HELPING OUR MEMBERS WORK TOGETHER TO KEEP THE LIGHTS ON... TODAY AND IN THE FUTURE.
INTERCONNECTIONS SEAM STUDY

IEEE West Michigan Chapter

Grand Rapids, Michigan

April 11, 2019

Jay Caspary, Director – Research, Development & Tariff Services
Our Mission
Helping our members work together to keep the lights on ... today and in the future.
OUR BEGINNING

- In 1941, 11 member utilities pooled electricity to power aluminum plant at Jones Mill needed for critical defense
- Maintained after WWII to continue benefits of regional coordination
THE SPP DIFFERENCE

• Relationship-based
• Member-driven
• Independence Through Diversity
• Evolutionary vs. Revolutionary
• Reliability and Economics Inseparable
THE VALUE OF SPP

• Transmission planning, market administration, reliability coordination, and other services provide net benefits to SPP’s members in excess of more than $1.7 billion annually at a benefit-to-cost ratio of 11-to-1.

• A typical residential customer using 1,000 kWh saves $6.02/month because of the services SPP provides.
SPP AT A GLANCE

- Located in Little Rock
- Approx. 600 employees
- Jobs in IT, electrical engineering, operations, settlements and more
- 24x7 operation
- Full redundancy and backup site
NORTH AMERICAN INDEPENDENT SYSTEM OPERATORS (ISO) AND REGIONAL TRANSMISSION ORGANIZATIONS (RTO)
SPP’S 95 MEMBERS: INDEPENDENCE THROUGH DIVERSITY

- Cooperatives (20)
- Investor-Owned Utilities (16)
- Independent Power Producers/Wholesale Generation (14)
- Power Marketers (12)
- Municipal Systems (14)
- Independent Transmission Companies (10)
- State Agencies (8)
- Federal Agencies (1)

As of April 12, 2017
SPP MANAGES THE GRID IN 5 OF THE TOP 100 CITIES IN AMERICA:
Kansas City, Oklahoma City, Tulsa, Omaha, and Wichita
MEMBERS IN 14 STATES

- Arkansas
- Kansas
- Iowa
- Louisiana
- Minnesota
- Missouri
- Montana
- Nebraska
- New Mexico
- North Dakota
- Oklahoma
- South Dakota
- Texas
- Wyoming
OPERATING REGION

- Service territory: 546,000 square miles
- Population served: 17.5 million
- Generating plants: 818*
- Substations: 5,054*

* In SPP's reliability coordination footprint
<table>
<thead>
<tr>
<th>Voltage (kV)</th>
<th>Miles of Transmission</th>
</tr>
</thead>
<tbody>
<tr>
<td>69</td>
<td>17,340</td>
</tr>
<tr>
<td>115</td>
<td>15,846</td>
</tr>
<tr>
<td>138</td>
<td>9,367</td>
</tr>
<tr>
<td>161</td>
<td>5,567</td>
</tr>
<tr>
<td>230</td>
<td>7,534</td>
</tr>
<tr>
<td>345</td>
<td>11,146</td>
</tr>
<tr>
<td>500</td>
<td>92</td>
</tr>
</tbody>
</table>

**Miles of transmission:** 66,892
2018 ENERGY PRODUCTION
BY FUEL TYPE (275,887 GWH TOTAL)

- Coal (42.4%)
- Wind (23.5%)
- Gas (23.4%)
- Nuclear (5.4%)
- Hydro (4.8%)
- Fuel Oil (0.2%)
- Solar (0.2%)
- Other (0.1%)
GENERATING CAPACITY* BY FUEL TYPE
(89,999 MW TOTAL)

* Figures refer to nameplate capacity as of 1/1/19
ENERGY CAPACITY
BY FUEL MIX OVER TIME
GENERATOR INTERCONNECTION REQUESTS UNDER STUDY (BY FUEL TYPE): 84,099 MW TOTAL

As of February 5, 2019
RELIABILITY COORDINATION: AIR TRAFFIC CONTROLLERS OF THE BULK POWER GRID

- Monitor grid 24 x 365
- Anticipate problems
- Take preemptive action
- Coordinate regional response
- Independent
- Comply with more than 5,500 pages of reliability standards and criteria
CONGESTION PREVENTS ACCESS TO GENERATION

Load pockets see higher prices (pay for more expensive, local generation)

Low prices in areas with high amount of cheap generation (wind), constrained by transmission outlets
WHY WE NEED MORE TRANSMISSION?

