# <u>High-voltage direct current (HVDC) transmission</u>:

*Part 1: Interregional HVDC designs to accommodate high US wind and solar;*

- James McCalley

*Part 2: Aluminum/calcium deformation metal-metal composites for lighter, stronger, and more conductive HVDC lines;*

- Charles Czahor

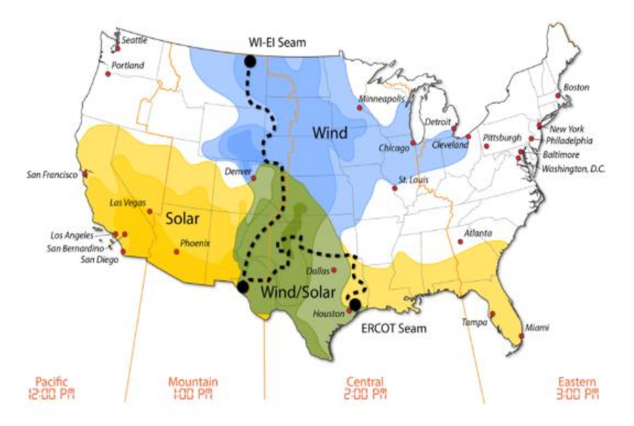
GRID MODERNIZATION LABORATORY CONSORTIUM
U.S. Department of Energy

## WESEP 594
## IOWA STATE UNIVERSITY, AMES, IOWA

WESEP is a Ph.D. degree program at Iowa State University in "Wind Energy Science, Engineering and Policy," funded in large part by the NSF as an Integrated Graduate Education and Research Traineeship.
This program has PhD students and faculty from EE, CprE, AeroE, ME, CE, IE, MSE, Statistics, and Meteorology.

# Interconnection seams study

- National Renewable Energy Lab
- Pacific Northwest National Lab
- Oak Ridge National Lab
- Argonne National Lab
- Iowa State University
- Southwest Power Pool
- MISO
- WAPA, WECC




# Capacity Expansion


## JAMES MCCALLEY

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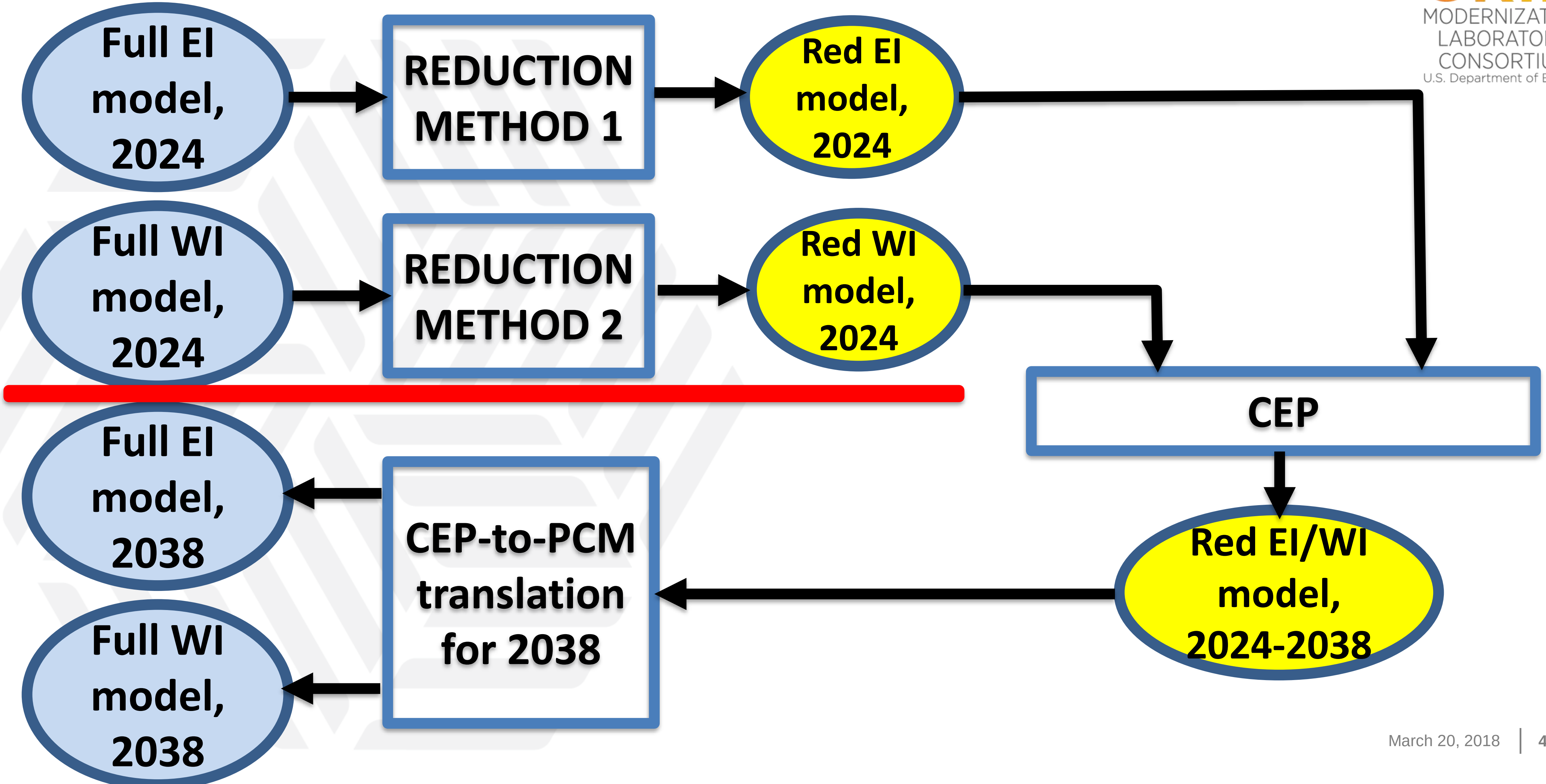
Abhinav Venkatraman

