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Interregional Transmission Design and Benefit Assessment

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SUMMARY

The U.S. Department of Energy's national congestion study [1] indicates that electric transmission congestion has become more severe inhibiting inter-regional power exchange. High quality renewable resources in the U.S. are generally remote from load centers; thus, renewable growth is inhibited by insufficient transmission as electric transmission is the only way to move renewable energy. A recent report on this issue [2] concludes that a national transmission overlay, defined as high-capacity, multi-regional grid that spans all interconnections, provides economic, environmental, and system performance benefits.

Such an interregional transmission grid is of increased interest when the cost of generation resources reflects high geographical variation as do renewables such as wind, solar, and geothermal. References [3]–[4] perform interconnection-wide planning studies, focusing on renewable deliverability. References [5]–[7] provide national overlay conceptual designs. These designs differ widely in terms of network topology and transmission technology. European efforts towards a similar 'supergrid' concept are well-documented [7]. The problem of designing an integrated national overlay is inherently different from transmission design that occurs in regional planning processes. First, economic justification typically requires a long planning horizon, at least 20 years but preferably longer, to account for economic value of investments having long lifetimes. Second, an integrated transmission overlay joining all interconnections is a large-scale, comprehensive addition to the existing grid, in contrast to more incremental additions that have driven the transmission planning process for decades.

In this paper, we introduce a planning approach for interregional transmission design at the national or continental level, for high renewable futures, and we apply it to the U.S. system to design transmission overlays under a high-renewable future. Benefits of the designed overlay are compared to those of the same renewable penetration but with interregional transmission capacity fixed at today's levels. Associated simulation results suggest that such an overlay provides social, economic and environmental benefits, by optimizing investment and production costs, reducing carbon emissions, creating renewable-related employment opportunities and lowering overall electricity prices.

KEYWORDS

Power transmission, power system planning, mathematical programming, renewable energy

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STUDY FRAMEWORK

Reference [8] develops a four-step study framework to systematically design, optimize and evaluate national transmission overlays. It begins with a generation forecast under certain future definitions. Next, transmission candidates are selected via the Iterative Reweighting Minimum Spanning Tree (IRMST) algorithm. The IRMST performs its function by operating on right of way (ROW) availability, geographical conditions and economic value, and selecting the most promising candidates. Based on the location-specified loadability and cost data of selected candidates, we formulate the multi-stage/circuit/technology transmission network expansion planning (TNEP) problem as a mixed integer linear programming (MILP) model. A particular design is then developed and evaluated. The study framework is summarized in Fig. 1. In this paper, we apply the study framework to the U.S. power system to design a transmission overlay based on a 40 year study horizon, under a high renewable generation future. The impacts of the high renewable future with the new interregional design are compared to the impacts of a benchmark design having the same renewable energy production but with interregional transmission fixed at today's levels. This benchmark design was chosen because it enables quantification of the benefits of interegional transmisison relative to an existing condition; it represents a future where a US renewable target is met with no additional investment in interregional transmission. Impacts considered were economic and environmental: total cost, greenhouse gas emissions, energy price and employment opportunity creation. Observations and conclusions are made related to characteristics of the designed overlay.

In the next three sections, we will introduce the scenario design tool, the model we use, and assumptions underlying this tool and the model. Simulation results, benefit quantification and analysis will be described in the next section. The last section concludes.

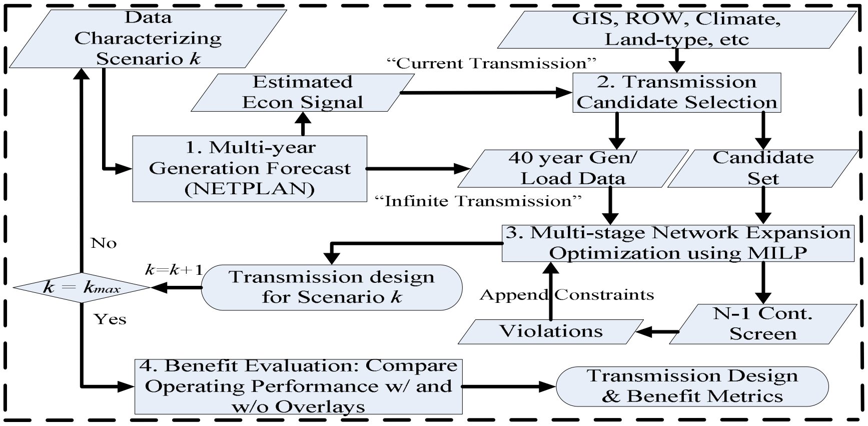

Fig. 1: Flow chart of study framework. (Source: [8])

