Influence Analysis of Wind Power Variation on Generation and Transmission Expansion in U.S. Eastern Interconnection

By Stanton W. Hadley and Shutang You

INTRODUCTION

Bulk power system expansion problems can be divided into three categories: generation expansion [1, 2], transmission expansion [2-4], and generation-transmission co-expansion [5]. Power system operation is subjected to influences from stochastic factors, such as forced outages, load, renewables and fuel cost variations. With the increase of renewable penetration rates, the stochastic features of wind and solar are becoming major uncertain factors of power systems. As studies predict that U.S. could have around 27% of its electricity coming from renewables by 2030 [6], their fluctuations need to be considered in not only the operations stage, but also the planning stage.

It has been widely accepted that co-optimization generation and transmission expansion can obtain better expansion results and more investment savings [7]. This co-optimization process involves multiple years of detailed market simulation for an accurate assessment of expansion plan candidates. Since renewable variation in different regions has significantly increased interface flow and energy exchange between regions, the expansion co-optimization should consider renewables output variations in the temporal and spatial dimension. This article investigates how wind power variation will influence generation and transmission expansion in the U.S. Eastern Interconnection (EI) system.

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METHODOLOGIES

Generation and transmission expansion aims to maximize the social welfare or minimize the total cost, which is comprised of the expansion cost, the operation cost, and the emission cost over the planning horizon. The breakdown of the objective function is shown in Table I.

Cost category	Cost items in the objective function
Expansion costs	Generation built cost
	The transmission expansion cost of all interfaces
Operation costs	The fuel cost
	The varying operation and maintenance cost
	The value of lost load
	Fixed operation and maintenance cost
	The wheeling cost of transmission lines
Emission cost	The emission cost

Table I. Constitution of the objective function in expansion planning

The objective function is the net present value of the sum of all of the system's cost items over the planning horizon. In addition, it is important that the expansion planning formulation does not inappropriately consider the end of the planning horizon to be the 'end of time'. Without considering the 'end-year effects', the expansion plan would select to build generators with low build costs in the last several years, even if their marginal generation costs are high, so that the average cost in the horizon would be low. To reflect the 'end-year effects', the last year of the horizon is repeated an infinite number of times [8] and it is reflected in the modified discount factor of the end year.

A practical expansion plan should also satisfy various planning and operation constraints. Constraints considered in this expansion planning problem are described in Table II.

Constraint category	Constraint items	Constraint descriptions
Expansion constraints	Maximum expansion constraint for generation	Due to resource limitation, the number of generator expansion in each region should be within its upper limit.
	Maximum expansion constraint for transmission	Due to the right-of-way limitation, the number of expanded interfaces should be within its upper limit.
	Integer constraint	The number of built generators and interfaces should be integers.
	Expansion speed constraint	Due to the construction resource limitation, the annual expansion speed of generators and transmission lines should be within their upper limits.
Operation constraints	Power balance constraint	In each region, the sum of generation output, unserved demand, and interface interchange should equal to the demand for all regions within the planning horizon.
	Capacity discount	Capacity discount considering the forced and maintenance outages
	Regional reserve capacity constraint	The reserve capacity of each region should be larger than a pre-determined level for regulation and contingencies.
	Interface capacity constraint	The power flow of each interface should be within the maximum transmission capacity.
	Wind resource constraint	The output of wind turbine generators is restricted by the available wind resource.
Other constraints	Regional renewable portfolio constraint	In those regions with renewable portfolio constraints, the percentage of renewables in the total installed generation capacity should be higher than a pre-determined value.