• In the past, built least-cost transmission to meet local needs
• Today, proactively building “highways” to benefit region
$7.7B in completed projects and $1.9B in scheduled projects, driven by Regional State Committee and Highway/Byway Cost Allocation
SPP’S 2015 VALUE OF TRANSMISSION STUDY

Study Scope:

• Assessed 348 projects from 2012-14, representing $3.4B of transmission investment

• Based on the first year of operation of Integrated Marketplace from March 2014 through February 2015

• APC Savings calculated at more than $660k/day, or $240M/year.

• Overall NPV of all benefits for considered projects are expected to exceed $16.6B over 40 years.

BENEFIT-COST RATIO OF 3.5 TO 1
Projects Constructed or with NTCs
(2005 - 2018)

Southwest Power Pool

- 115 kV
- 138 kV
- 161 kV
- 230 kV
- 345 kV

This map contains the intellectual property of SPP and may not be used, copied, or disseminated by third parties without the express permission of SPP. All rights reserved. Date Exported 10/19/2018 1 inch equals 189 miles.
345 KV+ TRANSMISSION GROWTH AT A GLANCE
345 KV+ TRANSMISSION GROWTH AT A GLANCE
345 KV+ TRANSMISSION GROWTH AT A GLANCE
345 kV+ Transmission Growth at a Glance
345 kV+ Transmission Growth at a Glance
OPPORTUNITIES TO RIGHT SIZE SELECT AGING 230KV?
WIND, SOLAR & ENERGY STORAGE

• **Wind**
  - Installed: **21,578 MW** 4/1/2019
  - Wind Turbines: **11,000** 4/1/2019
  - Wind Peak: **16,382 MW** 12/20/2018
  - GI Queue: **61 GW** 4/6/2019
  - Wind Penetration % of Load: **63.96%** 4/30/2018

• **Solar**
  - SPP Market: **215 MW** 4/1/2019
  - GI Queue: **25 GW** 4/6/2019

• **Energy Storage**
  - Installed: **10MW/20MWh** 4/1/2019
  - GI Queue: **4,373 MW** 4/6/2019

• **Total Renewable Energy Penetration**
  - **69.44%** 4/29/2018
ANNUAL AVERAGE WIND SPEEDS

WIND ENERGY IN SPP

- Maximum Wind Penetration:
  - Instantaneous: 64% (4/30/18)
  - Despite Over 1GW Curtailments
  - Hourly Average: 63% (4/29/18)
  - Daily Average: 54% (4/29/18)
  - 2018
    - >60%, 10 days
    - >50%, 70 days
  - Max wind swing in a day: >10 GW
    (12.5 GW → 2 GW → 12 GW)
  - Max 1-hour Wind Ramp: 3,700 MW
Installed Wind is higher than Min Load!
SPP’s Generator Interconnection Queue

GI Requests Since 2013 (MW)

Current Status of GI Queue

- Wind 60,895 MW
- Solar 24,914 MW
- Storage 4,373 MW
- Other 397 MW

Other
Wind
Solar
Storage
PV Solar Radiation
(Flat Plate, Facing South, Latitude Tilt)

Model estimates of monthly average daily total radiation using inputs derived from satellite and/or surface observations of cloud cover, aerosol optical depth, precipitable water vapor, albedo, atmospheric pressure and ozone resampled to a 40km resolution. See http://www.nrel.gov/gis/1_solar_pvw.html documentation for more details.