GENERATION FORECAST AND ASSUMPTIONS

In this section, we describe the forecast of the generation portfolio over the next 40 years to achieve a high renewable future. This forecast will be used as the future scenario to perform the interregional transmission design. A 62-node US national energy system model [9] has been developed as the base case to design the high renewable future. The 62-node transmission network for the initial year accurately represents aggregated transmission capacity between larger control areas, using estimated reactance for AC corridors. Generation for each control area was modeled in aggregated form using a single unit for each generation technology utilized within that control area.

An in-house tool called NETPLAN, developed at Iowa State University [10], was utilized as the scenario design tool to perform the generation forecast, which is step 1 in Fig. 1. NETPLAN develops a generation forecast by selecting generation according to a cost-minimization optimization algorithm, where the costs that are minimized include generation investment cost, generation operation and maintenance cost, and fuel cost. Although the 62 node model does include accurate interregional transmission capacity, in this step, this capacity is assumed to be infinite, so as to identify the most economic generation protfolio possible (the assumption of infinite transmission capacity is lifted in steps 2-3 of the process - see Fig. 1). Other assumptions affecting the generation forecast step include:

a) Location-specified active load growth rate is set so that it is consistent with the data provided in reference [11], as summarized in Table 1.
b) Major types of conventional generation, including nuclear, hydro, and combustion turbines, maintain the investment trends consistent with projections made in [12] to year 2035 and beyond.We assume that no future investment is made in coal-fired generation.
c) Location-specified renewable capacity factors and investment costs are calibrated from [3], [4], [13] and [14]. Inland wind is modeled as the major renewable generation in the future, due to its maturity level and current development trend.

Table 1: Regional active load growth rate.

Node	Growth	Node	Growth	Node	Growth	Node	Growth
AE	0.63%	ET	1.55%	NY-J	0.64%	ERC_H	1.72%
AZ	2.00%	ERC_W	1.72%	NY-K	0.64%	ERC_N	1.72%
CAS	1.72%	FE	1.40%	NY-CHI	0.64%	ERC_S	1.72%
SF	1.10%	FL	1.30%	NY-F	0.64%	PJM4	1.40%
SDGE	1.20%	ID	2.20%	NY-CDE	0.64%	PJM5	1.40%
CE	1.80%	IID	1.20%	NY-AB	0.64%	PJM6	1.40%
CI	1.40%	KY	1.40%	NE-MA	1.40%	PJM7	1.40%
CAI_N	1.10%	LADWP	1.20%	NE-W	1.40%	PJM8	1.40%
SCE	1.20%	MISO1	0.63%	NM	2.00%	MISO7	1.24%
CAI_CV	1.10%	MISO2	1.40%	NN	2.20%	MISO8	1.24%
CW	1.80%	MISO3	1.24%	NE-E	1.40%	MT	2.20%
CAI_ZP	1.20%	MISO5	1.40%	NESWCT	1.40%	SPP1	1.30%
DK	1.24%	MISO6	1.24%	NW	1.20%	SPP2	1.30%
TVA	1.82%	PJM3	1.40%	PJM1	1.40%	SPP3	1.30%
UT	2.20%	SN	2.00%	PJM2	1.40%	SPP4	1.24%
WY	2.20%	SERC	1.96%				