Table II. Constraints in expansion planning

The U.S. EI multi-regional dataset comes from Charles River Associates [9]. This dataset partitions the EI system into 25 regions and the interfaces between adjacent regions as shown in Figure 1 [10]. The load profile is represented by 20 load blocks per year. The EI multi-regional dataset and

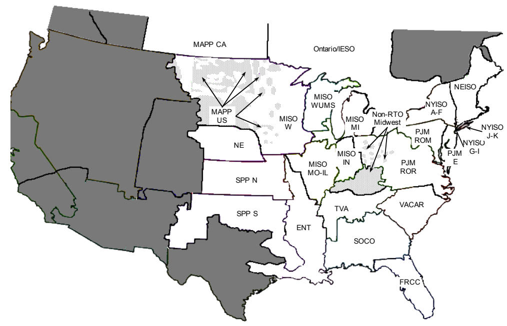


Figure 1. Regions of the U.S. EI system (EI includes all regions in the east) [11]

Case Name	Number of wind blocks (modelling detail levels)	Case Description
20 Blocks (20-Blk)	$N_{S_W} = 1$	• The base case has 20 load blocks in each year • Wind is the average value in each load scenario
40 Blocks Non-Synchronized (40-Blk-NonSync)	$N_{S_W} = 2$	• Splitting each load block in two equal number of hours • Average of high wind in a half and average of low wind in the other half (*wind data are not synchronized across regions*).
40 Blocks Synchronized (40-Blk-Sync)	$N_{S_W} = 2$	• Determining hours of high and low wind capacity factors based on the weighted average system-scale data in each of the 20 load blocks • Synchronizing wind, solar, and load to the average of the region's values in those hours
80 Blocks Synchronized (80-Blk-Sync)	$N_{S_W} = 4$	• Breaking each load block into four quartiles based on the weighted average system-scale data in each of the 20 load blocks • Synchronizing all regions' wind, solar, load, and fuel prices to those hours
160 Blocks Synchronized (160-Blk-Sync)	$N_{S_W} = 8$	• Breaking each load block into eight sub-blocks based on the weighted average system-scale data in each of the 20 load blocks • Synchronizing all regions' wind, solar, load, and fuel prices to those hours

Table III. Description on the developed cases

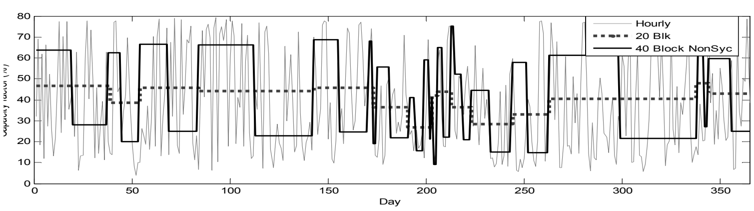


Figure 2. Wind variation representation of SPP_N in the 20-Blk Case and the 40-Blk-NonSync Case

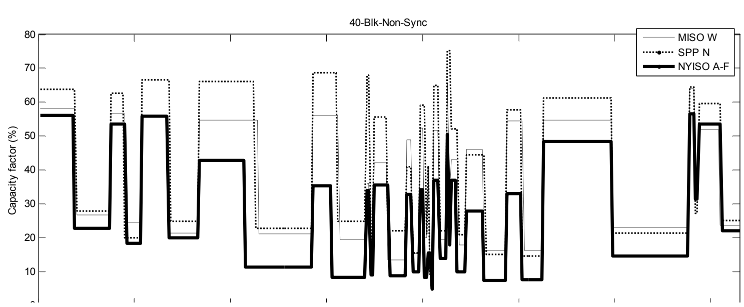


Figure 3. Wind blocks of four regions in the 40-Blk-NonSync Case

the generation and transmission expansion problem are modelled in PLEXOS [8]. The planning horizon is from 2015 to 2030. Five developed cases with different number of wind blocks (representing different detail levels of wind modelling) are developed as shown in Table III, which is followed by further graphical descriptions.

Figure 2 shows the wind capacity factor of the SPP_N region in three datasets: 1) hourly; 2) 20 Block; 3) 40 Blocks Non-Synchronized. It shows that the output profile of the 20-Blk Case is very smooth compared to the raw hourly data. The 40 Blocks Non-Synchronized Case preserves some wind power variation information since it splits each original block into two blocks with equal number of hours that represent high and low wind in half. The total amount of wind power available in each combined high and low wind scenario block remains the same under all three cases.

In the 40-Blk-NonSync Case, it is assumed that the wind in all regions is highly correlated. In other words, high wind is supposed to happen simultaneously in all regions, as does low wind. This phenomenon can be seen from the wind blocks of three regions in the 40-Blk-NonSync Case shown in Figure 3.

