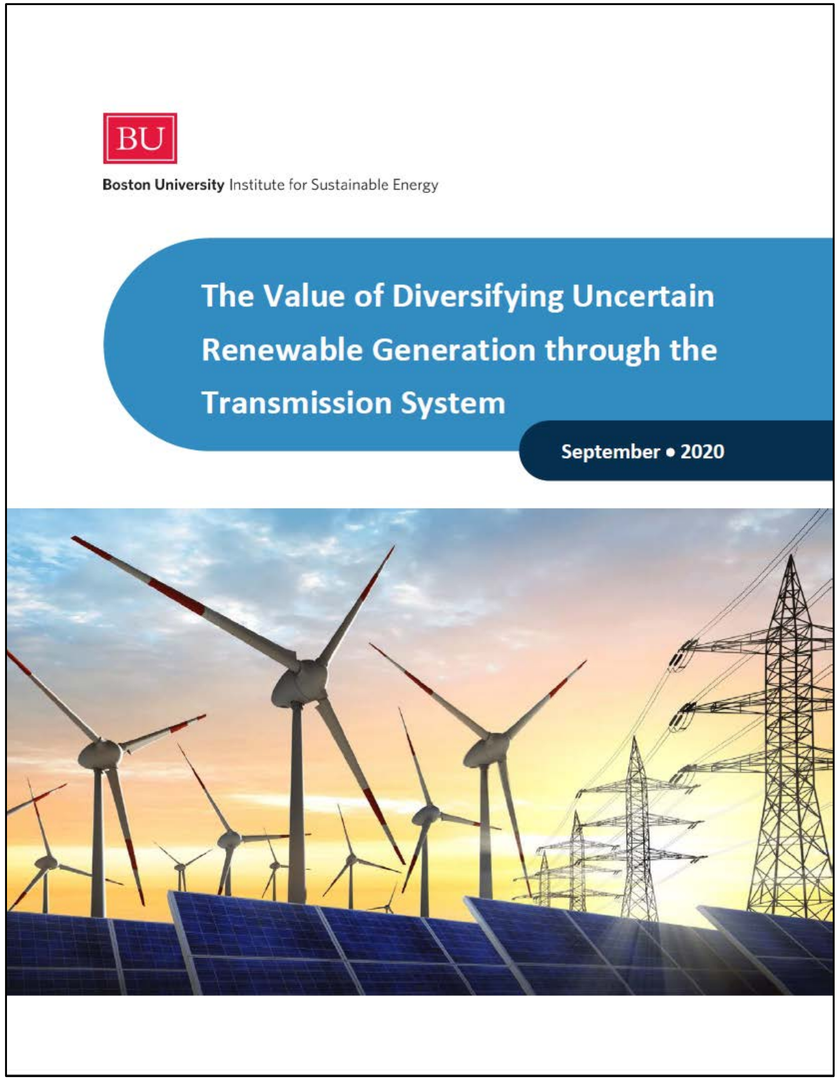
Newly-Released Report



Available at
https://bit.ly/34slZai

The authors would like to thank The Brattle Group and other colleagues who reviewed earlier versions of this manuscript and provided feedback. We are additionally grateful for the detailed comments received from Robert Gramlich (Grid Strategies), Michael Jacobs (Union of Concerned Scientists), David Kelley (SPP), Jennifer Curran (MISO), Robert Sparks (CAISO), Will Hazelip (National Grid), Alex Klein (National Grid), and Prof. Peter Fox-Penner (BU ISE).

All results and any errors in this report are the responsibility of the authors and do not represent the opinion of the BU ISE, The Brattle Group, National Grid, NewGrid, or their clients.

Content

Transmission's central role in the energy transition

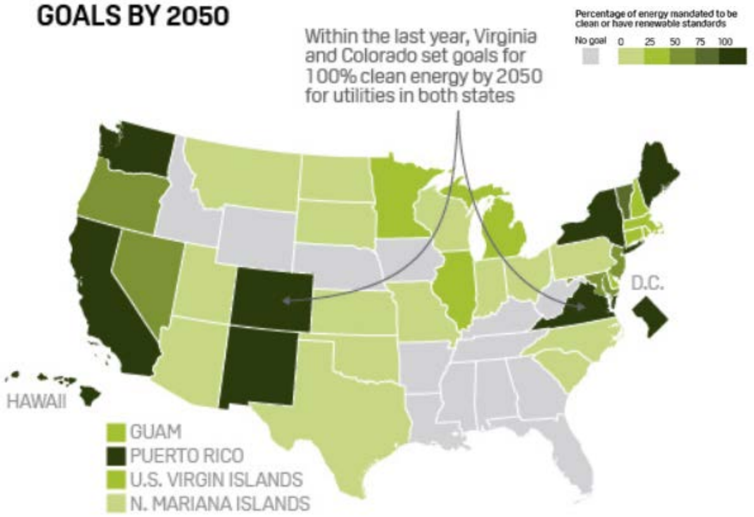
The US electricity sector is in the midst of an accelerating transformation

- More than 20 states currently have mandates or goals to get the majority of their energy from renewables by 2050
- Onshore wind and solar plants have been the largest sources of new generation capacity in recent years
- Offshore wind commitments have grown to 29 GW by 2035

Transmission plays a critical role in the cost-effective integration of these resources to meet state targets

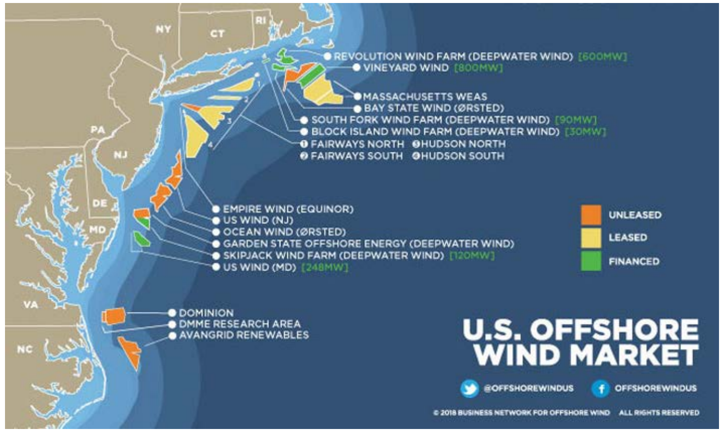
- Interconnect renewable generation areas and load centers
- Connect offshore wind into the grid
- Reinforce the existing grid to adapt to changing generation mix and load patterns
- **Diversify renewable resource variability by interconnecting regions beyond the size of typical weather systems**

Clean Energy Goals/Mandates Proliferate



Source: S&P Global

US Offshore Wind Poised to Take Off

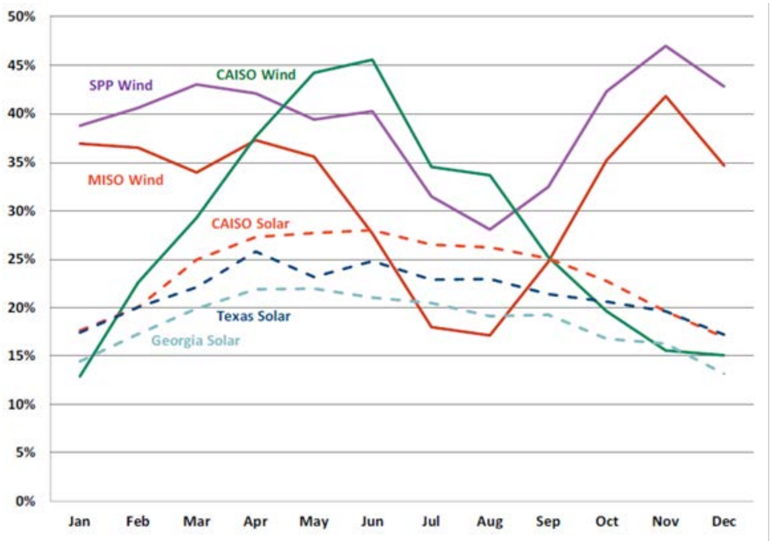


Source: Business Network for Offshore Wind; Leases as of 2018

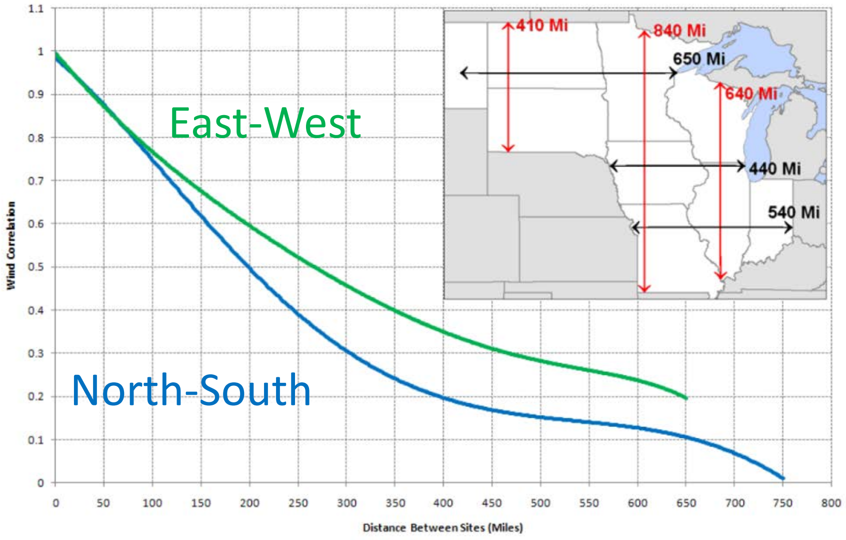
The value of diversifying renewable generation?

Correlation of renewable generation variability can be diversified across technologies and geographically. Diversifying both the predictable and uncertain variability of renewable generation over large geographic areas can reduce system-wide uncertainty and lower costs. But by how much?