TRANSMISSION CANDIDATE SELECTION

Transmission candidate selection and routing is among one of the most complex engineering problems. Selecting many transmission candidate routes for a single integrated system design is rare in traditional planning process as transmission investments are traditionally studied one at a time. A wide variety of issues, including socio-economic features, health and safety features, engineering features, environment and geographical features, should be addressed in the selection process [15]. To simplify this problem without losing too much accuracy, we carefully select a few representative influencing factors, which could significantly influence transmission investment decisions. These factors include: right-of-way (ROW) availability, restricted lands including Native American reserves, national and state parks and extreme natural conditions such as high lightning density regions, terrain condition, population density along the route, forest areas, wind and ice-loading and economic values. We then apply the IRMST algorithm from [8] to perform screening on all possible connections, resulting in a 383-arc nationwide candidate set.

NETWORK EXPANSION OPTIMIZATION

For bulk national transmission design, consideration is given to those high-capacity, long distance technologies, including 765kV EHVAC (Single Circuit (SC), 4-bundle), 500kV EHVAC (SC), 600kV HVDC (Bipolar, Voltage Source Converters (VSC)) and 800kV HVDC (Bipolar, VSC). These are today's most mature and cost-effective technologies for bulk power transfer. Their loadability and cost data has been summarized in Table 2 below.

Based on the future generation portfolio and candidate transmission circuit set and possible transmission technologies, we model the network expansion problem as a Mixed Integer Linear Programming (MILP) problem, expressed below. The analytical model is described in detail in [8].

Minimize Generation Production Cost + Transmission Investment Cost
Subject to Nodal power balance for all time step
DC power flow equation in disjunctive format
Generation capacity limit
Transmission maximum loadability
Additional constraints needed for modeling purposes

Table 2: Cost and loadability data for transmission technologies.

Technology	765kV	500kV	600kV	800kV
Typical Rating(GW)	SIL=2.25@300mile	SIL=1@300mile	3GW	6GW
Circuit Breaker(M$)	2.88	2.27	–	–
Transformer(M$)	9.02	6.8	–	–
Voltage Control(M$)	4.24	3.5	–	–
Converter(M$/MW)	–	–	0.155	0.17
Line Cost (M$/mile)	3.49	2.75	1.8	1.95

STUDY RESULTS

The designed generation scenario is summarized in Figs. 2 and 3. From Fig. 2 we observe the generation portfolio models significant inland wind and a relatively low amount of geothermal. Inland wind penetration increases to 50.61% at year 40, and at that time most current coal and oil generation facilities are retired. Integrated gasification combined cycle (IGCC) and geothermal also show significant increase, while other types of conventional generation are expected to slowly increase. Fig. 3 shows most inland wind is invested in the Midwest where high capacity factor wind energy exists.

The transmission design algorithm is coded in MATLAB and solved using the CPLEX commercial solver on an Iowa State University server. The designed transmission overlay is displayed in Fig. 4, for year 15, and in Fig. 5, for year 40. In Figs. 4 and 5, it can be observed that in order to carry wind power from the Midwest to load centers in the East near the south region of the Great Lakes area, major transmission requirements become pronounced after year 2025. There is also a requirement for significant transmission between SPP and ERCOT, and MISO and TVA. The design is a hybrid AC/DC network, and 800kV HVDC is the preferred type of transmission technology. Reference [16] provides a full description of this study.

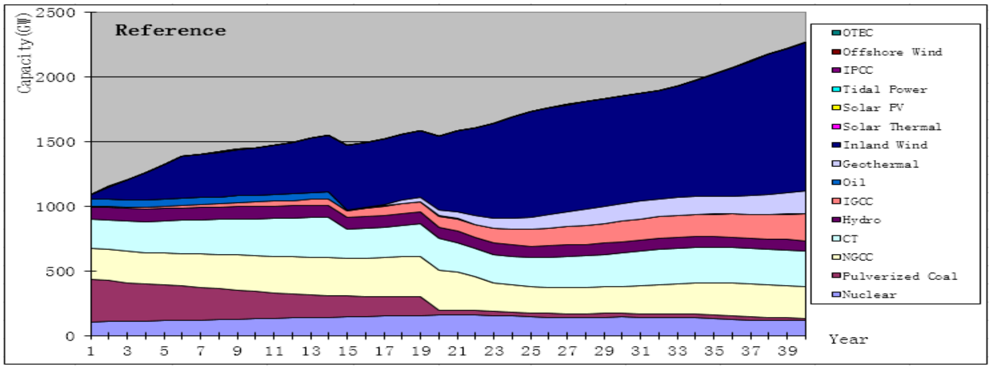

Fig. 2: Generation capacity vs. year for reference case.