# Outline for CEP section

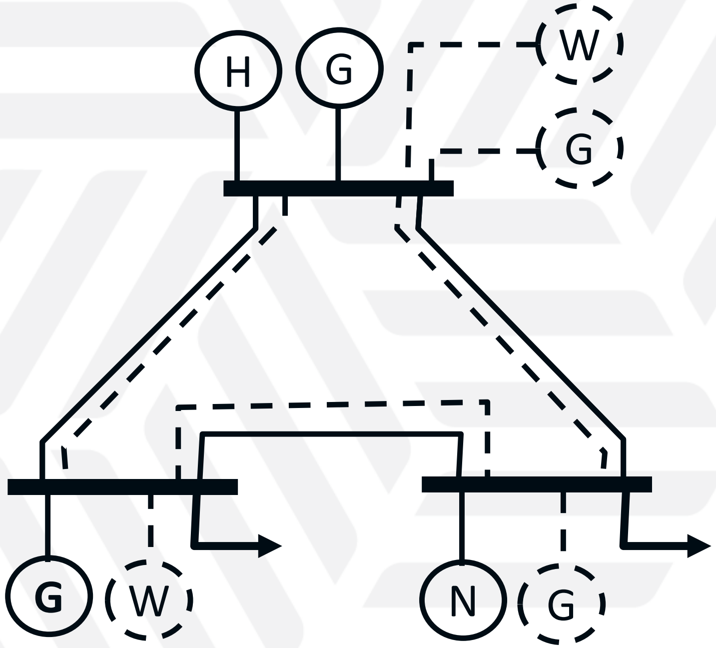
- ▶ Modeling approach
- ▶ Base design conditions
- ▶ Results
- ▶ Top findings

# Modeling approach:
# Co-optimized G&T Expansion Planning (CGT-Plan)



# Modeling approach:
# Co-optimized G&T Expansion Planning (CGT-Plan)

Identify investment & retirement decisions to MINIMIZE




**NET PRESENT VALUE**

G&T Investment Costs
+ Fixed O&M Costs
+ Var O&M Costs
+ Fuel Costs
+ Reserve Costs
+ Environmental Costs

**SUBJECT TO:**

Investment constraints

Operational, planning, environmental constraints

**Year 1** | **Year 2** | • • • | **Year 15**

# Base design conditions

## All designs – General Info

- 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
- RPS not enforced
- Gen capacity investment limited to 40GW/yr
- Demand growth per NEEM & WI (E3) per state
- DG growth per AEO 2016, 3% per yr

**All designs achieve ~50% renewables (wind, solar, hydro) while reducing $CO_2$ emissions to ~30% of 2024 levels.**

## All designs – Cost Info

- All O&M/investment costs assessed at NPV w/ real DR=5.7%.
- Annual $CO_2$ cost rate of increase: $3/mton per yr
- Run for 15 yrs w/ 7 investment periods (every other yr)
- 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