Monthly Wind and Solar Generation

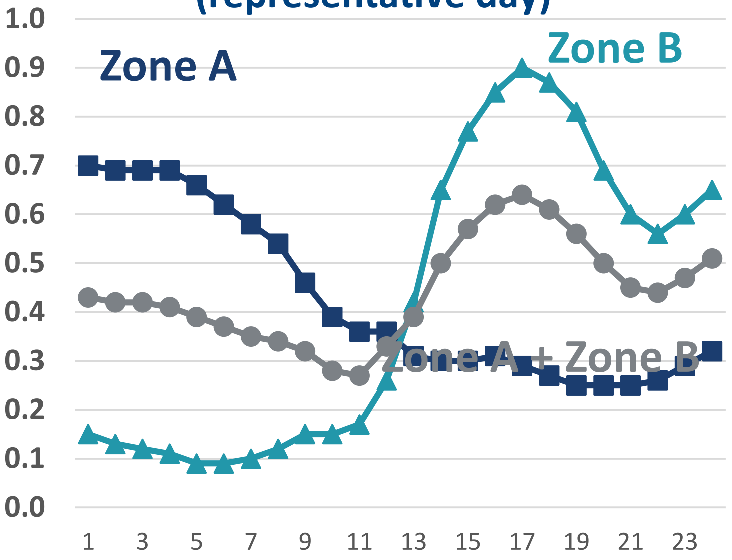


Wind Correlation vs Distance in MISO



Source: MISO

Wind Generation in Case Study (representative day)



Note: Actual wind data from ERCOT for two sites that are approximately 300 miles apart

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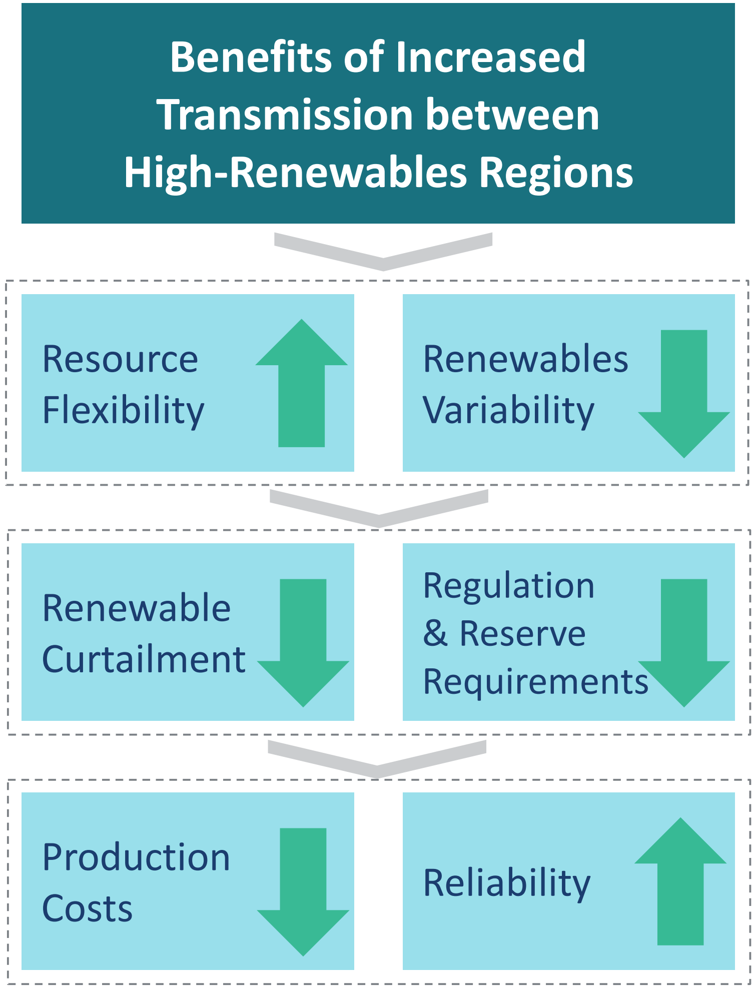
The case for a comprehensive view of transmission benefits

Developing transmission infrastructure to support a cost-effective energy transition requires a more comprehensive understanding of the multiple benefits provided by the grid

Our work demonstrates sizeable "diversification benefits" beyond those typically quantified:

- **The benefits of unlocking the geographic diversity of variable renewable generation are large:** For grids with 10-60% renewable generation, the regional diversification through the transmission grid can reduce system-wide production costs by between 3% and 23% and renewable generation curtailments by 45% to 90% (all else equal)
- **Renewable generation and load uncertainty needs to be considered in measuring benefits:** Relative to conventional studies that are based on "perfect foresight", quantifiable benefits are 2 to 20 times higher when renewable generation and load uncertainty is considered



Implications for planning, public policy, and markets

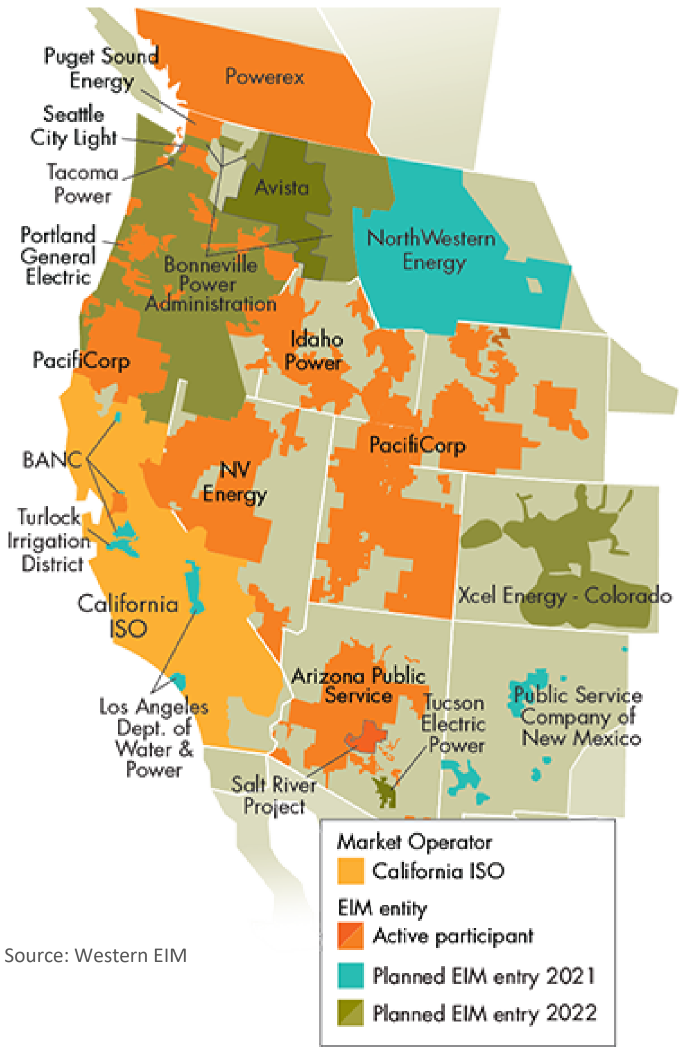
Implications for regional and interregional planning of economic, public policy, and "multi-value" transmission projects:

- Policies that encourage a highly-diverse renewable generation portfolio will be more cost effective than those that do not consider the benefits of broad geographical and technological diversity
- Existing economic planning models—which do not typically simulate load and renewable generation uncertainty—significantly understate transmission benefits related to the geographic diversification of renewable generation
- Planning based on understated transmission benefits will result in a less cost-effective, higher-cost electricity system

Implications for market design

- At low levels of renewable generation, much of the geographic diversification benefits of transmission can be captured if the interconnected areas operate in a real-time energy market, such as the Western Energy Imbalance Market
- As the share of renewable generation grows, the benefit of a geographically-integrated day-ahead market increases

The Western EIM Footprint



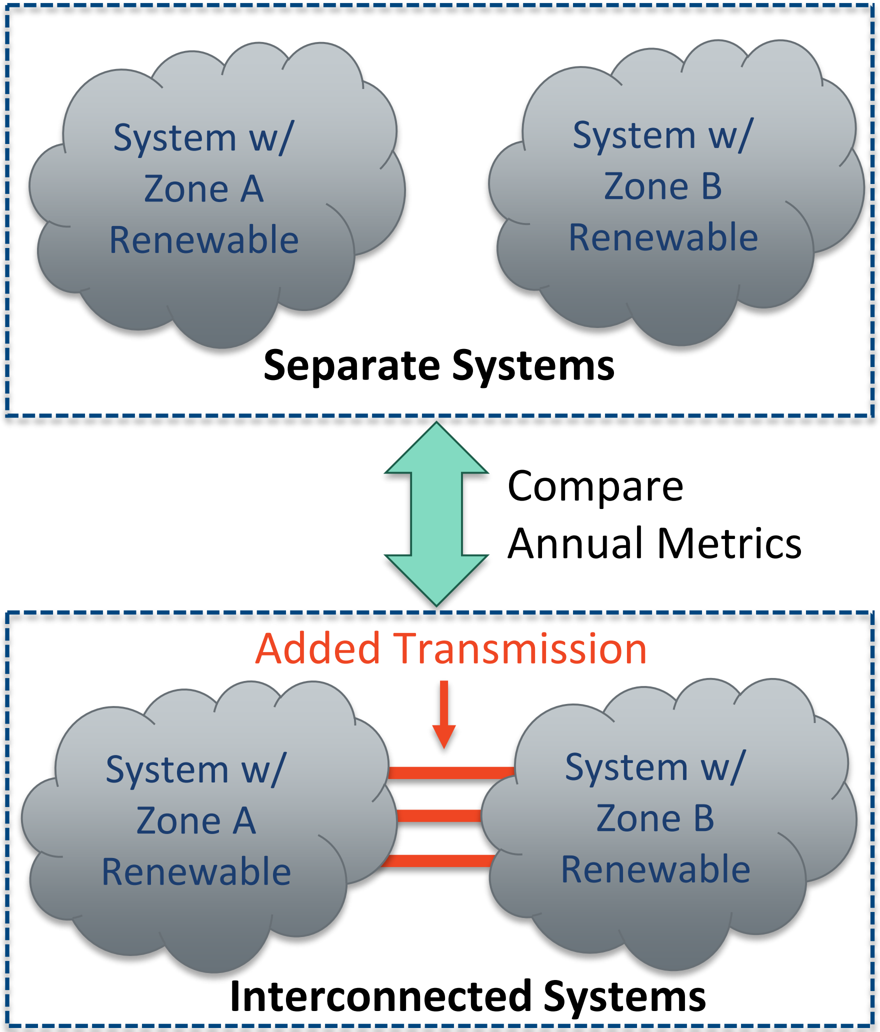
Source: Western EIM

Estimating transmission value through unlocking geographic diversity

Objectives

A To isolate the benefits associated with interconnecting diverse renewable resources

B Test the impact of capturing uncertainty on those benefits (vs perfect foresight)



Approach

1. Create **two identical systems**, except for the renewable generation profiles
   - Because generation and load are identical, dispatch would be identical except for differences due to renewable generation profiles
2. Analyze benefits of the systems as **Separate** and **Interconnected**
3. Compare benefits from results capturing **uncertainty** to those considering only day-ahead "**perfect foresight**"