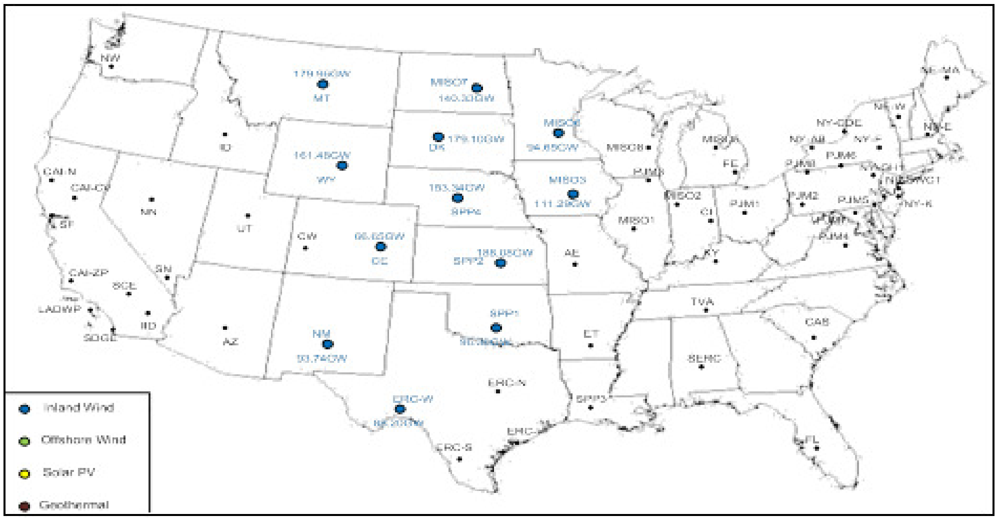

Fig. 3: Major inland wind generation location for reference case.

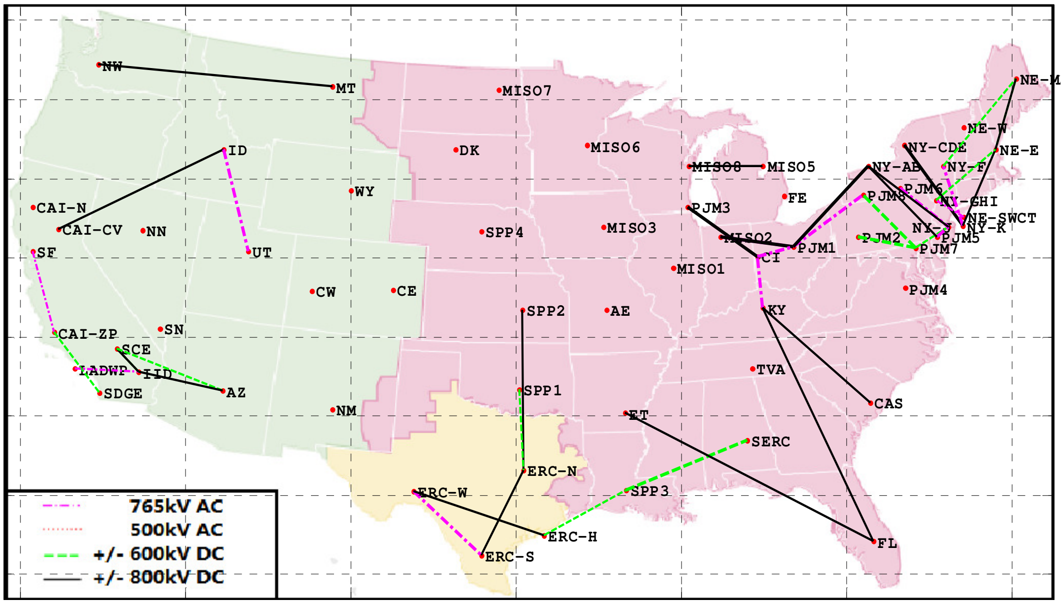

Fig. 4: Transmission overlay design for reference case at year 15.