# RESULTS SUMMARY: TOP TABLE - ECONOMIC RESULTS; BOTTOM TABLE - CAPACITY RESULTS

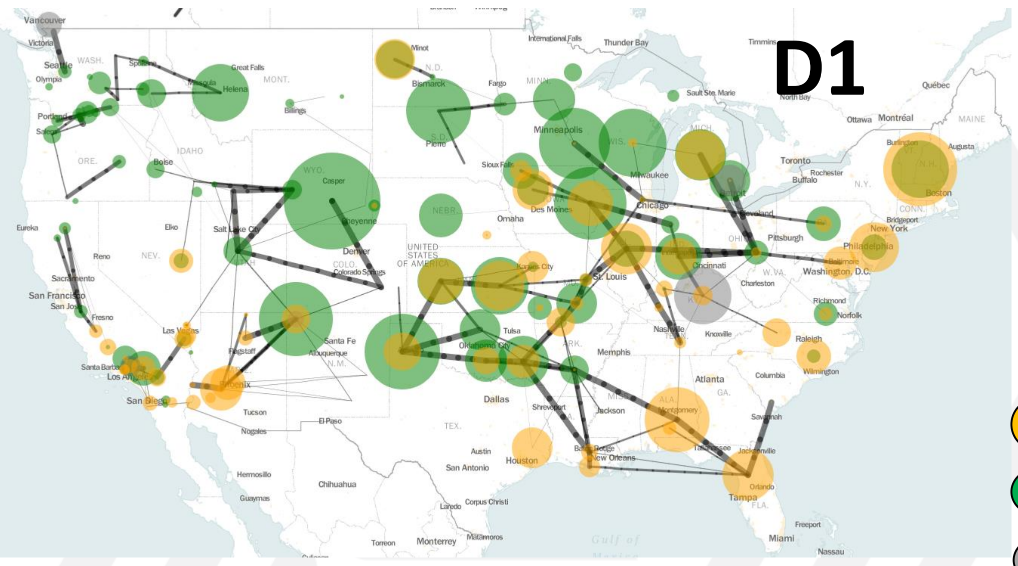
| ECONOMICS, NPV $B | Design 1 | Design 2a | Delta | Design 2b | Delta | Design 3 | Delta |
|---|---|---|---|---|---|---|---|
| Line Investment Cost | 61.21 | 73.89 | 12.68 | 74.88 | 13.67 | 80.1 | 18.89 |
| Generation Investment Cost | 704.03 | 703.32 | -0.71 | 696.99 | -7.04 | 700.51 | -3.52 |
| Fuel Cost | 753.8 | 738.98 | -14.82 | 737.3 | -16.5 | 736.12 | -17.68 |
| Fixed O&M Cost | 455.6 | 450.2 | -5.4 | 448.95 | -6.65 | 450.23 | -5.37 |
| Variable O&M Cost | 64.5 | 63.9 | -0.6 | 64.27 | -0.23 | 64.39 | -0.11 |
| Carbon Cost | 171.1 | 164.2 | -6.9 | 162.6 | -8.5 | 162.5 | -8.6 |
| Regulation-Up Cost | 33.29 | 31.63 | -1.66 | 29.96 | -3.33 | 26.63 | -6.66 |
| Regulation-Down Cost | 4.76 | 4.52 | -0.24 | 4.29 | -0.47 | 3.81 | -0.95 |
| Contingency Cost | 24.41 | 23.19 | -1.22 | 21.97 | -2.44 | 19.52 | -4.89 |
| Total Non-Xm Cost (Orange) | 2,211.49 | 2,179.94 | -31.55 | 2,166.33 | -45.16 | 2,163.71 | -47.78 |
| 15-yr B/C Ratio (Orange/Blue) | - | - | 2.48 | - | 3.30 | - | 2.52 |

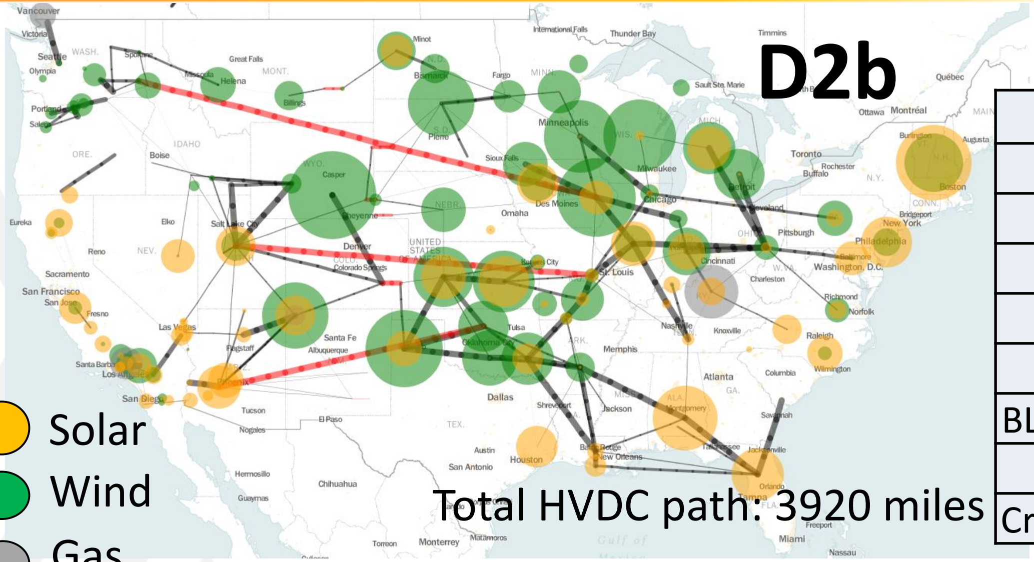
**The below row provides annualized (over 20 yrs) perpetuity cost for the base designs. Interpretation is that base designs 2a, 2b, & 3 will see the above 15-year B/C plus a savings each year over 20 years equal to the annualized perpetuity cost in yellow.**

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Perpetuity (Annualized 20-yr) Cost | 83.71 | 82.35 | -1.37 | 81.20 | -2.51 | 79.53 | -4.19 |

| CAPACITY, GW | Design 1 | Design 2a | Delta | Design 2b | Delta | Design 3 | Delta |
|---|---|---|---|---|---|---|---|
| Total gen invested (W/S/G) | 600 (386/177/37) | 600 (392/172/36) | 0 (-6/5/1) | 600 (393/172/35) | 0 (7/-5/-2) | 600 (392/169/38) | 0 (7/-6/1) |
| Total gen retired | 240 | 285 | 45 | 287 | 47 | 294 | 54 |
| Total 2024 creditable capacity | 838.5 | 809.5 | -29.0 | 792.0 | -46.5 | 794.1 | -44.4 |
| Total AC Xm invested | 228.9 | 251.3 | 22.4 | 234.8 | -5.9 | 195.1 | -33.8 |
| Total DC Xm invested | 0 | 25.7 | 25.7 | 28.4 | 28.4 | 125.8 | 125.8 |