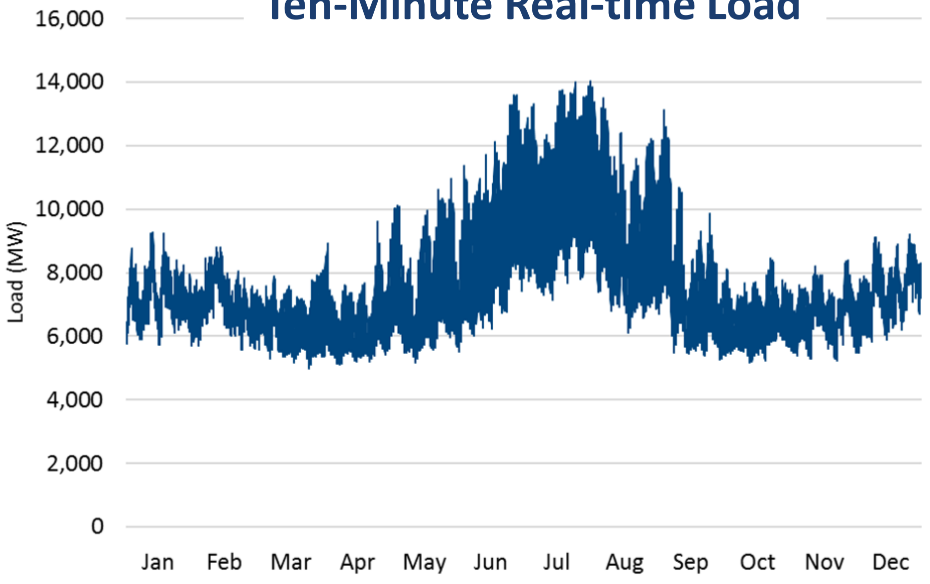
Modeling day-ahead to intra-hour operations of two systems

Constructed a test system representing two almost **identical systems** to isolate renewable generation diversification effects from interconnection benefits:

- Approximately **generating capacity of 16,000 MW** with different technologies and diverse fuel mix.
- **Actual load** data, with 14,000 MW peak
- **Actual wind generation** data from two windy regions
- Only difference: **Uncertainty in load and wind forecast** between day-ahead (DA), hour-ahead (HA), and real-time (RT)

Used **Enelytix**, powered by **Power System Optimizer (PSO)**, to simulate unit-commitment and dispatch on a DA, HA, and RT basis, including explicit simulations of spinning, regulation-up and -down, and intra-day commitment option (ICO) reserves

Ten-Minute Real-time Load



Study Generation Mix and Characteristics

Technology	Nameplate Capacity (MW)	Fraction of Total Capacity (%)	Min Up/Dn Time (hrs)	Min Output (% of nameplate)	Ramp Rate (MW/min)**
Gas CC	3,328	20%	3/4	50%	10
Gas ST	2,420	15%	10/8	30%	6
Gas Peaker	1,967	12%	-	80%	-
ICE	300	2%	-	1%	-
Nuclear	793	5%	N/A	100%	N/A
Coal ST	7,488	46%	24/12	30, 50%*	3
Total	16,296				

* Coal ST units with capacity >=600 MW were assigned min outputs of 30%

** Ramp rates were used in the model only to determine the quantity of reserves units can provide. Gas Peakers and ICE units were assumed to be able to ramp over their entire operating range

We examined multiple benefits and benefits drivers

Reduced production costs

- Lower cost generation from interconnected areas is shared across the regions

Reduced wind curtailments

- Generator flexibility shared across the regions reduces the need to curtail wind during times of high wind output and/or low load

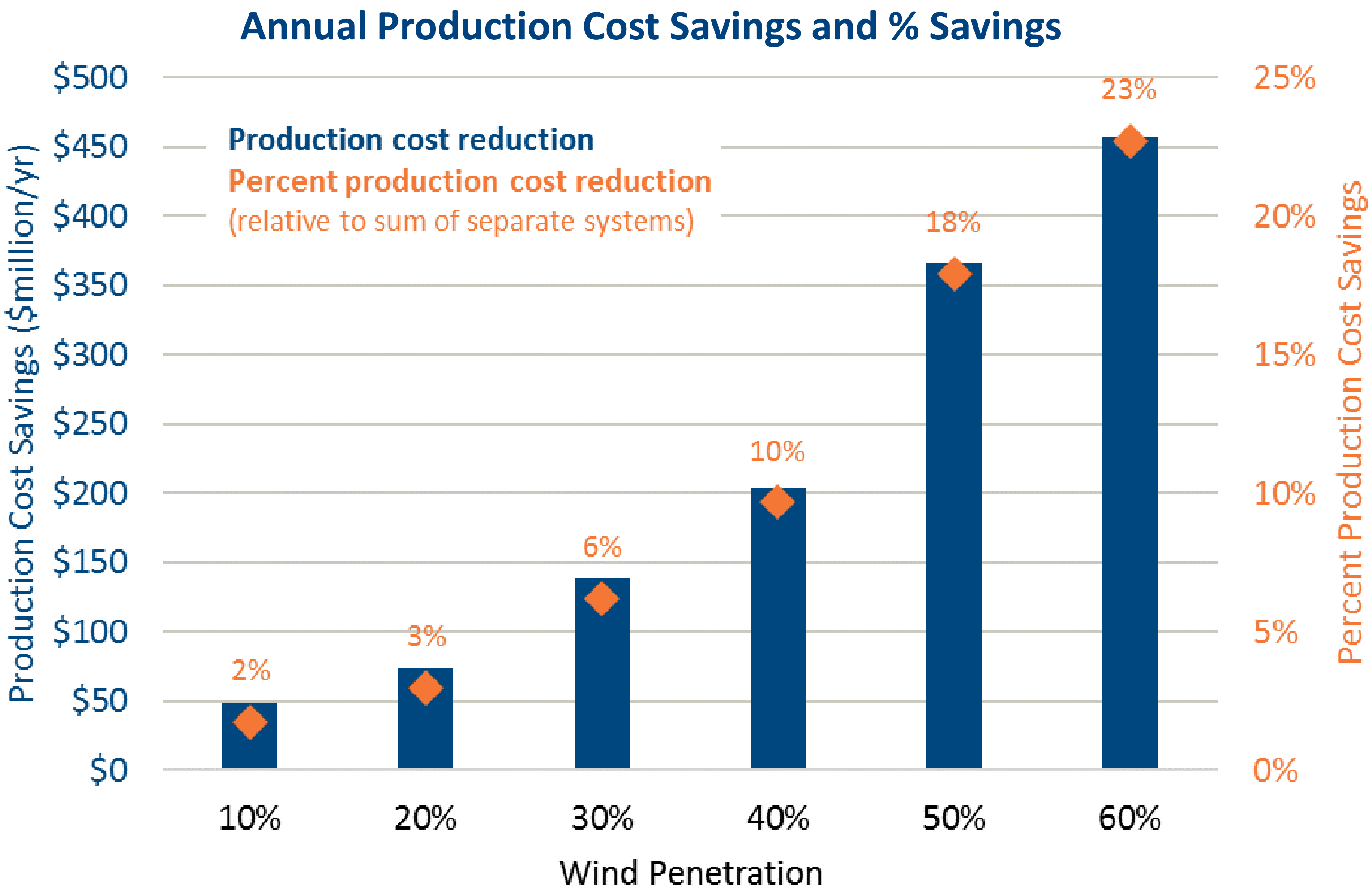
Reduced regulation and operating reserve requirements

- Reserves needed (based on system contingency requirements) by the interconnected area is less than the sum of those needed by the separate systems
- Reduced net load volatility reduces regulation needs
- Reduced net load forecast error reduces Intra-Day Commitment reserve needs

Increased available flexibility and reliability

- The availability of additional generator flexibility and reduced net-load volatility will also reduce incidents of load shedding and contingency reserve calls (though not quantified in this case study)

Unlocking geographic diversity offers significant production cost savings



Key takeaways

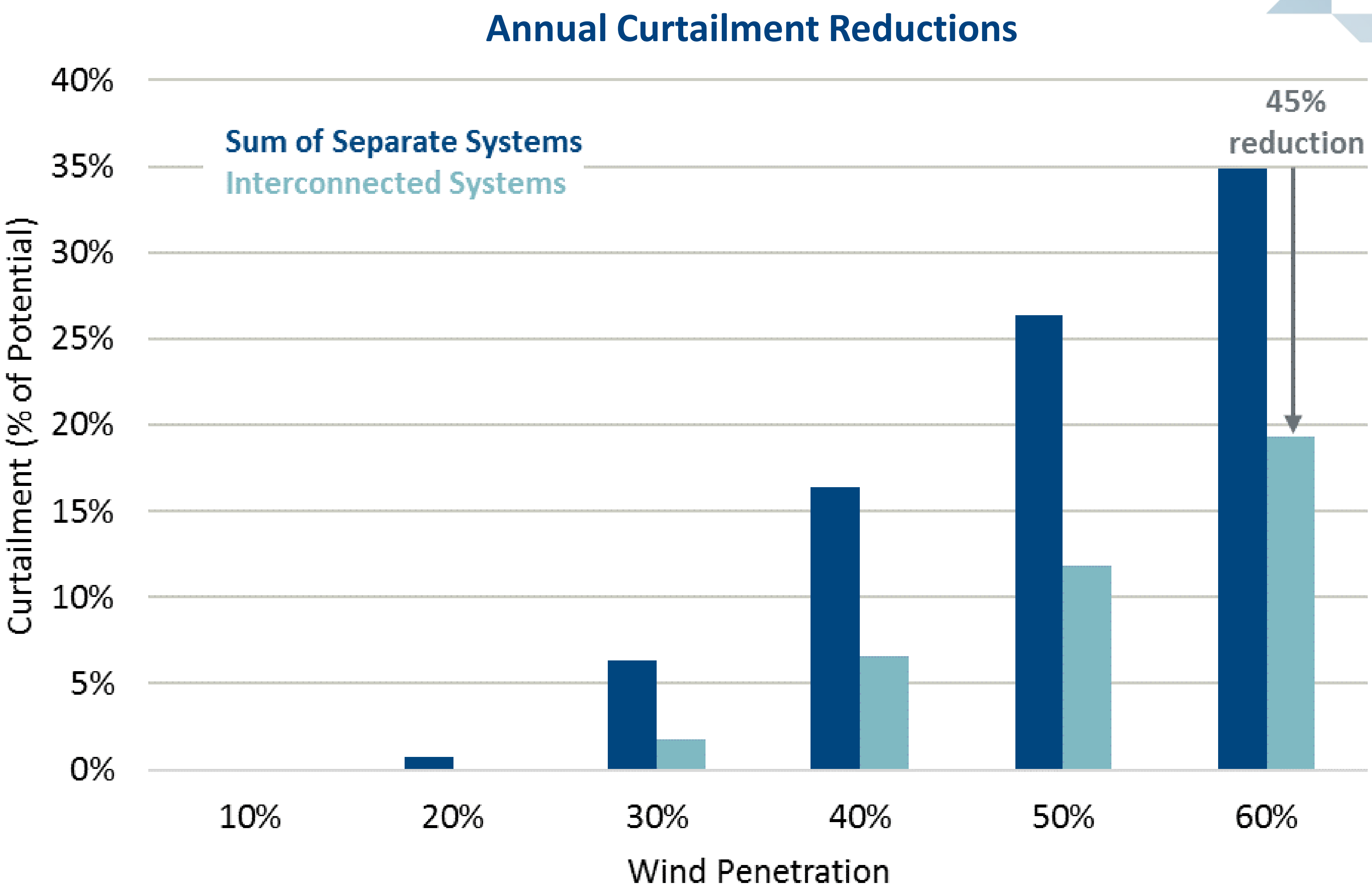
- Substantial increases in operational efficiency gains from interconnecting the two areas
  - **Reduces total production costs by 2% to 23%**
- The increased capability of the system to absorb previously curtailed renewable generation is another key driver of savings