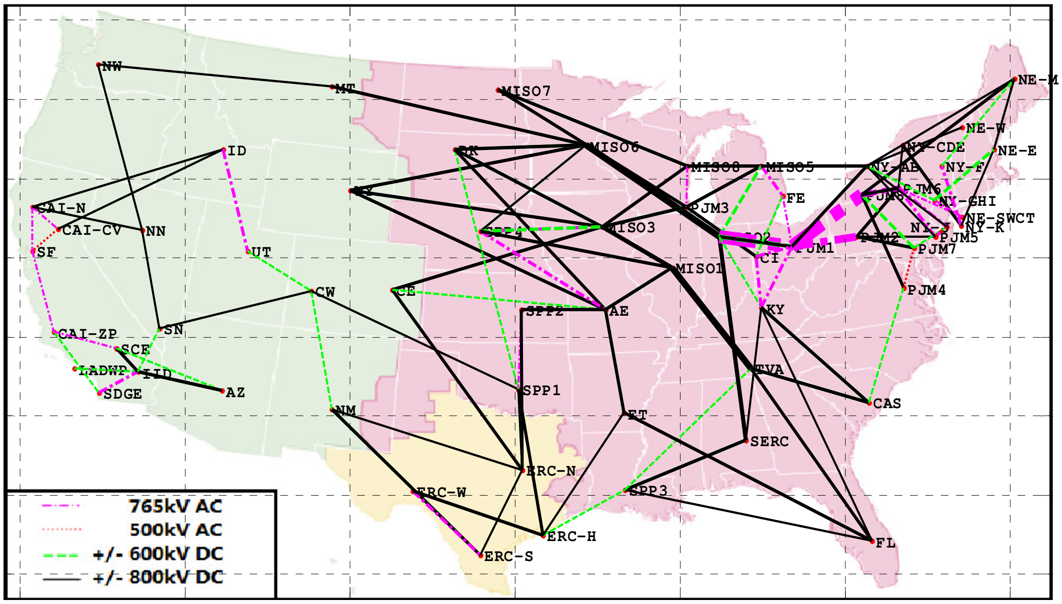

Fig. 5: Transmission overlay design for reference case at year 40.

BENEFIT AND IMPACT EVALUATION

In this section, we perform comparative studies between the cases with and without transmission overlay, to quantify its social, economic and environmental impact.

Cost and CO_2 Emissions

Comparisons between the system performance with and without the national transmission overlay, in terms of cost (in 2010 trillion \$) and emissions (in trillion short ton CO_2) metrics, are summarized in Table 3. The generation investment cost of the 'Fixed Current Trans' exceeds that of the 'With Trans. Overlay' because fixing the transmission required additional generation to meet demand. To better illustrate results, we also plotted bar charts in Fig. 6, from which we can observe that the national transmission overlay lowers both total cost and CO_2 emissions, by 37.4 billion dollars and 3.6 billion short tons, respectively.

Energy Price vs. Employment Opportunity

From an engineering and market perspective, the benefit (or loss) to a certain region in energy systems may be expressed by energy price change and job creation opportunity in that region. Employment opportunity creation is produced by the investment of infrastructure, mainly renewable generation expansion facilitated by transmission overlay. The energy price can be shown by the LMP. Hence, we calculate the LMP change and number of jobs created by renewable generation expansion due to transmission overlays, using the following estimations of job creation associated with renewable generation expansion: (a) in-land and Offshore Wind: 4.55 jobs per MW expansion [17]; (b) Solar PV: 9.76 jobs per MW expansion [18]; (c) Geothermal: 8.92 jobs per MW expansion [19]. The numbers of jobs here are all refer to permanent employment. Based on these estimations and renewable generation investment capacities, we calculated the LMP change and total job creation numbers at each node during the next 40 years, with the results shown in Table 4 and plotted in Figs. 7-8.