Produced by the Electric & Hydrogen Technologies & Systems Center - May 2004
SOLAR IN SPP

- Solar installed today: 215 MW
- Solar in all stages of study and development: 24.9 GW
- Many solar projects are being co-located with battery projects
Former Mountain West Participants
NREL-LED, DOE-FUNDED INTERCONNECTIONS SEAM STUDY
NREL Interconnections Seam Study

Aaron Bloom and Joshua Novacheck
UVG Spring Workshop, Tucson, AZ
March 2018
The Interconnections Seam Study
Eastern Interconnection Seams

- U.S. Interconnections are tied together with HVDC Back-to-Back Ties
- All EI ties in U.S are on the SPP Seam
1,320 MW transfer capability between U.S. EI and WI
Partners are Everything
More Data, Better Resolution

• 1,000 times more wind and solar data, from GBs to TBs
• Transmission models have moved from 10s of nodes to nearly 100,000
• Every generator in North America, and many more around the world
• It’s not just the data, it’s the tools to use the data: ReV (above)
Integrated Power System Models and Data
New algorithms enable more accurate models that solve in days not weeks.
Modeling Approach

Current Models
- LCGS (NREL WECC)
- ERGIS (NREL EI)

Updated Data
- SEAMs West 2024
- SEAMs East 2024

Manual Updates

PCM Updates (NREL & PNNL)
B2B Data (ORNL & NREL)

Seams/HVDC Costs (ORNL)

Scenarios
- Design 1: No upgrades
- Design 2A: Reconfigure Seam
- Design 2B: Reconfigure Seam
- Design 3: Macro Grid Overlay

PCM
- Design 1: No upgrades
- Design 2A: Reconfigure Seam
- Design 2B: Reconfigure Seam
- Design 3: Macro Grid Overlay

AC Power Flow

Initial conditions for capacity expansion & test model for PCM
## Conceptual Scenarios

<table>
<thead>
<tr>
<th>Scenario Name</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Design 1</strong></td>
<td>Existing B2B facilities are replaced at their current (2018) capacity level and new AC transmission and generation are co-optimized to minimize system wide costs.</td>
</tr>
<tr>
<td><strong>Design 2a</strong></td>
<td>Existing B2B facilities are replaced at a capacity rating that is co-optimized along with other investments in AC transmission and generation.</td>
</tr>
<tr>
<td><strong>Design 2b</strong></td>
<td>Three HVDC transmission segments are built between the Eastern and Western Interconnections and existing B2B facilities are co-optimized with other investments in AC transmission and generation.</td>
</tr>
<tr>
<td><strong>Design 3</strong></td>
<td>A national scale HVDC transmission network, Macro Grid, is built and other investments in AC transmission and generation.</td>
</tr>
</tbody>
</table>
The four conceptual transmission designs were studied under two different system conditions: Base Case and High Variable Generation.
TRC Driven Assumptions

- North American Eastern and Western Interconnections
- Retire generation based on economic performance
- Run for 15 years, with 7 investment periods
- Fuel cost forecasts according to AEO 2017 (med-gas)
- Gen investment base costs & maturation rates from NREL ATB 2016
- Transmission base costs according to EIPC/B&V
- Gen & trans regional cost multipliers from EIPC/WECC
- Use of 169 bus model (68 EI, 101 WI)
- 4 regions: West, Northwest, Midwest, East
- Wind uses 100-m tower CFs ~ 0.45-0.50
- Gen capacity investment limited to 40GW/yr
- Demand growth per NEEM & WI (E3) per state
- DG growth per AEO 2016, 3% per yr
- New nuclear, offshore wind, geothermal, concentrating solar power, and carbon capture technologies were not studied
Production Cost Models

• Simulate the unit commitment and economic dispatch of a power system
• Approximate the daily operations of an IOU or RTO/ISO (Day ahead and Real Time)
• Used to simulate an entire year of hourly operations
• Calculates the cost of producing electricity
• Linearized DC Power flow
Design 1
Base Case
Design 2a
Base Case
Design 2b
Base Case
Design 3
Base Case
Design 1
High VG Case
Design 2a
High VG Case
Design 2b
High VG Case
Design 3
High VG Case
## Installed Capacity (GW)