# Results – Base Design 2b: cross-seam Tx investment at B2B ties & lines

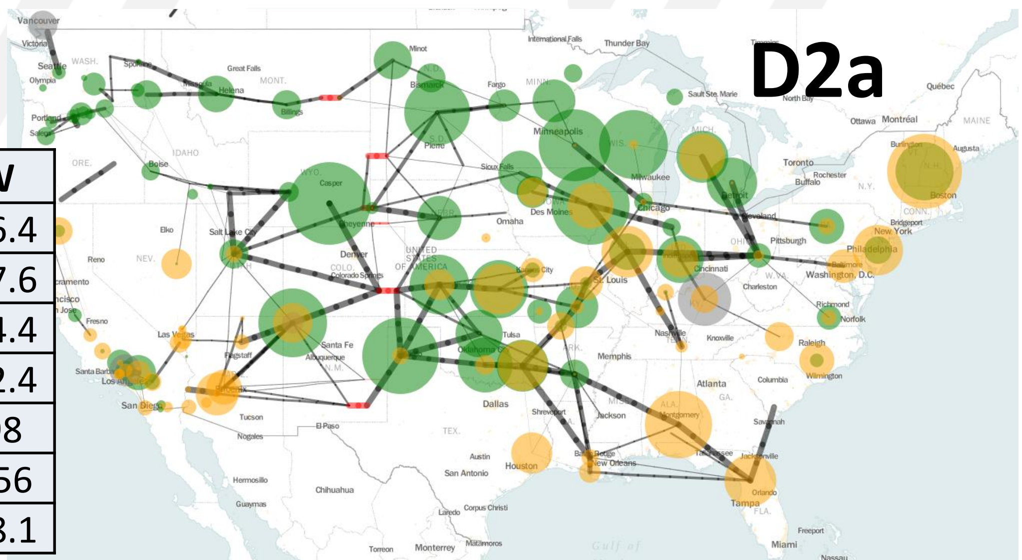


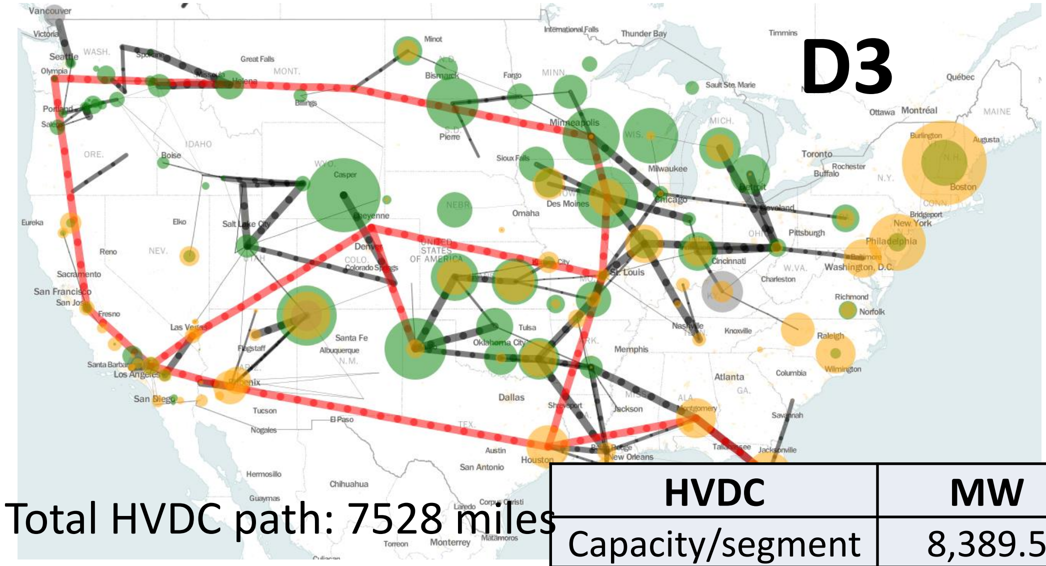

Total HVDC path: 3920 miles

| B2B Facility | MW |
|---|---|
| MC-ACDC | 1119.4 |
| RC-ACDC | 1389 |
| STEGAL-ACDC | 1681.9 |
| SIDNEY-ACDC | 1054.9 |
| LAMAR-ACDC | 2074.9 |
| BLACKWATER-ACDC | 34.411 |
| EDDYACDC | 138.42 |
| Cross-Tx. HVDC/line | 9481.3 |