Comparing the numbers in Table 4, it is easy to observe that, in the areas where LMP increases, there will be large number of employment opportunities created. In contrast, in those areas (mainly load centers) where LMP decreases, few jobs are created. In regions where renewable generation is invested, bulk transmission exports energy, so compared to the case without transmission, the LMP will increase. This result indicates in a benefit trade-off between energy price and job development. In most areas, the disadvantage of losing jobs (or having higher electricity bills) will be compensated for by the other types of benefits.

Table 3: Cost and emission comparison with and without transmission overlay.

	Fixed Current Trans.	With Trans. Overlay	Cost/CO_2 Reduction
Gen. Prod. Cost (T$)	1.1294	1.0837	0.0457
Gen. Inv. Cost (T$)	3.1488	2.6850	0.4638
Trans. inv. Cost (T$)	0.0000	0.4721	-0.4721
Total Cost (T$)	4.2783	4.2409	0.0374
CO_2 (T short ton)	0.0954	0.0918	0.0036

Table 4: Node Specified LMP change and number of permanent employment created.

Node	Jobs (10^3)	Annual ave. LMP Change (M$/GW)	Node	Jobs (10^3)	Annual ave. LMP Change (M$/GW)	Node	Jobs (10^3)	Annual ave. LMP Change (M$/GW)
CAI-N	0	0.897542	NW	311	0.137697	SDGE	0	1.385564
CAI-CV	104	2.660852	SF	0	0.355761	SPP4	698	-0.53138
CAI-ZP	0	0.441598	SCE	0	1.383633	SPP2	856	-0.54462
LADWP	0	1.299666	IID	24	-0.02877	SPP1	439	-0.49421
ERC-N	0	0.951902	AZ	0	0.065698	PJM3	0	1.028004
ERC-W	401	-0.64242	SN	0	0.021044	PJM1	0	1.154764
ERC-S	0	1.364163	NN	565	4.670752	SPP3	0	-0.27221
ERC-H	0	2.124438	ID	367	-0.77312	SERC	0	1.344338
MISO7	639	-0.99665	UT	73	2.102321	TVA	0	1.187815
MISO6	431	-0.53531	MT	819	-1.44953	CAS	0	1.347452
MISO3	506	-0.5359	WY	758	-1.06938	PJM2	0	1.022446
MISO8	0	1.612176	CW	46	-1.08331	PJM4	0	1.296399
MISO1	0	1.309379	NM	500	-0.3711	PJM7	0	1.016026
NE-MA	0	1.032953	CE	303	-1.04093	PJM8	0	0.825193
MISO2	0	-2.28918	DK	815	-1.11291	PJM5	0	1.479002
MISO5	0	1.574446	ET	0	1.752997	PJM6	0	1.1188
NE-SWCT	0	1.1151	FL	0	1.389748	NY-J	0	2.480318
NY-GHI	0	1.236645	AE	0	1.416237	NY-K	0	2.724167
NY-AB	0	0.630315	FE	0	0.569767	NY-F	0	0.91833
NY-CDE	0	0.996188	CI	0	1.02165	NE-W	0	0.40329
			KY	0	0.028148	NE-E	0	0.440418