Note: 2 x Systems of ~16 GW generation, ~14 GW peak load; no limit on flow between interconnected systems; results from RT cycle

Reduced curtailment is a primary driver of cost reductions

Key takeaways

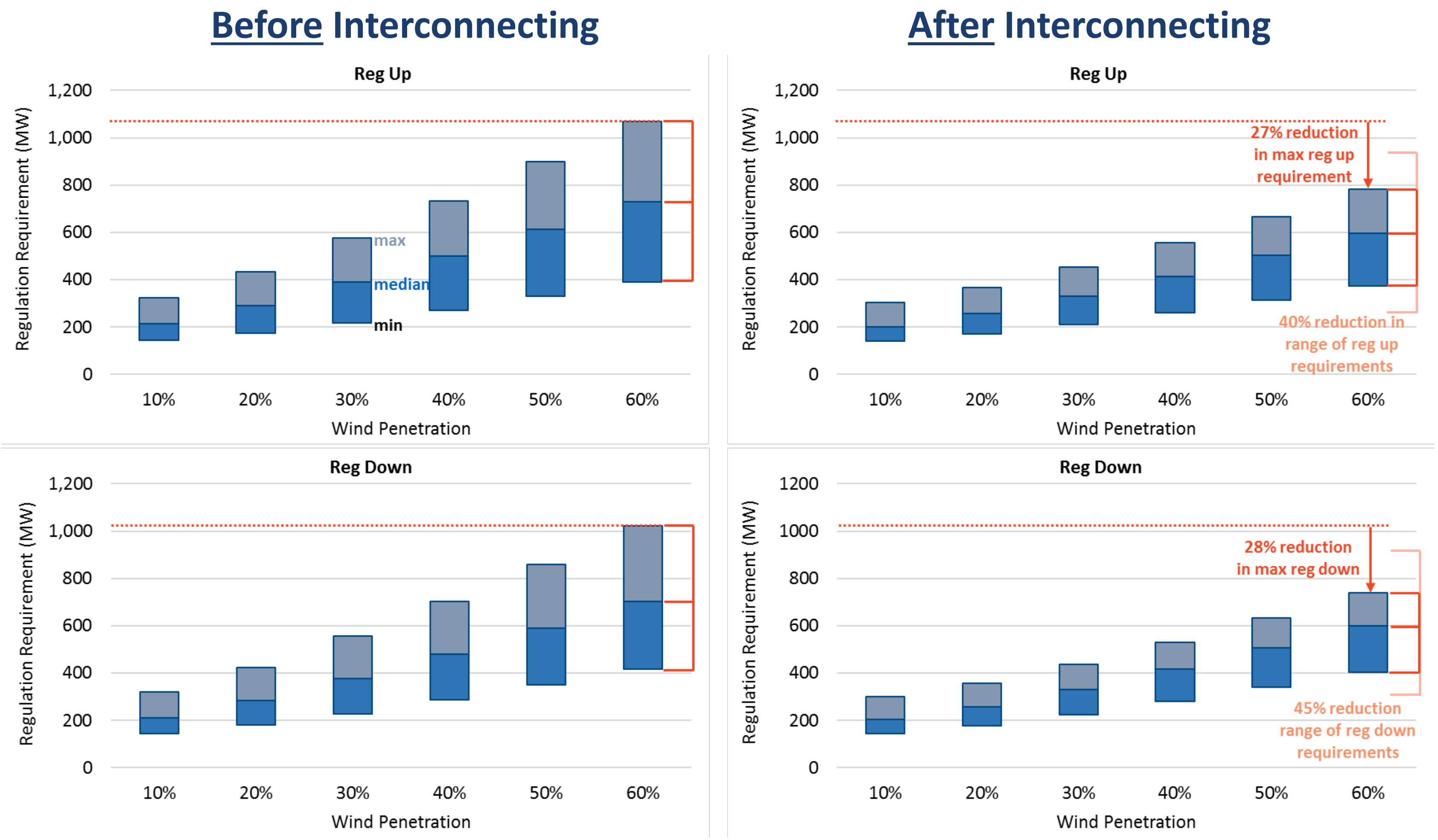
- Interconnecting the systems allows for access to **additional flexibility**, which reduces renewable generation curtailment
- Reduced curtailment will reduce the scale of renewable capacity needed to meet policy targets, **reducing investment costs**



Note: 2 x Systems of ~16 GW generation, ~14 GW peak load; no limit on flow between interconnected systems; results from RT cycle

Reduced regulation and reserve requirements drive additional savings

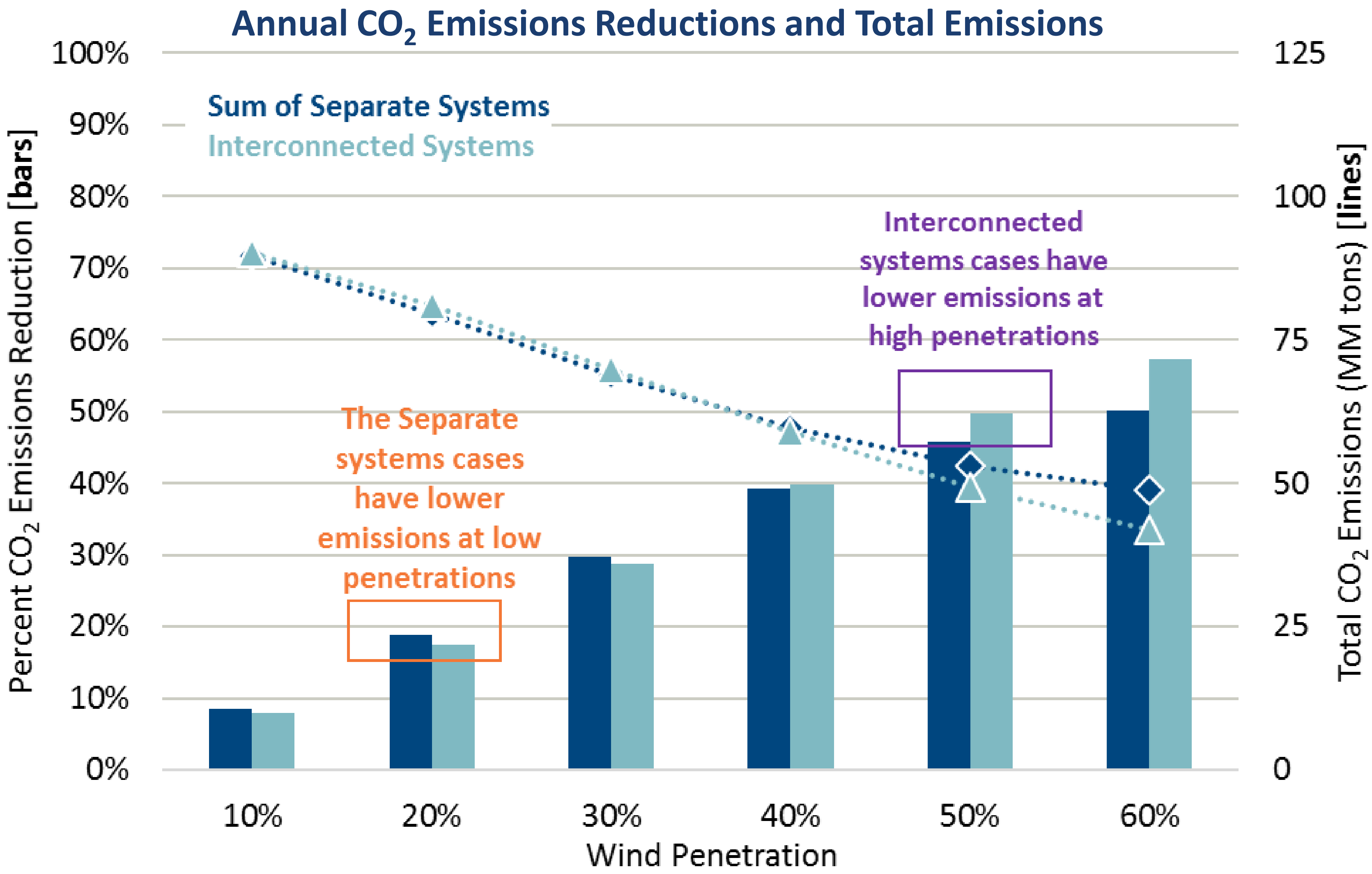
Before Interconnecting / After Interconnecting



In this example, the regulation and reserve reduction is modest at 30% renewable penetration

But for sub-regions with higher renewable generation, the reduction can be significantly higher, amplifying the impacts on curtailment and production cost reductions