<table>
<thead>
<tr>
<th></th>
<th>2024</th>
<th>2024 Base Case</th>
<th>2024 High VG Case</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>D1</td>
<td>D2a</td>
</tr>
<tr>
<td>Coal</td>
<td>266</td>
<td>120</td>
<td>113</td>
</tr>
<tr>
<td>Hydro</td>
<td>198</td>
<td>198</td>
<td>198</td>
</tr>
<tr>
<td>Natural Gas</td>
<td>443</td>
<td>437</td>
<td>431</td>
</tr>
<tr>
<td>Nuclear</td>
<td>132</td>
<td>132</td>
<td>132</td>
</tr>
<tr>
<td>Solar</td>
<td>64</td>
<td>281</td>
<td>277</td>
</tr>
<tr>
<td>Wind</td>
<td>94</td>
<td>320</td>
<td>324</td>
</tr>
</tbody>
</table>
## Transmission Capacity Additions (GW)

<table>
<thead>
<tr>
<th></th>
<th>Base Case</th>
<th>High VG Case</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>D1</td>
<td>D2a</td>
</tr>
<tr>
<td>AC Transmission</td>
<td>92</td>
<td>95</td>
</tr>
<tr>
<td>HVDC Transmission</td>
<td>0</td>
<td>7</td>
</tr>
</tbody>
</table>
Expansion Overview

- All cases imagine a future where it is feasible to build multi-region transmission
- Design 1 is the only case without new HVDC and without new transmission across the Seam
- The generation mix changes substantially in all cases
- Results are known to be imperfect, yet informative
- Substantial AC transmission is added in all cases
- All cases meet the same Resource Adequacy target (15% planning reserve margin). Details here: https://lib.dr.iastate.edu/etd/16128/
Annual Generation

- Base Case
- High VG Case
Regional Generation Base Case
2038 Peak Week High VG
### Total Costs 2024-2038 (NPV $B)

<table>
<thead>
<tr>
<th>ECONOMICS, NPV $B</th>
<th>Base Case</th>
<th></th>
<th>High VG Case</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>D1</td>
<td>D2a</td>
<td>Delta</td>
<td>D2b</td>
</tr>
<tr>
<td>Line Investment Cost</td>
<td>23.5</td>
<td>26.69</td>
<td>3.19</td>
<td>31.5</td>
</tr>
<tr>
<td>Generation Investment Cost</td>
<td>493.6</td>
<td>494.7</td>
<td>1.1</td>
<td>492.5</td>
</tr>
<tr>
<td>Fuel Cost</td>
<td>855.1</td>
<td>852.7</td>
<td>-2.4</td>
<td>851.2</td>
</tr>
<tr>
<td>Fixed O&amp;M Cost</td>
<td>416.4</td>
<td>415.6</td>
<td>-0.8</td>
<td>413.7</td>
</tr>
<tr>
<td>Variable O&amp;M Cost</td>
<td>81</td>
<td>81.1</td>
<td>0.1</td>
<td>81.2</td>
</tr>
<tr>
<td>Carbon Cost</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Regulation-Up Cost</td>
<td>31.6</td>
<td>30.97</td>
<td>-0.63</td>
<td>31.13</td>
</tr>
<tr>
<td>Regulation-Down Cost</td>
<td>45.1</td>
<td>44.2</td>
<td>-0.9</td>
<td>44.42</td>
</tr>
<tr>
<td>Contingency Cost</td>
<td>23.9</td>
<td>23.42</td>
<td>-0.48</td>
<td>23.54</td>
</tr>
<tr>
<td>Total Non-transmission Cost (Orange)</td>
<td>1,947.00</td>
<td>1,943.00</td>
<td>-4.01</td>
<td>1,937.70</td>
</tr>
<tr>
<td>15-yr B/C Ratio (Orange/Green)</td>
<td>1.26</td>
<td>1.13</td>
<td>1.15</td>
<td>2.48</td>
</tr>
</tbody>
</table>