Solar
Wind
Gas



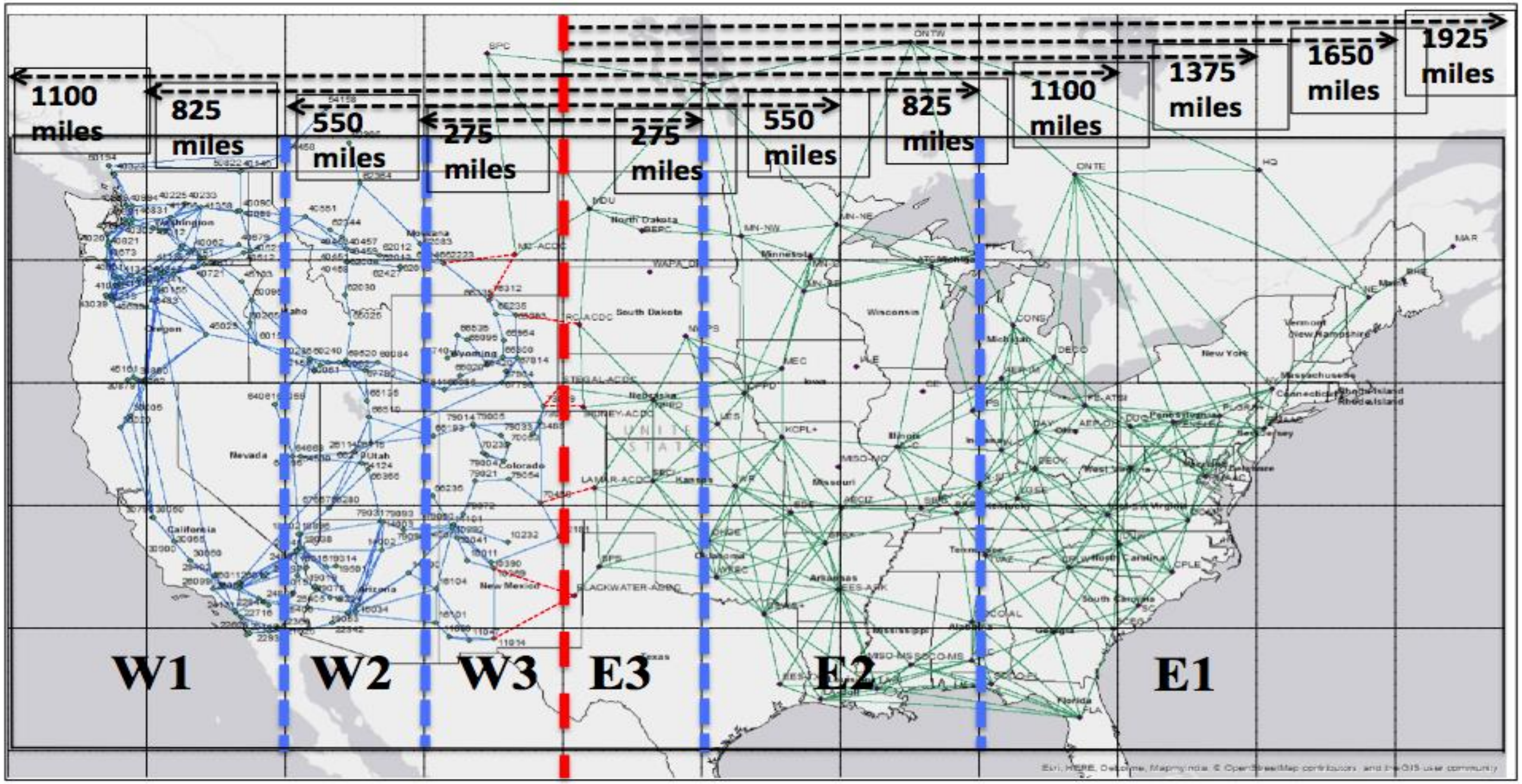

| B2B Facility | MW |
|---|---|
| MC-ACDC | 2,636.4 |
| RC-ACDC | 3,387.6 |
| STEGAL-ACDC | 4,864.4 |
| SIDNEY-ACDC | 1,042.4 |
| LAMAR-ACDC | 7,298 |
| BLACKWATER-ACDC | 358.56 |
| EDDYACDC | 1,458.1 |