CO_2 emissions impacts are system-dependent

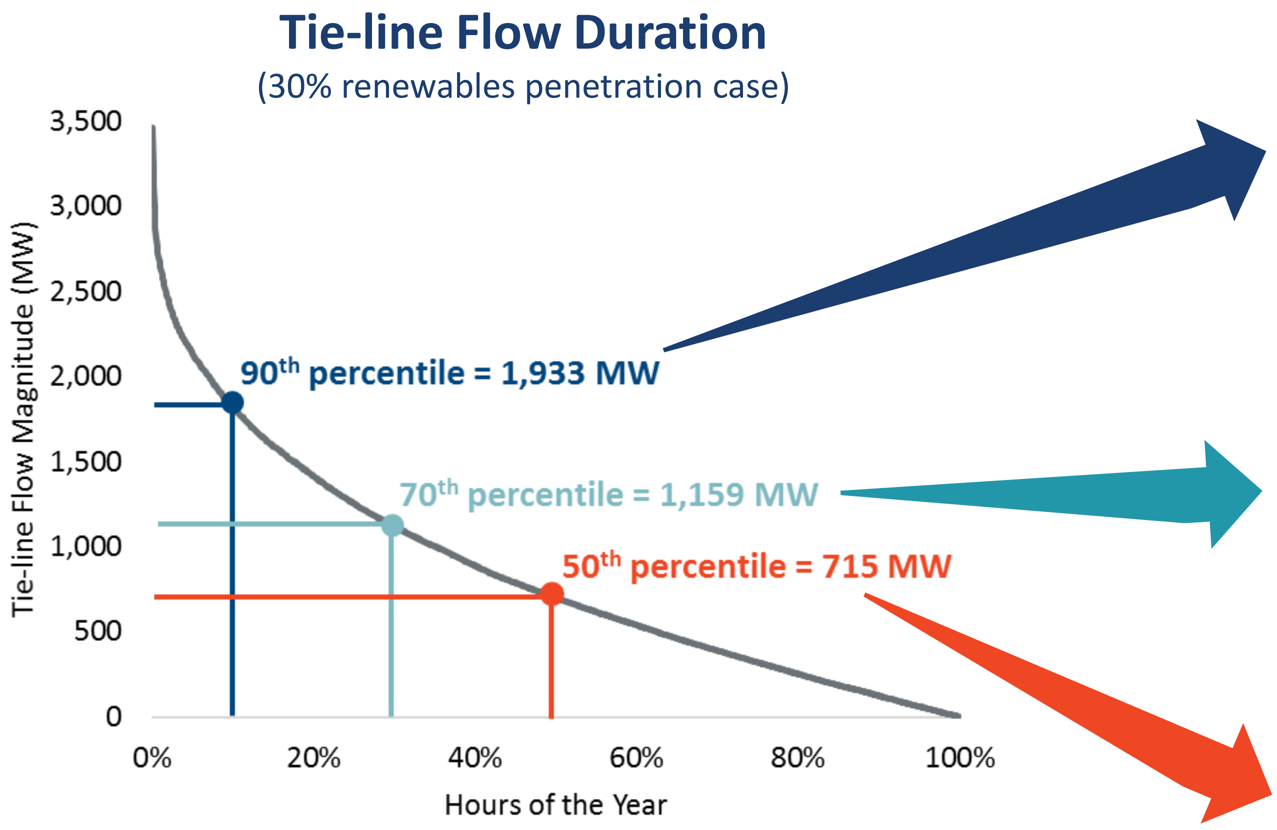


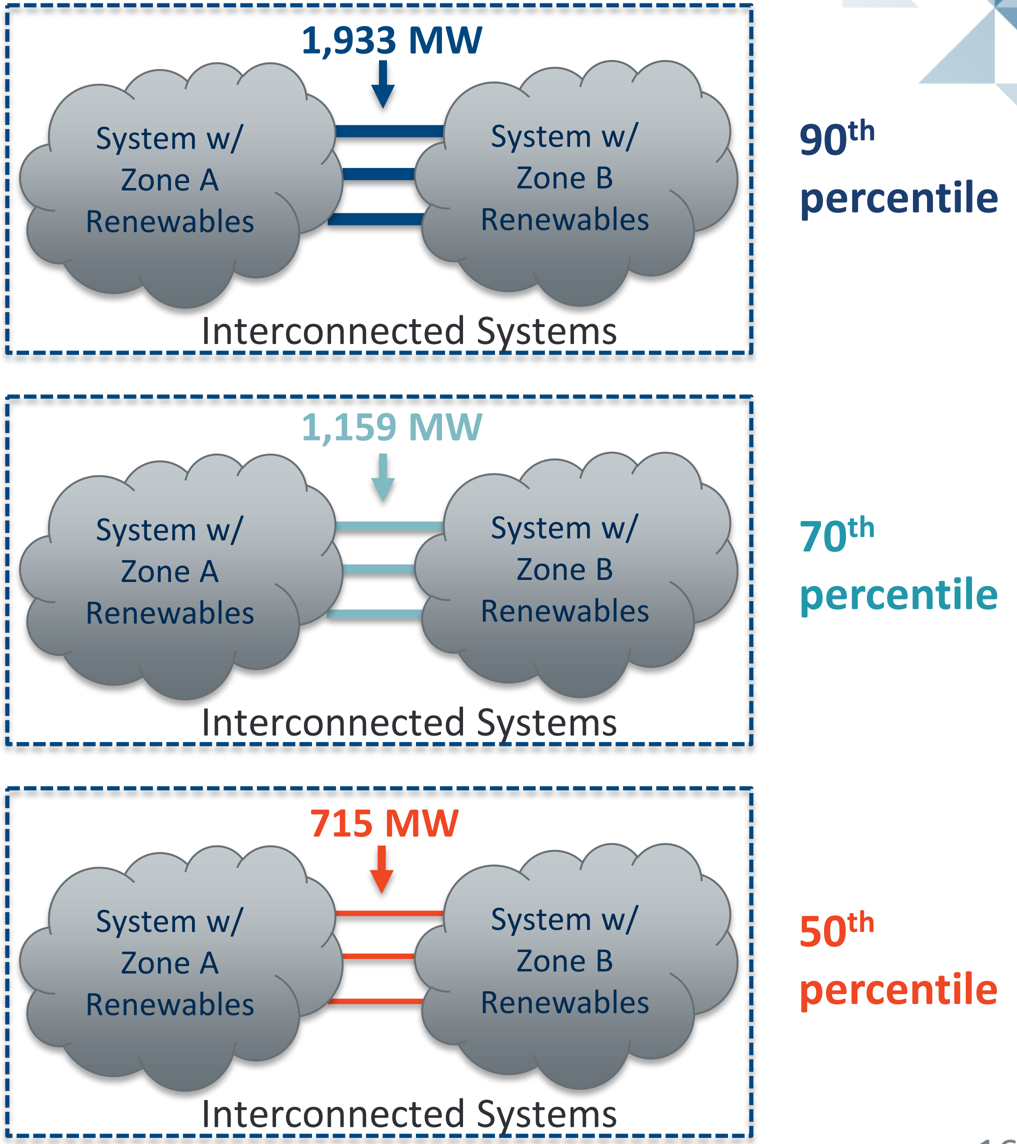
Key takeaways

- The emissions impacts of system interconnection are varied and depend on the thermal generation mix of the two systems
- At higher renewable penetrations, when the curtailment reductions of interconnection are substantial, interconnecting systems tends to more consistently reduce CO_2 emissions

Note: 2 x Systems of ~16 GW generation, ~14 GW peak load; no limit on flow between interconnected systems; results from RT cycle

How much transmission is needed to capture most benefits?