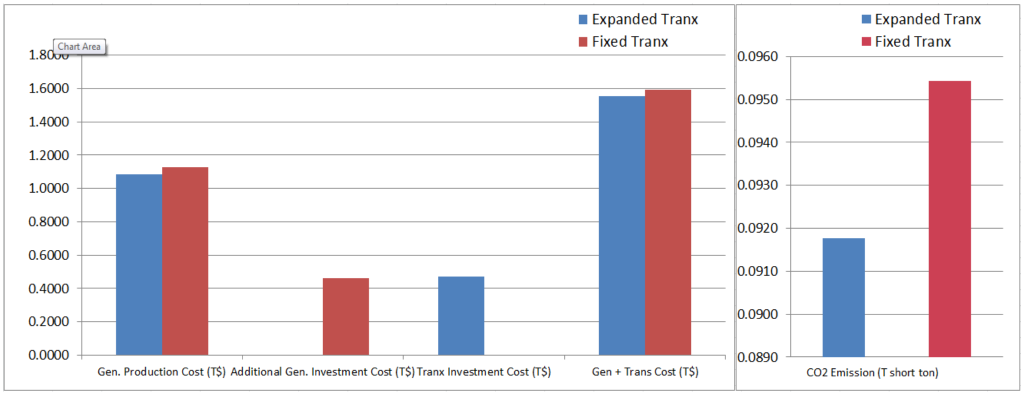

Fig. 6: Cost and emission metrics comparison for reference case.

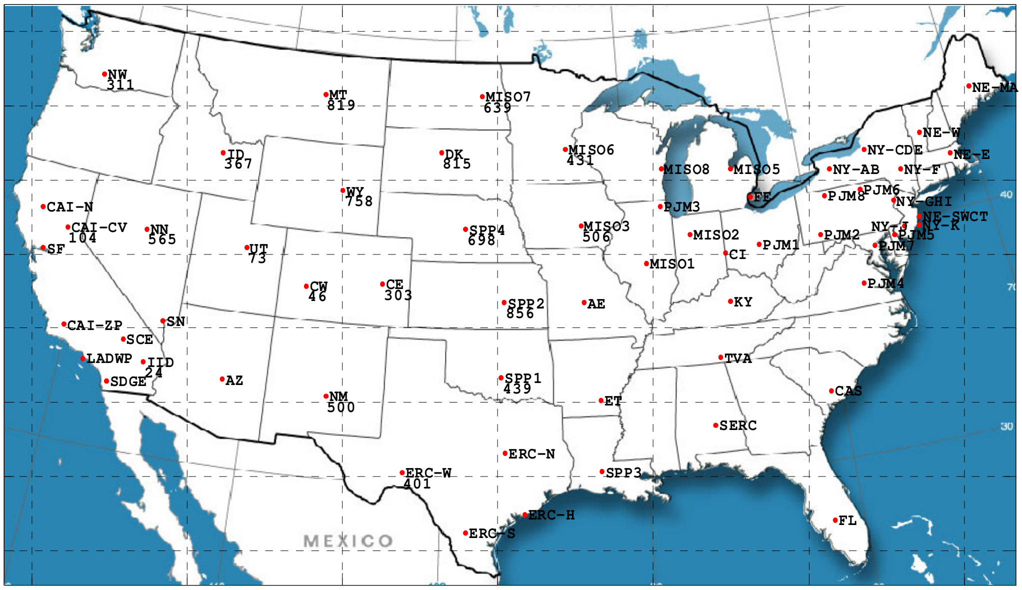

Fig. 7: Number of jobs created (in million permanent jobs).