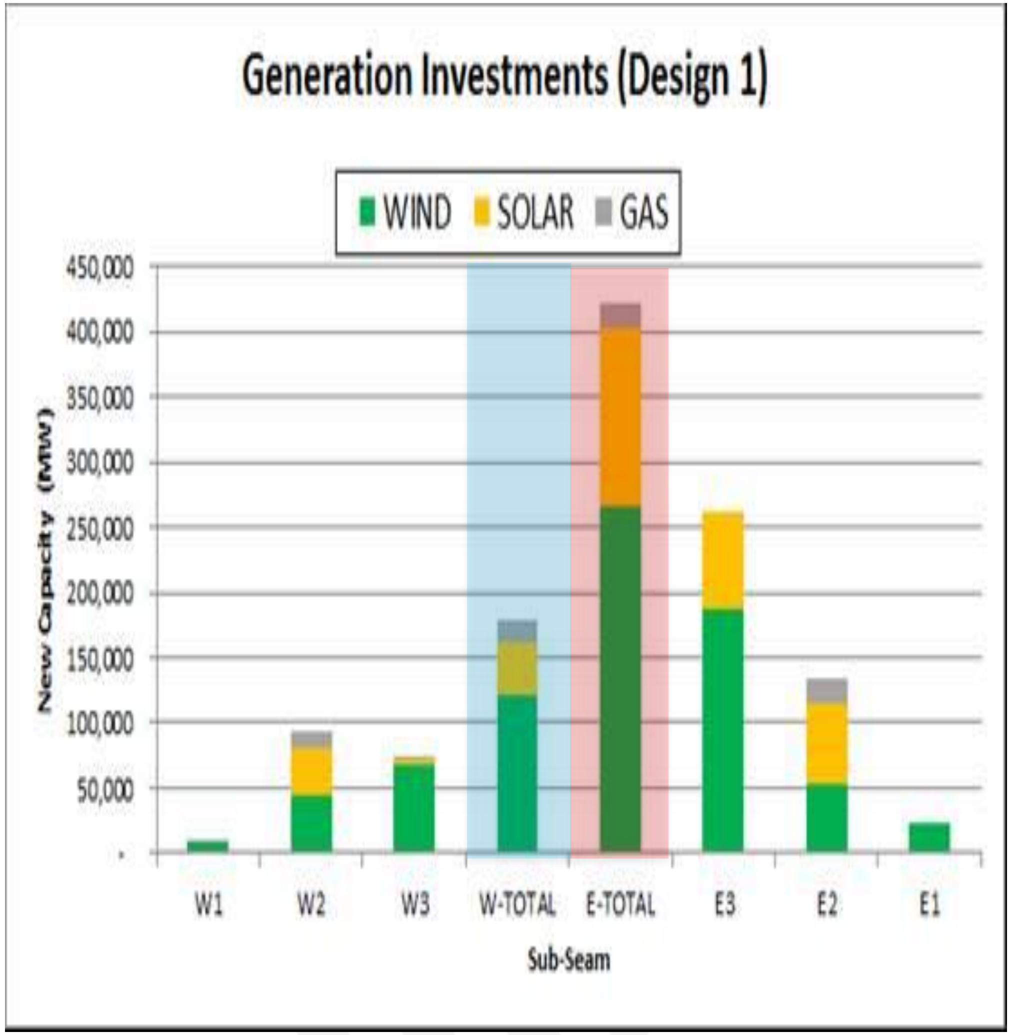

Total HVDC path: 7528 miles

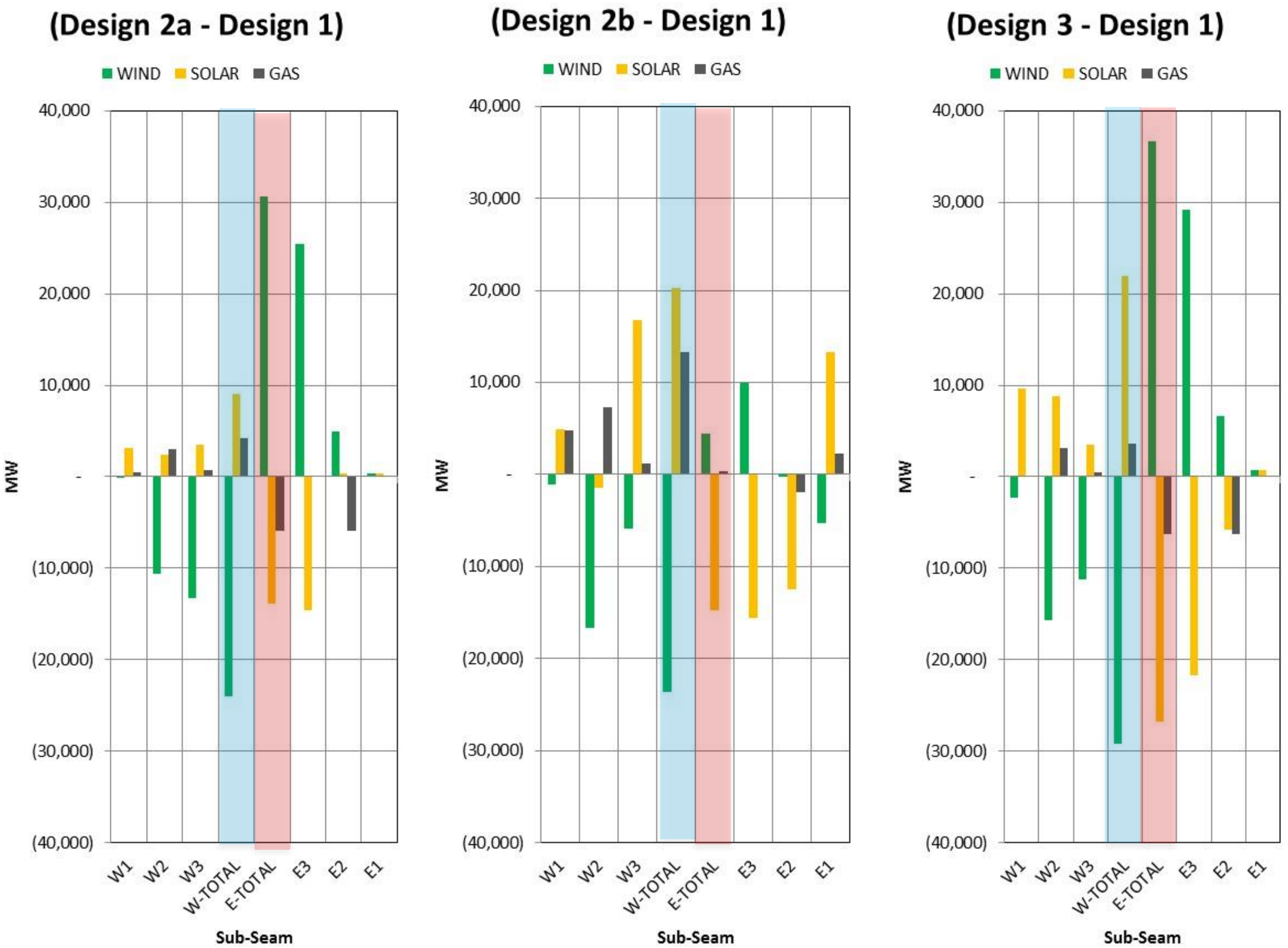
| HVDC | MW |
|---|---|
| Capacity/segment | 8,389.5 |