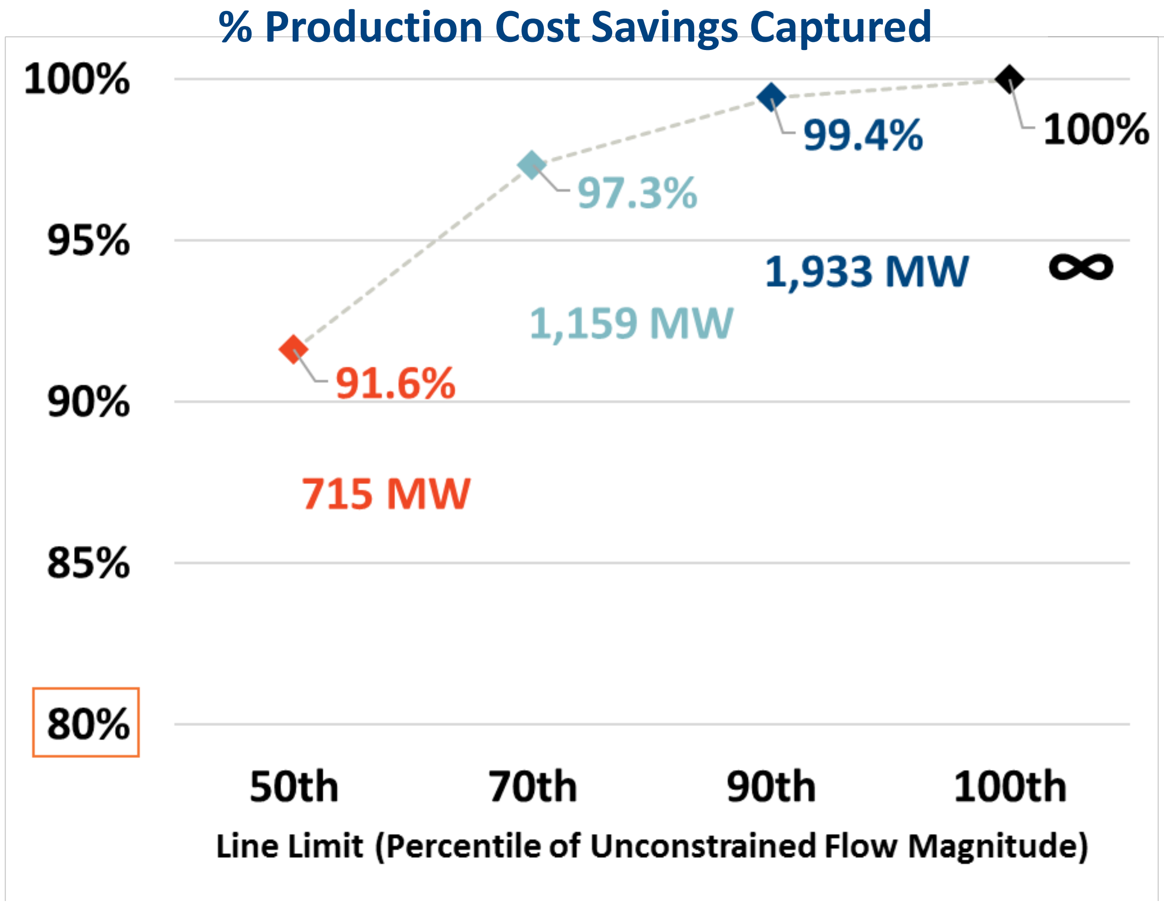


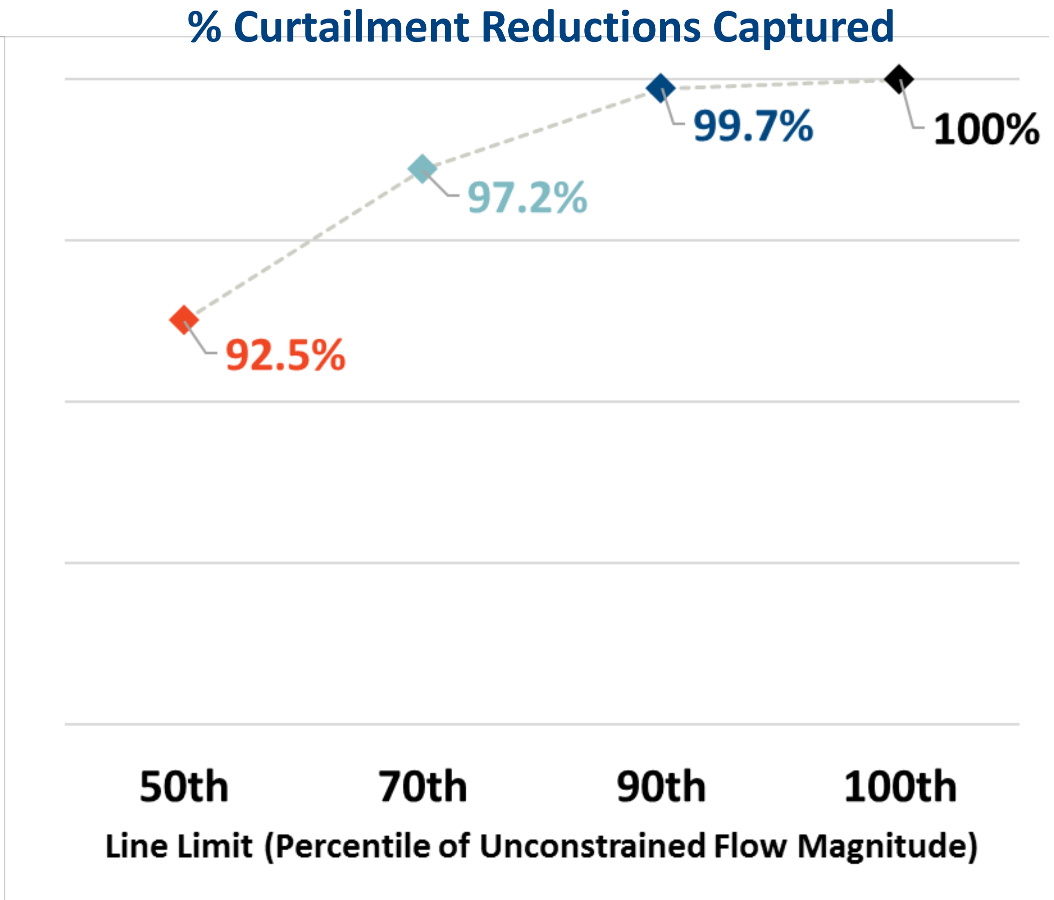


Limited the tie-line capacities based on measured flows in copper-sheet scenario

Most benefits captured with "70th percentile" transmission

In this 30% renewable generation case, interconnecting the 14,000 MW market areas with 1,200 MW of transmission captures 97% of the geographic diversity benefit. More transmission will be beneficial as renewable generation shares increase.





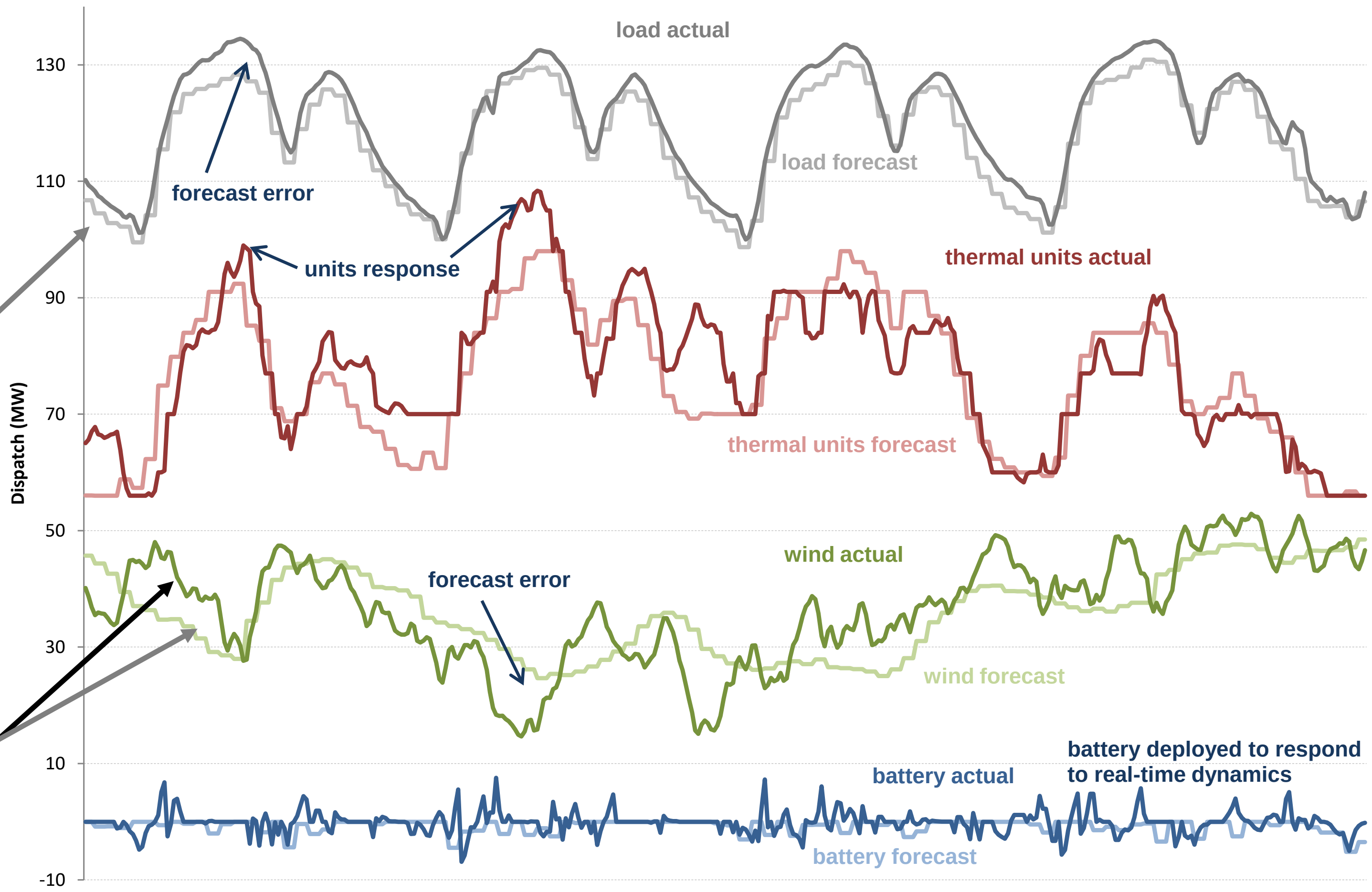
Forecast uncertainty is a major driver of dispatch and production costs

Our study starts with the conventional "Perfect Foresight" study approach by simulating multiple scheduling horizons with day-ahead load and renewable generation forecasts

A "Perfect Foresight" simulation typically focuses on just one view, often the day-ahead

We additionally simulate the need to respond to uncertainty in real-time with a more limited set of resources, considering both scheduling and actual operations