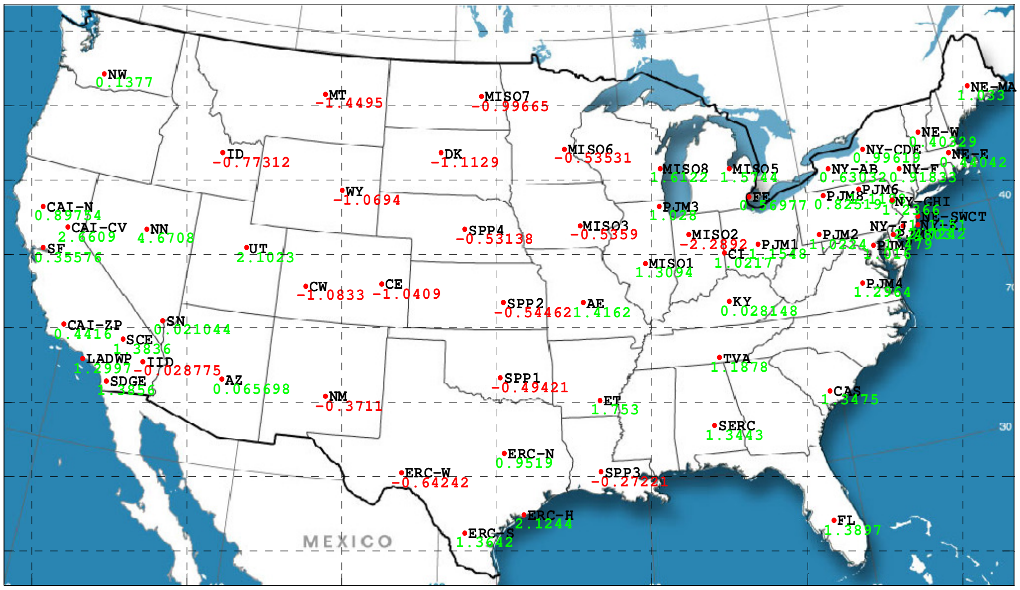

Fig. 8: LMP change (+green means drop; -red means increase).

PATHS FORWARD

Despite the benefits, interregional transmission is difficult to build in the U.S. One reason for this is the balkanization of authority. Most lines in each design are long, often routing through the lands of two or more states. Because states have siting authority for electric transmission, a state may reject a transmission project through its lands and would likely do so if it does not perceive sufficient benefit to its own populace (operating companies could also impede transmission development through their service area, but recently, FERC Order 1000 lifted an operating company's right of first refusal for circuit development in their service area). Another reason why interregional transmission is difficult to build is resource parochialism, where a state or region may prefer to forgo economic benefits of inexpensive energy made available by interregional transmission, electing instead to build more expensive generation locally. Such a choice may seem justified based on economic development resulting from building local generation; however, such a perspective does not consider the net benefit of transmission from lowered energy prices in the receiving region and the economic development in the sending region, a benefit that may be significantly greater than what can be obtained by buidling local generation.

In [2, 20], we describe three distinct paths that could be pursued to realize continent-wide interregional transmission design: market driven investment, federal initiative, and interregional coordination. There are elements of each of these three approaches ongoing today. The market-driven approach has appeared via several recent efforts towards building merchant transmission, and in several recent FERC rulings on such proposals. An initial movement towards the federal initiative approach can be observed in Section 1221 of the Energy Policy Act of 2005 giving some authority to FERC to site interstate transmission lines, although no transmission siting applications have yet to be approved as a result of this authority. Interregional coordination is ongoing via the DOE-funded interconnection-wide planning efforts, and these kinds of activities are receiving support from at least two governor's associations as well as the recent FERC Order 1000. Ultimately, a hybrid approach may be most effective, where an interregional transmission system is designed by a multiregional collaborative stakeholder group of industry, states, advocacy organizations, and DOE, with input from governors associations. Impasses would be addressed by federally-appointed arbiters. Merchant transmission developers are incentivized to build consistent with the design; what merchant developers will not or cannot build is federalized, but with careful Federal-State coordination and cooperation.

CONCLUSIONS

This paper summarizes the study method and results of national transmission overlay design under a high inland wind future generation scenario. We make the following observations based on the results of this paper:

a. A national transmission overlay benefits the U.S. system, by reducing cost and emissions. It lowers the overall cost of energy, although it may increase LMPs within certain regions. Energy prices tend to increase in regions with new renewables, but this local impact is countered by the large number of jobs that may be created in these regions;
b. The optimized overlays are hybrid AC/DC networks, with 800kV HVDC being the preferred technology in most regions and 765 kV AC having significant presence as well;
c. Major transmission needs are pronounced near the Great Lakes for all cases, with 765kV AC being preferred there. There are significant transmission needs from MISO to TVA to SERC, between SPP and ERCOT, and along East and West coasts.
d. Actual development of this level of transmission in the U.S. will require changes to the regulatory processes and procedures for transmission investment.

An additional issue that requires attention in the future is the handling of uncertainties in attributes characterizing the future. A multiple-future study is needed, and a proper methodology should be developed to identify a single overlay design which balances what is actually built with adaptation needed as the future unfolds. Reference [16] presents a new method to accomplish this.

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