However, in reality the half periods with high wind output in one region do not totally overlap with those in another region due to weather and geographic factors. Typically, nearby wind regions have more synchronicity on wind output levels, while further ones have less. Using the time series generation method in Section 3, the 40-Blk-Sync Case is able to capture the correlation degree of wind output between regions. The wind variation in three regions represented by data in the 40-Blk-Sync Case is shown in Figure 4. In the 40-Blk-Sync Case, the hourly solar, load, and fuel price data are also synchronized with the wind data to form their 40 synchronized blocks for LT expansion planning. In this way, the wind, solar, load, and fuel prices keep their synchronization in the 40-Blk-Sync Case.

Similarly, wind blocks in the 80-Blk-Sync Case and the 160-Blk-Sync Case are developed. The wind variation in three regions represented by data in the 160-Blk-Sync Case is shown in Figure 5. It can be seen that more blocks will capture more information on regional wind resources, especially in peak load periods during summer.

RESULTS AND ANALYSIS

The expansion results of the five cases are summarized in Table IV. It can be noted that the planning results of Case 40-Blk-Sync is between that of Case 20-Blk and Case 40-Blk-NonSync. Since Case 20-Blk only includes one wind output block (i.e., the average wind output) in each load block, it overestimates the capacity of wind power and underbuilds transmission capacity. Compared with 40-Blk-Sync, the 40-Blk-NonSync Case underestimates the capacity value of wind power since it assumes all regions' wind power is at the high or low half simultaneously, which also leads to more transmission expansion. The 80-Blk-Sync and 160-Blk-Sync Cases add less wind than 40-Blk-Sync but more transmission. This is because the two cases modelled higher wind peak generation blocks, which need more transmission capacity to export. In the meantime, modelling lower wind blocks reduces wind power's capacity value, thereby reducing wind power expansion in the planning result.

Figure 6 shows the transmission expansion over the planning horizon of the five cases. It can be seen that using more detailed wind blocks will make the transmission expansion more dispersed in space. Particularly, compared with 20-Blk, both 40-Blk-Sync, 80-Blk-Sync, and 160-Blk-Sync have smaller transmission expansion on the interface MISO_IN to PJM_ROR.

Table V shows the expansion of gas and wind generation capacity in PJM_ROR and SPP_N. Figure 7 shows the energy flow in 2030 for the Case 20-Blk and Case160-Blk-Sync. It can be seen that in the 20-Blk Case, a large proportion of import energy to PJM_ROR comes from wind in SPP_N. When detailed wind blocks are incorporated (such as in Case 160-Blk-Sync), PJM_ROR relies more on its local gas generation.

In addition, it can be noted from Figure 7 that the annual energy flow of almost all interfaces in 160-Blk-Sync increase except for those on the major wind power delivery corridor: SPP_N – MISO_MO_IL – MISO_IN – PJM_ROR. This indicates that detailed wind blocks will increase the energy exchange frequency and amount between adjacent regions, while decreasing the economy of enforcing transmission networks to transmit a large amount of wind power through a long distance.

For comparison, Figure 8 shows the annual energy flow of the not-co-optimized case (which optimizes generation and transmission expansion separately). It can be seen that this expansion result chooses to expand the interface between MISO_W and PJM_ROR. In fact, expansion of this interface requires high investment, making the whole expansion plan uneconomic.