Illustrative 4-Day Operations Simulation Summary

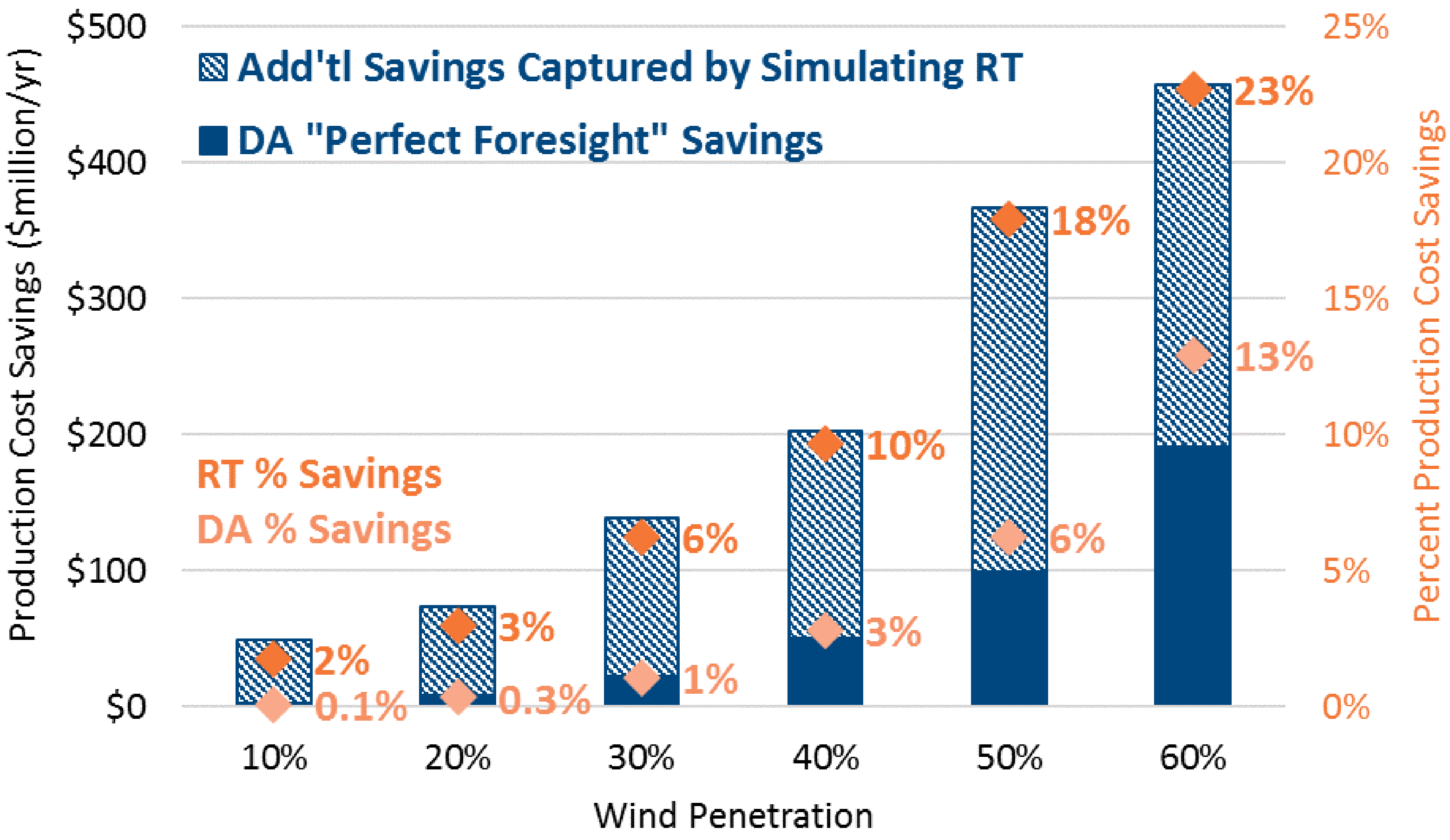


Dark lines are real-time "actual" outcomes

Light lines are day-ahead scheduling outcomes, based on forecasted conditions

Simulating forecast uncertainty captures substantially higher benefits

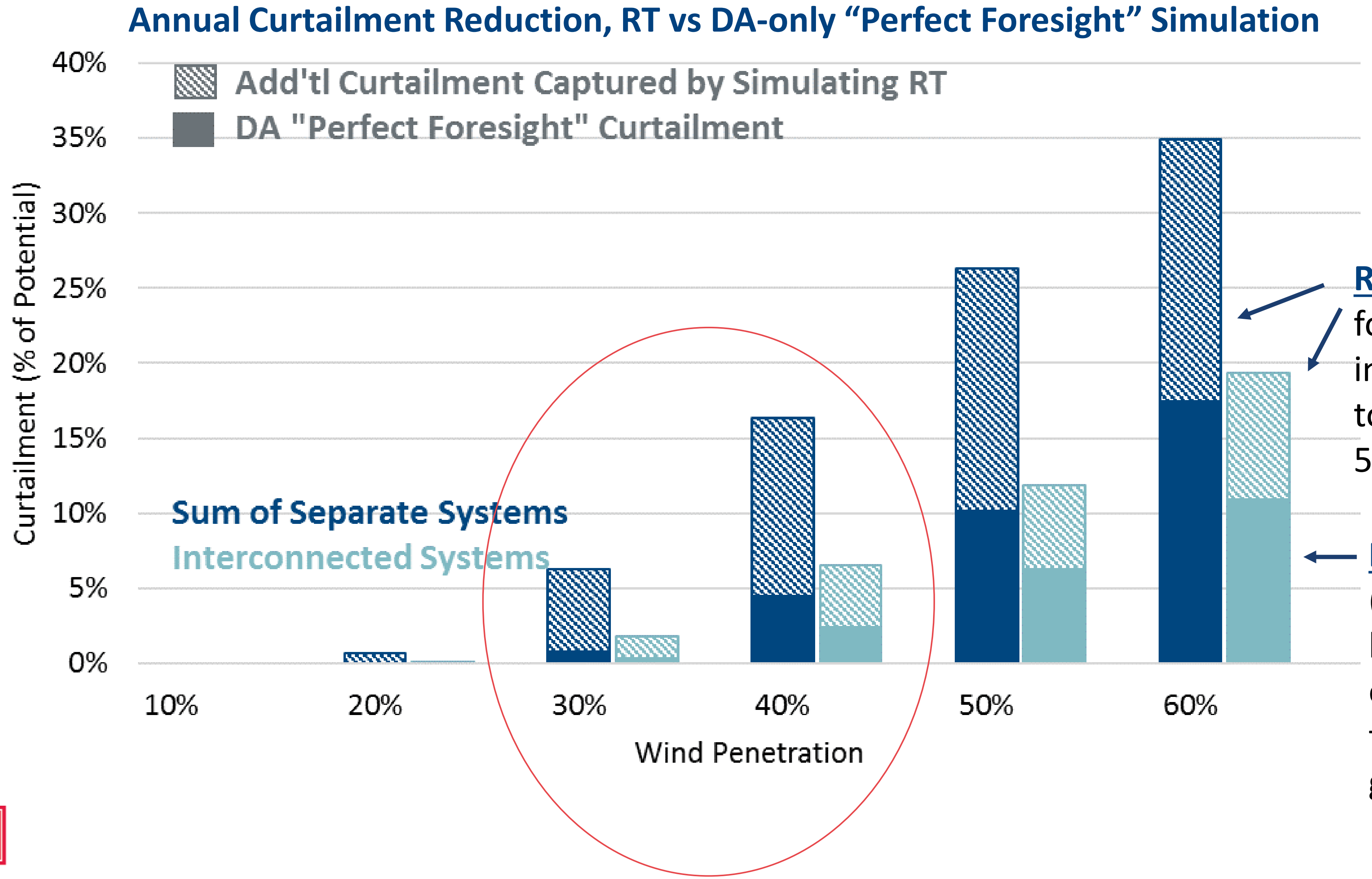
Annual Production Cost Savings, RT vs DA-only "Perfect Foresight" Simulation



Key takeaways

- Quantified transmission benefits can be significantly understated using the prevailing "Perfect Foresight" simulation approach:
  - **RT = 10x DA at 20% renewables**
  - **RT = 3x DA at 50% renewables**
- The higher benefit means optimal tradeoff shifts more from building local renewables to building more regional and interregional transmission to cost-effectively meet policy goals

RT curtailments are significantly higher than DA curtailments



Real Time curtailments (due to forecasting uncertainty and intra-hour variance) dominate total curtailments at less than 50% renewable generation

Day Ahead curtailments (assuming perfect foresight of hourly generation) reach half of total curtailments at more than 50% renewable generation

Content

Main Takeaways

Our analysis quantifies the significant uncertainty-diversification benefits of transmission between renewable generation areas

- Total diversification benefits considering day-ahead forecast uncertainties and intra-hour real-time market operations are up to 20 times larger than the diversity benefits captured with hourly simulations assuming perfect foresight of load and renewable generation

This real-time diversification benefit is in addition to other often-quantified transmission benefits:

- Traditional "Production Cost Savings" based on hourly, perfect-foresight simulations
- Reliability and Resource Adequacy Benefits
- Installed Generation Capacity Cost Savings
- Environmental and Public Policy Benefits (based on hourly, perfect-foresight simulations)
- Market Liquidity and Competitive Benefits
- Employment and Economic Stimulus Benefits
- Other Project-Specific Benefits

Underestimated transmission benefits → underinvestment in transmission → higher overall costs

At low levels of renewable generation, most diversification benefits can be captured through integrated real-time market operations (such as the Western EIM). As renewable generation grows, so do the benefits of regionally-integrated day-ahead operations.

Appendix A

TRANSMISSION BENEFIT-COST ANALYSES

Prior Reports on Transmission Planning and Benefit-Cost Analyses

Well-Planned Electric Transmission Saves Customer Costs:

Improved Transmission Planning is Key to the Transition to a Carbon-Constrained Future

Link: https://bit.ly/3dnKrxe

PREPARED FOR

WIRES

PREPARED BY

Judy W. Chang

Johannes P. Pfeifenberger

May 2016

THE Brattle GROUP

Toward More Effective Transmission Planning:

Addressing the Costs and Risks of an Insufficiently Flexible Electricity Grid

PREPARED FOR

WIRES

PREPARED BY

Johannes P. Pfeifenberger

Judy W. Chang

Akarsh Sheilendranath

April 2015

Link: https://bit.ly/2GU4h7w

The Brattle Group

Link: https://bit.ly/3jS0PsB

The Benefits of Electric Transmission: Identifying and Analyzing the Value of Investments

July 2013

Judy W. Chang

Johannes P. Pfeifenberger

J. Michael Hagerty

Regional Planners Are Getting Better at Identifying Broad Range of Transmission-related Benefits

SPP ITP Analysis

Quantified

1. production cost savings*
2. reduced transmission losses*
3. wind revenue impacts
4. natural gas market benefits
5. reliability benefits
6. economic stimulus benefits of transmission and wind generation construction

Not quantified

7. enabling future markets
8. storm hardening
9. improving operating practices/maintenance schedules
10. lowering reliability margins
11. improving dynamic performance and grid stability during extreme events
12. societal economic benefits

(SPP Priority Projects Phase II Final Report, April 27, 2010; SPP Metrics Task Force, *Benefits for the 2013 Regional Cost Allocation Review*, July, 5 2012.)

MISO MVP Analysis

Quantified

1. production cost savings *
2. reduced operating reserves
3. reduced planning reserves
4. reduced transmission losses*
5. reduced renewable generation investment costs
6. reduced future transmission investment costs

Not quantified

7. enhanced generation policy flexibility
8. increased system robustness
9. decreased natural gas price risk
10. decreased CO_2 emissions output
11. decreased wind generation volatility
12. increased local investment and job creation

(Proposed Multi Value Project Portfolio, Technical Study Task Force and Business Case Workshop August 22, 2011)

CAISO TEAM Analysis
(DPV2 example)

Quantified

1. production cost savings* and reduced energy prices from both a societal and customer perspective
2. mitigation of market power
3. insurance value for high-impact low-probability events
4. capacity benefits due to reduced generation investment costs
5. operational benefits (RMR)
6. reduced transmission losses*
7. emissions benefit

Not quantified

8. facilitation of the retirement of aging power plants
9. encouraging fuel diversity
10. improved reserve sharing
11. increased voltage support

(CPUC Decision 07-01-040, January 25, 2007, Opinion Granting a Certificate of Public Convenience and Necessity)

NYISO PPTN Analysis
(AC Upgrades)

Quantified

1. production cost savings* including savings not captured by normalized simulation
2. capacity resource cost savings
3. reduced refurbishment costs for aging transmission
4. reduced costs of achieving renewable and climate policy goals

Not quantified

5. protection against extreme market conditions
6. increased competition and liquidity
7. storm hardening and resilience
8. expandability benefits

(Newell, et al., Benefit-Cost Analysis of Proposed New York AC Transmission Upgrades, September 15, 2015)