# Sub-seam definitions

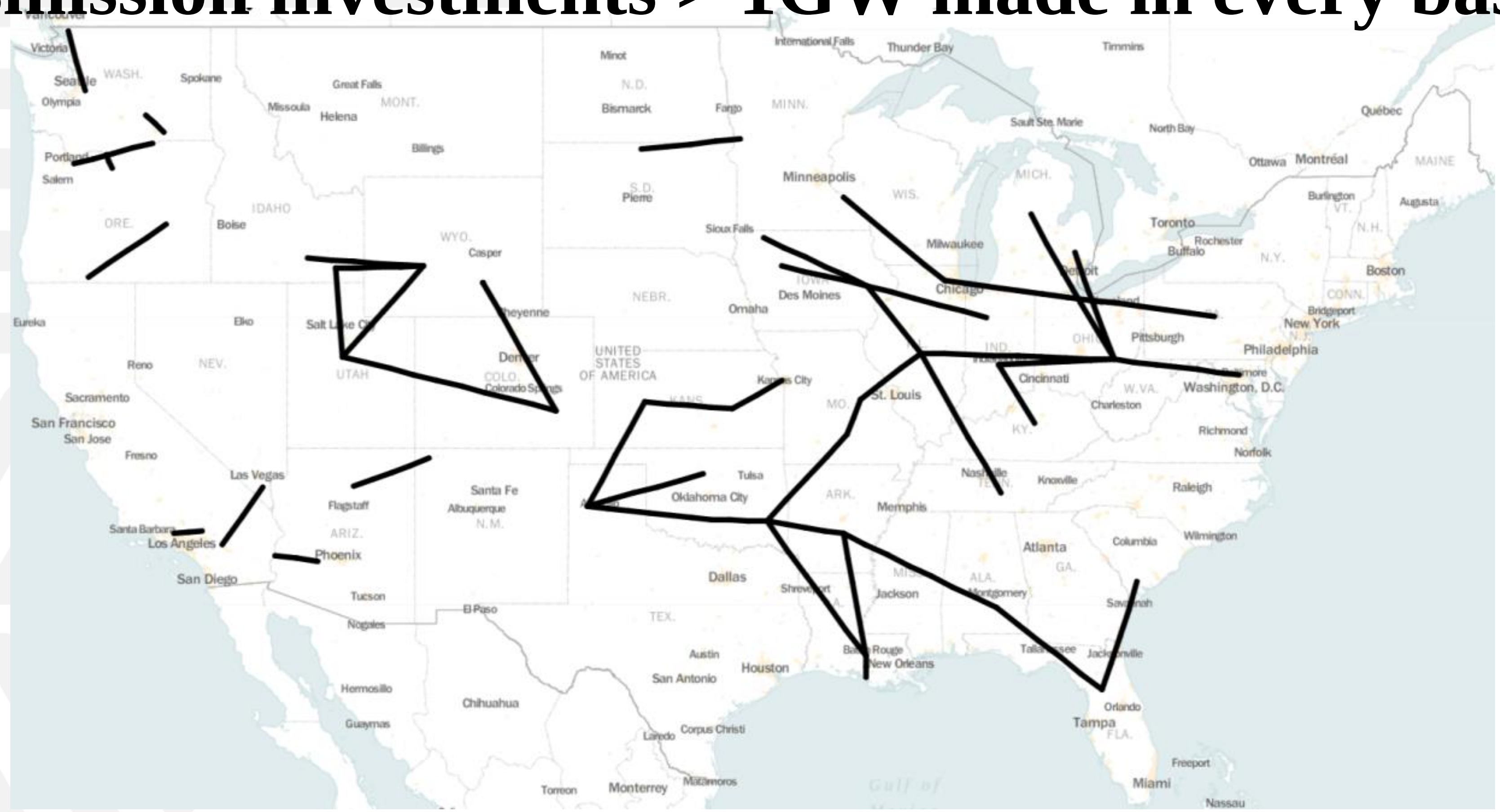


# Results – Subseam generation investments for D1 (left) and cross-seam Tx designs D2a, D2b, D3 *relative to D1* (right)

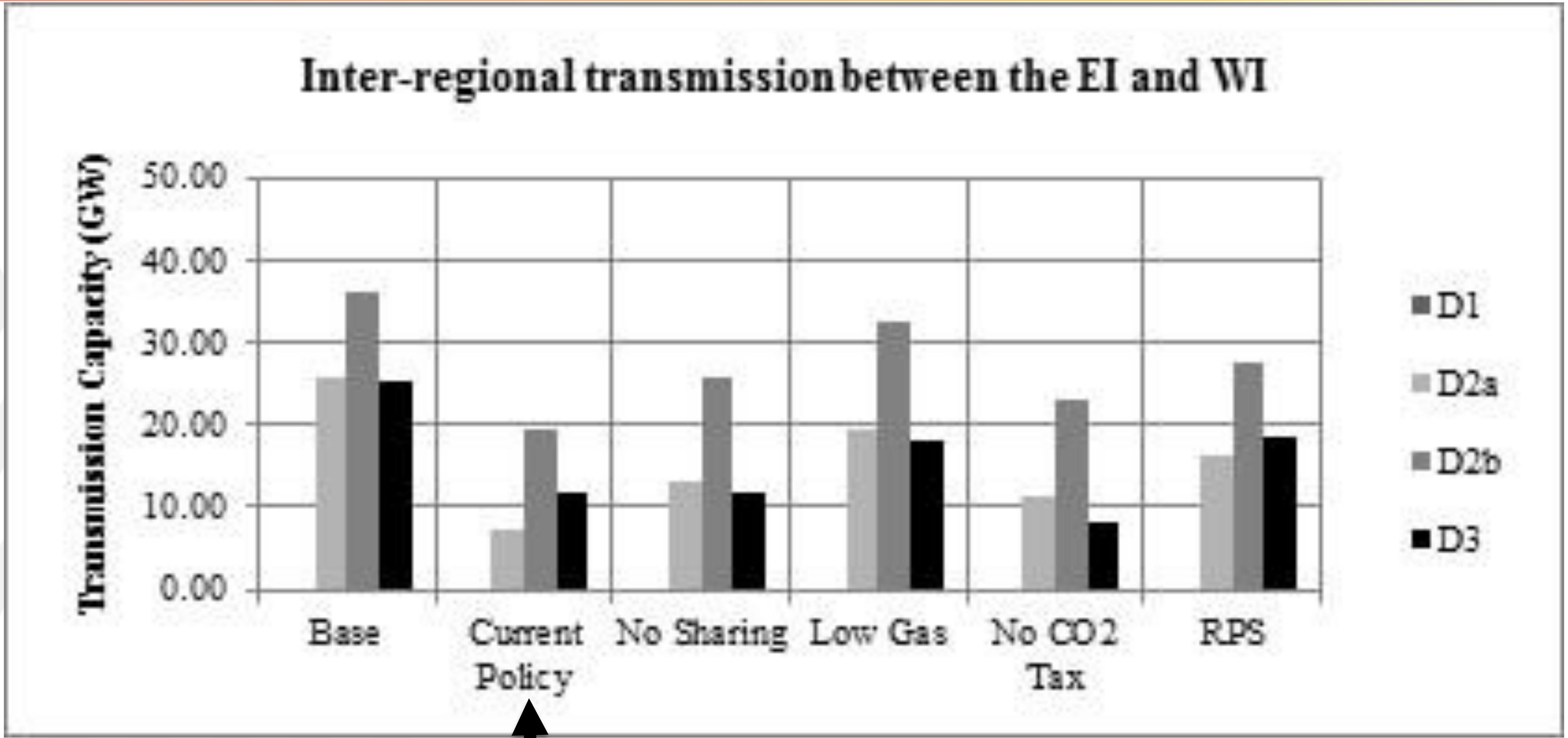


# AC transmission investments > 1GW made in every base design.



# Results – Sensitivities




Current policy =
No CO2 tax, with RPS.

## Top findings

1. **B/C ratios**:
   - Base conditions > 2.4; VERY ATTRACTIVE!!!
   - Current policy conditions ~1.13→1.26, BARELY ATTRACTIVE
   - Other sensitivities are between these two, ATTRACTIVE.
   - Operational savings continue beyond 2038; the above B/C's are lower bounds
2. **Generation capacity**:
   - Invested capacity is mainly Midwestern wind, southern & eastern solar
   - Cross-seam Tx moves wind investments from WI to EI and solar investments from EI to WI
   - Capacity sharing benefits greatly enhanced by cross-seam Tx
   - Some fossil generation should be retained for capacity but run very little
   - Midwestern wind+transmission is lower cost than tall towers on the coast and/or offshore
3. **Time zones**: Cross-seam Tx enables energy & op-resrv sharing on diurnal basis
4. **AC Tx investments**: ***EI***: Seam to E. coast/SE; ***WI***: Seam-Wy-Ut; to load cntrs.
5. **Non-quantified benefits (NQBs)**: dynamics, resilience, adaptability
6. **Designs**: D2a requires no DC lines but may provide less NQBs; D2b is highest B/C but not self-contingent; D3 is self-contingent and may maximize NQBs.

**D2b**:
3920 miles @9481 mw~$12B for lines
**D3**:
7528 miles@8390 mw~22B for lines.

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