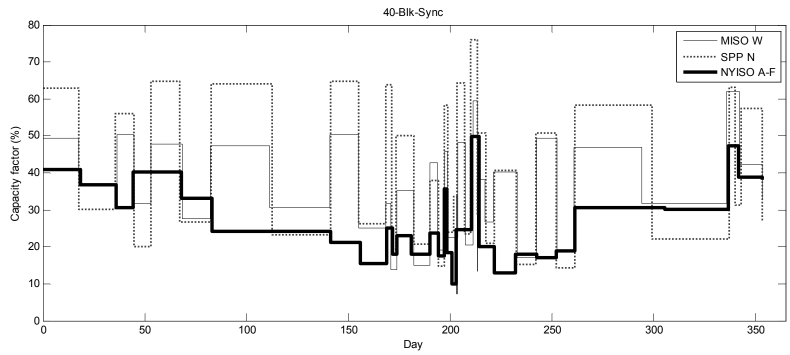


Figure 4. Wind blocks of four regions in the 40-Blk-Sync Case

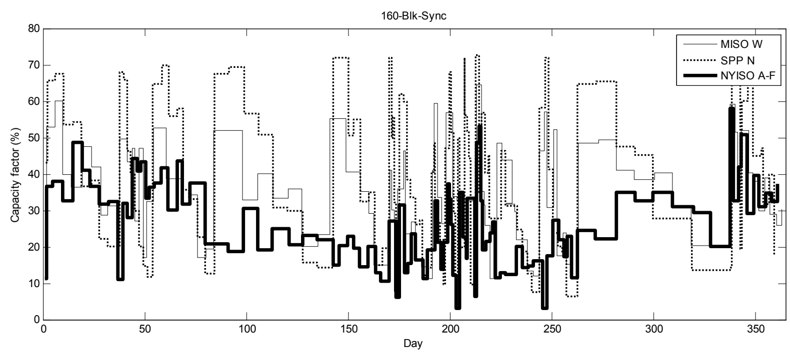


Figure 5. Wind blocks of four regions in the 160-Blk-Sync Case

Expansion results	20-Blk	40-Blk-NonSync	40-Blk-Sync	80-Blk-Sync	160-Blk-Sync
Wind Candidates Built Capacity[a] (GW)	262	218	223	221	218
All Gen Built Capacity (GW)	407	373	381	380	378
Wind Capacity in 2030 (GW)	304	260	265	263	260
Wind Generation in 2030 (TWh)	917	768	783	776	766
All Gen Build Cost (NPV) (billion $)	649	595	603	601	598
Trans Build Cost (NPV) (billion $)	20.2	26.1	22.1	22.5	25.0
Emission in 2030 (million ton)	305	365	358	362	368
Fuel Offtake 2030 (million GBTU)	17.1	18.2	18.1	18.1	18.2

Table IV. The expansion result summary of the five cases

[a] Excluding wind power that has already been decided to build.

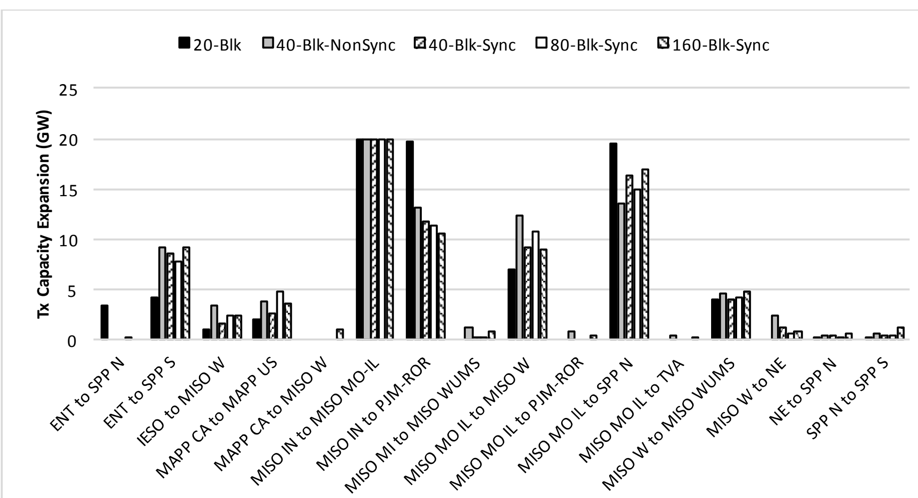
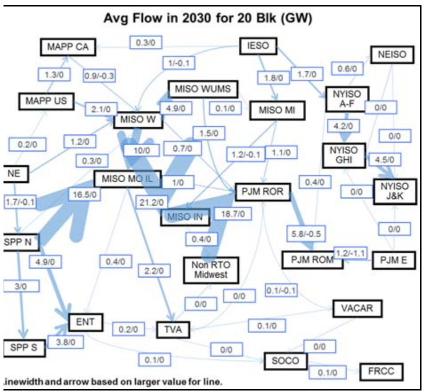