**Example, D1 vs D2a Current Policy: 4.01/3.19 = 1.26**

$$BCR = \frac{\text{Change in Total non-Transmission Costs}}{\text{Change in Transmission Investment Costs}}$$
## 2038 Production Costs

|                  | Base Case |              |              |              | High VG Case | D1 | ΔD2a | ΔD2b | ΔD3  |
|------------------|-----------|--------------|--------------|--------------|--------------|----------------|-------|-------|-------|-------|
| **Design**       | D1        | ΔD2a         | ΔD2b         | ΔD3          |              | D1    | ΔD2a | ΔD2b | ΔD3  |
| **Emissions**    | 0         | 0            | 0            | 0            | 24.3         | -1.5  | -1.6  | -1.1  |
| **Fuel**         | 98.3      | -0.4         | -0.9         | -3.2         | 83.0         | -2.3  | -2    | -0.1  |
| **Start & Shutdown** | 2.8      | -0.1         | -0.1         | -0.3         | 3.1          | -0.4  | -0.6  | -0.5  |
| **VO&M**         | 6.5       | -0.1         | -0.1         | -0.1         | 4.9          | -0.1  | -0.1  | -0.1  |
| **Total**        | 107.6     | -0.6         | -1.2         | -3.6         | 115.2        | -4.2  | -4.1  | -1.8  |
Benefits

• All designs produce benefits that exceed costs.

• Results should be viewed directionally, not definitively.

• Comparisons are made to D1, which includes significant AC expansion, but no cross seam expansion.

• Full asset life is assumed to be 35 years, over the long run, the benefit may be significantly higher.

• Not appropriate to assume 2038 savings will stay the same until retirement, they may increase or decrease depending on the rest of the system.

<table>
<thead>
<tr>
<th>Benefit-to-Cost Ratio 2024-2038</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base Case</td>
</tr>
<tr>
<td>D1</td>
</tr>
<tr>
<td>D2a</td>
</tr>
<tr>
<td>D2b</td>
</tr>
<tr>
<td>D3</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Production Cost Savings 2038 ($B)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base Case</td>
</tr>
<tr>
<td>D1</td>
</tr>
<tr>
<td>D2a</td>
</tr>
<tr>
<td>D2b</td>
</tr>
<tr>
<td>D3</td>
</tr>
</tbody>
</table>
Areas for Improvement

- Refine multi-model integration to remove modeling seams, e.g. capacity and network translation, and retirements.

- Study more designs: no new transmission, synchronize systems, all of North America

- Analyze multiple weather years of simulation to inform resilience to weather.

- Conduct comprehensive stability and contingency analysis
Observations

► Further analyses are warranted since status quo appears to be least desirable scenario among HVDC alternative futures
► Significant AC expansion is needed 2024-2038 absent any changes to EI-WECC Seams facilities.
► EHV/UHV voltages for backbone AC facilities need further analysis and consideration given preliminary results. Study results do not capture big economies of scale for 765kV, let alone double circuit 345kV, vs single circuit 345kV assumed in SPP and MISO.
► Transmission expansion costs are understated since they are based on equivalized EHV models and don’t consider substations as well as integration to underlying existing AC systems. Significant system reconfiguration would be required for any of these futures.
► HVDC designs are not optimized given preselected nodes
► Harmonized models and datasets are an important and valuable step in shaping future dialogue and assessments
Next Steps

► Need to investigate relocated B2B ties and HVDC terminals, as well as potential AC and Hybrid Seam scenarios

► Update models to reflect expected / potential utility and merchant projects: Grain Belt Express, Power From The Prairie Project which includes Soo Green HVDC, significant EHV AC projects, etc.

► Update models to reflect expected resource retirements, 100% renewable/clean energy mandates and electrification futures

► Need to scope supplemental analyses to inform regional planning and shape dialogue about next steps:
  □ DOE’s North American Resiliency Model initiative
  □ Shared vision to provide a roadmap to address aging infrastructure
THE FUTURE OF SPP HVDC TIES
## SPP HVDC Lifetime Expectancy

<table>
<thead>
<tr>
<th>Tie</th>
<th>State</th>
<th>Age</th>
<th>Rated MW</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stegall</td>
<td>NE</td>
<td>41</td>
<td>100</td>
</tr>
<tr>
<td>Eddy County</td>
<td>NM</td>
<td>38</td>
<td>200</td>
</tr>
<tr>
<td>Oklaunion</td>
<td>TX</td>
<td>4¹</td>
<td>200</td>
</tr>
<tr>
<td>Blackwater</td>
<td>NM</td>
<td>36²</td>
<td>200</td>
</tr>
<tr>
<td>Miles City</td>
<td>MT</td>
<td>36</td>
<td>200</td>
</tr>
<tr>
<td>Sidney</td>
<td>NE</td>
<td>30</td>
<td>200</td>
</tr>
<tr>
<td>Welsh</td>
<td>TX</td>
<td>23³</td>
<td>600</td>
</tr>
<tr>
<td>Rapid City</td>
<td>SD</td>
<td>15</td>
<td>200</td>
</tr>
<tr>
<td>Lamar</td>
<td>CO</td>
<td>13</td>
<td>210</td>
</tr>
</tbody>
</table>