* Fairly consistent across RTOs

2013 WIRES Study: Documenting Best Practices for Quantifying Transmission-related Benefits

Benefit Category	**Transmission Benefit** (see 2013 WIRES paper)
Traditional Production Cost Savings	Production cost savings as currently estimated in most planning processes
1. Additional Production Cost Savings	a. Impact of generation outages and A/S unit designations
	b. Reduced transmission energy losses
	c. Reduced congestion due to transmission outages
	d. Mitigation of extreme events and system contingencies
	e. Mitigation of weather and load uncertainty
	f. Reduced cost due to imperfect foresight of real-time system conditions
	g. Reduced cost of cycling power plants
	h. Reduced amounts and costs of operating reserves and other ancillary services
	i. Mitigation of reliability-must-run (RMR) conditions
	j. More realistic "Day 1" market representation
2. Reliability and Resource Adequacy Benefits	a. Avoided/deferred reliability projects
	b. Reduced loss of load probability <u>or</u> c. reduced planning reserve margin
3. Generation Capacity Cost Savings	a. Capacity cost benefits from reduced peak energy losses
	b. Deferred generation capacity investments
	d. Access to lower-cost generation resources
4. Market Benefits	a. Increased competition
	b. Increased market liquidity
5. Environmental Benefits	a. Reduced emissions of air pollutants
	b. Improved utilization of transmission corridors
6. Public Policy Benefits	Reduced cost of meeting public policy goals
7. Employment and Economic Stimulus Benefits	Increased employment and economic activity; Increased tax revenues
8. Other Project-Specific Benefits	Examples: storm hardening, fuel diversity, flexibility, reducing the cost of future transmission needs, wheeling revenues, HVDC operational benefits

Additional Reading

Pfeifenberger, Newell, Graf and Spokas, "Offshore Wind Transmission: An Analysis of Options for New York", prepared for Anbaric, August 2020.

Pfeifenberger, Newell, and Graf, "Offshore Transmission in New England: The Benefits of a Better-Planned Grid," prepared for Anbaric, May 2020.

Tsuchida and Ruiz, "Innovation in Transmission Operation with Advanced Technologies," T&D World, December 19, 2019.

Pfeifenberger, "Cost Savings Offered by Competition in Electric Transmission," Power Markets Today Webinar, December 11, 2019.

Pfeifenberger, "Improving Transmission Planning: Benefits, Risks, and Cost Allocation," MGA Ninth Annual Transmission Summit, November 6, 2019.

Chang, Pfeifenberger, Sheilendranath, Hagerty, Levin, and Jiang, "*Cost Savings Offered by Competition in Electric Transmission: Experience to Date and the Potential for Additional Customer Value*," April 2019.

Chang, Pfeifenberger, Hagerty, and Cohen, "Response to Concentric Energy Advisors' Report on Competitive Transmission," August 2019.

Ruiz, "Transmission Topology Optimization: Application in Operations, Markets, and Planning Decision Making," May 2019.

Chang and Pfeifenberger, "Well-Planned Electric Transmission Saves Customer Costs: Improved Transmission Planning is Key to the Transition to a Carbon-Constrained Future," WIRES and The Brattle Group, June 2016.

Newell et al. "Benefit-Cost Analysis of Proposed New York AC Transmission Upgrades," on behalf of NYISO and DPS Staff, September 15, 2015.

Pfeifenberger, Chang, and Sheilendranath, "Toward More Effective Transmission Planning: Addressing the Costs and Risks of an Insufficiently Flexible Electricity Grid," WIRES and The Brattle Group, April 2015.

Chang, Pfeifenberger, and Hagerty, "The Benefits of Electric Transmission: Identifying and Analyzing the Value of Investments," on behalf of WIRES, July 2013.

Chang, Pfeifenberger, Newell, Tsuchida, Hagerty, "Recommendations for Enhancing ERCOT's Long-Term Transmission Planning Process," October 2013.

Pfeifenberger and Hou, "Seams Cost Allocation: A Flexible Framework to Support Interregional Transmission Planning," on behalf of SPP, April 2012.

Pfeifenberger, Hou, "Employment and Economic Benefits of Transmission Infrastructure Investment in the U.S. and Canada," on behalf of WIRES, May 2011.

Appendix B

THE PSO SIMULATION MODEL

PSO Functionality

The analysis was undertaken with the **Power System Optimizer ("PSO")** developed by Polaris Systems Optimization and **Enelytix** to support the nodal simulation of multi-level nested time intervals that simultaneously optimize energy and ancillary services dispatch, considering forecast uncertainties.

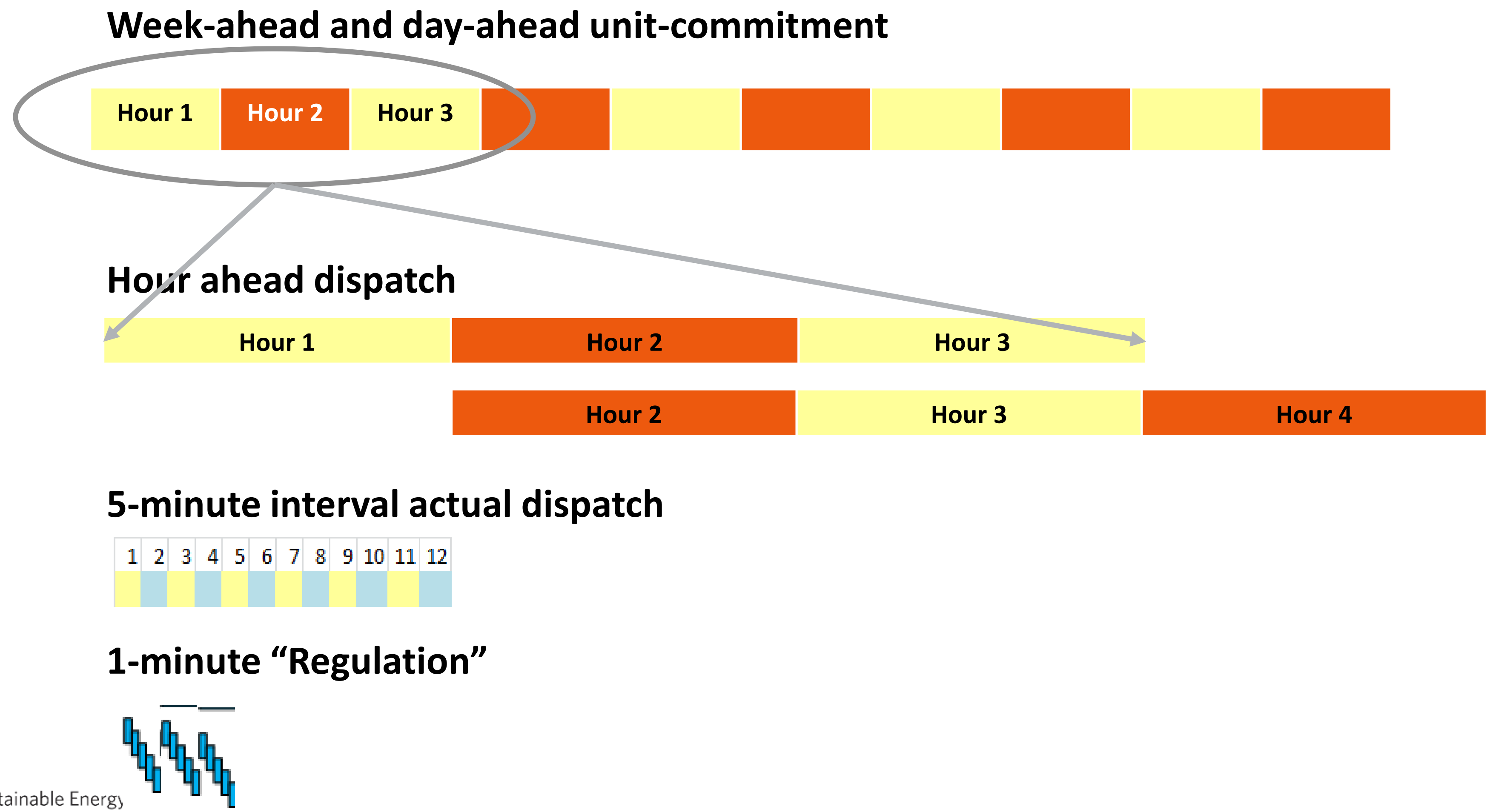
The model can:

- Simulate either full nodal or zonal power systems
- Model generation commitment and dispatch decision at different time intervals (e.g., day-ahead, intra-day, hour-ahead, intra-hour, real-time) and the impact of generation and load uncertainties on decision making
- Flexibly model new types of resources (generation, load, transmission, storage, services, …) without predetermined parameters – allows users to define the operational characteristics of each resource
- Co-optimize across regions all energy and individual types of ancillary service markets
- Support state-of-the-art modeling approaches (transmission switching, stochastic methods, contractual scheduling limits, block trading, multi-product models, …)

For more details, see: http://www.enelytix.com/

PSO Decision Cycles – Example

PSO evaluates maintenance, commitment, and dispatch decisions on timescales that match real-world decision-making processes and updated information flows (year-ahead to minutes)



Traditional Production Simulation Tools vs. PSO

TRADITIONAL PRODUCTION SIMULATION MODELS

Strengths

- Decision support tools for developing trading strategies and operating plans
- Detailed modeling of operational characteristics of thermal units with transmission system constraints
- Pre-packaged

Weaknesses

- Unable to model **different decision timeframes**
    - Real time (e.g., 5-minutes ahead)
    - Hour-ahead
    - Day-ahead
- **Deterministic** decision methodologies do not optimize accounting for forecast uncertainty.
    - Uncertainty captured only in additional simulation mode (Monte Carlo approaches)
- Decisions **not strongly linked between different timeframes** lead to operational and trading issues (e.g., real time issues due to lack of appropriate modeling in intermediate time decisions)
- **Preset interval length** modeling

POWER SYSTEMS OPTIMIZER (PSO)

Strengths

- Has all capabilities of traditional simulation models
- Supports decisions at various overlapping timeframes (year, month, week, day, hours, minutes)
- Flexible intra-hour modeling, can set user-defined time intervals and decisions
- Can simulate user-defined individual ancillary services and products
- Can simulate forecast uncertainties for load and generation
    - Can use user-specified probabilistic parameters to generate forecast and realization time series
    - Can also directly use historical time series
- Can simulate uncertainties (costs, outages, etc.) and obtain results in probabilistic distributions of the variables of interest using a Monte Carlo approach
- Can perform stochastic optimization of commitment and dispatch
- Can simulate energy storage directly based on efficiency parameters
- Can view all dispatch decisions graphically