Figure 6. Transmission expansion over the planning horizon in the five cases

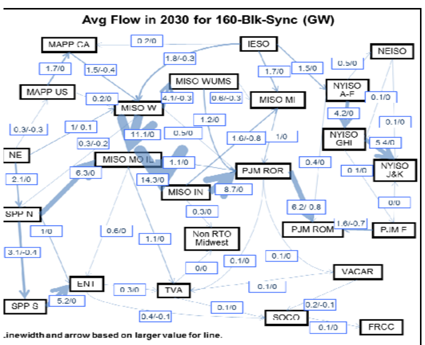
Expansion Results	20-Blk	40-Blk_NonSync	40-Blk-Sync	80-Blk-Sync	160-Blk-Sync
PJM_ROR Gas Combined Cycle Built (GW)	6	12	15.5	16	17.5
SPP_N Wind Built[a] (GW)	76.8	37.4	41.0	37.4	37.4
PJM_ROR Net Interchange	153 TWh Import	82 TWh Import	78 TWh Import	69 TWh Import	61 TWh Import

Table V. Expansion of gas and wind generation in Region PJM_ROR and SPP_N
[a]Excluding wind power that has already been decided to build.

In order to quantify the accuracy improvement through the proposed scenario generation method, the long-term expansion result is compared with the short-term simulation result for each case. The long-term simulation applies economic dispatch based on the blocks generated in the expansion planning model, while short-term simulation uses unit commitment and economic dispatch based on the chorological hourly data. The LT-and ST comparison result is shown in Table VI. It can be noted that there are always gaps between the short-term and long-term results. This is because long-term expansion uses the aggregated blocks that omit some information in the hourly data. In addition, it shows that Case 160-Blk-Sync has the smallest difference between long-term and short-term simulations, indicating that the operation simulation in Case 160-Blk-Sync is closest to short-term realistic operation. Therefore, on the basis of more accurate modelling of the system operation, the expansion co-optimization result obtained in Case 160-Blk-Sync is more reasonable.



(a) Case 20-Blk



(b) Case 160-Blk-Sync

Figure 7. Annual energy flow of Case 20-Blk and 160-Blk-Sync. Width of arrow indicates amount of flow.

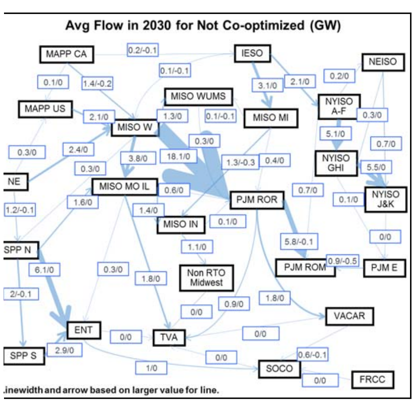


Figure 8. Annual energy flow of the not-co-optimized case

CONCLUSIONS

In this paper, U.S. EI system generation and transmission expansion is co-optimized considering wind power variation. The result shows that more detailed information of wind variation among regions significantly improved expansion results. Some additional findings in this study are:

(1) Incorporating more-variable wind (i.e., the temporal diversity) in the scenarios instead of more averaged wind in long-term planning will decrease the optimal wind expansion capacity and make transmission expansion more dispersed in space.

(2) Incorporating the spatial diversity of wind speed through synchronization will slightly increase wind generation and transmission expansion. However, this increase caused by the spatial diversity is less significant than the decrease when considering more detailed wind temporal diversity. In addition, detailed wind scenarios will reveal that it may be less economic to expand transmission networks to transmit a large amount of wind power through a long distance in the EI system.

Results	LT/ST	20-Blk	40-Blk-NonSync	40-Blk-Sync	80-Blk-Sync	160-Blk-Sync
Generation cost (NPV billion $)	LT	47.9	55.0	54.4	54.9	55.2
	ST	60.3	61.9	60.0	59.7	59.5
Emission cost (NPV billion $)	LT	42.8	51.0	50.0	50.5	51.3
	ST	50.9	52.6	52.5	53.1	53.2
LT-ST Gap		18.36%	7.48%	7.13%	6.57%	5.52%

Table VI. LT and ST simulation results in 2030

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