1 New LCC converter station built in 2014
2 LCC refurbishment in 2009
3 LCC refurbishment 2017

### Table 1. Major components and their typical lifetimes.

<table>
<thead>
<tr>
<th>Component</th>
<th>Expected Lifetime (Years)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Converter and SVC transformers</td>
<td>40</td>
</tr>
<tr>
<td>Thyristor valves</td>
<td>30</td>
</tr>
<tr>
<td>HVdc controls and protection (analog)</td>
<td>25</td>
</tr>
<tr>
<td>HVdc controls and protection (digital)</td>
<td>15</td>
</tr>
<tr>
<td>Valve hall cooling</td>
<td>20</td>
</tr>
<tr>
<td>Thyristor valve cooling systems (wet surface cooling tower)</td>
<td>15</td>
</tr>
<tr>
<td>Thyristor valve cooling systems (dry surface cooling tower)</td>
<td>20</td>
</tr>
<tr>
<td>dc smoothing reactors (air core)</td>
<td>25</td>
</tr>
<tr>
<td>dc smoothing reactors (oil filled)</td>
<td>35</td>
</tr>
<tr>
<td>dc filters</td>
<td>20</td>
</tr>
<tr>
<td>Ground electrode</td>
<td>40</td>
</tr>
</tbody>
</table>
Questions Needing To Be Addressed

- Significant changes have occurred within the EI and WI interconnected systems over the past four decades
  - Major stations and EHV outlet installed
  - Equipment life expectancy approaching
  - EHV transmission projects in process and UHV projects near seam getting approved

- Refurbish?
- Replace?
- Relocate?
- Bypass?
- Increase Capacity?
- New HVDC Lines?

Much more analysis required to determine the correct answer!
“...it is clear we need an in-depth understanding of the resilience of our electricity and related infrastructure in order to know how best to either modify existing market structures or build new resiliency standards into the system.

To that end, I propose that DOE undertake a detailed analysis that: 1) integrates into a single North American energy infrastructure model of the ongoing resilience planning efforts at the local, state, and regional level, including interconnections that reach into Canada and Mexico...

I believe building this resilience model should be the top priority for DOE’s Office of Electricity Delivery and Energy Reliability over the coming years.”

Bruce J. Walker
Assistant Secretary
Office of Electricity Delivery and Energy Reliability
U.S. Department of Energy
January 23, 2018
MILESTONES

1968  Became NERC Regional Council
1980  Implemented telecommunications network
1991  Implemented operating reserve sharing
1994  Incorporated as nonprofit
1997  Implemented reliability coordination
MILESTONES

1998  Implemented tariff administration
2004  Became FERC-approved Regional Transmission Organization
2007  Launched EIS market
2009  Integrated Nebraska utilities
2010  FERC approved Highway/Byway cost allocation methodology and Integrated Transmission Planning Process
MILESTONES

2012  Moved to new Corporate Center
2014  Launched Integrated Marketplace
       Became regional Balancing Authority
2015  Integrated System joins SPP
ISO/RTO GROWTH BEFORE 1996

1996: ERCOT

1998: CAISO

ISO/RTO GROWTH BY 1996

ISO/RTO GROWTH BY 1998

ISO/RTO GROWTH BY 2000

ISO/RTO GROWTH BY 2002

ISO/RTO GROWTH BY 2004

ISO/RTO GROWTH BY 2006

ISO/RTO GROWTH BY 2008

ISO/RTO GROWTH BY 2010

ISO/RTO GROWTH BY 2012

ISO/RTO GROWTH BY 2014

ISO/RTO GROWTH TODAY