the selected buses was obtained three phase fault values using ASCC module in PSSE. Weighted SCR[46] was used if more than two renewable resources at one point of interconnection.

Performance Criteria	Threshold	Potential Solutions (if threshold is breached)
1. Undamped oscillations seen in transient stability study (Voltage, MW) near new or existing generating resources due to low SCR 2. Voltage collapse during model initialization or contingency	TO's Planning or NERC Criteria	1. If oscillations originate from the new plant, then tune control parameters of wind/solar farm. 2. If tuning does not mitigate the issue, turn on nearby synchronous generation. 3. Install new synchronous condensers or STATCOM if #1 and #2 do not work. 4. Install HVDC network if severe issues are observed

Table TA-41: Weak - area study process metrics and modelling and potential solutions

Frequency Response Fundamentals

In the U.S. RTOs, ISO and utilities maintain frequency close to 60 Hz by constantly balancing instantaneous generation and load. A large generator trip may cause instantaneous frequency to drop, for example, currently approximately 1,000 MW trip causes approximately 40mHz drop in Eastern Interconnection (EI). Post generator trip, many layers of action are required to restore frequency (Figure TA-26). Automatic action of governors on conventional generating resources provides most of the primary frequency response. For inverter-based resources, governing action is performed by electronic controls.

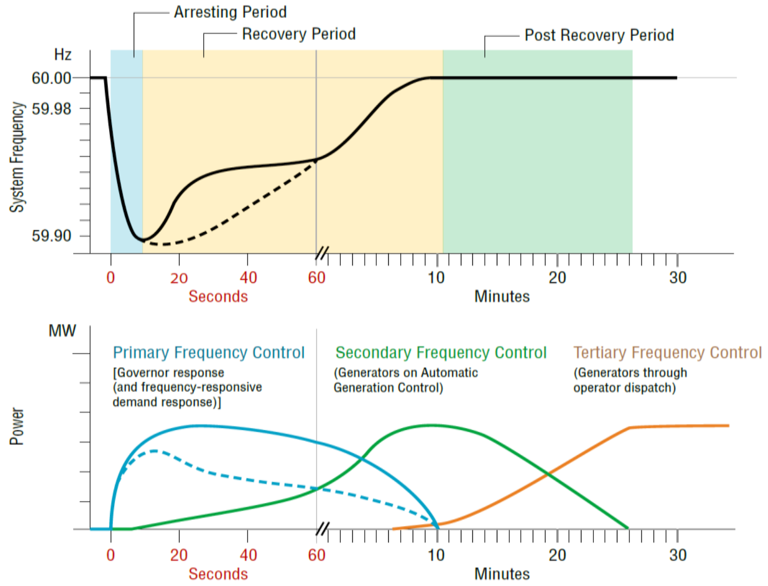


Figure TA-26: Frequency Response Fundamentals [Image source LBNL]

[46] Refer NERC: Integrating Inverter-Based Resources into Low Short Circuit Strength Systems Reliability Guideline, December 2017

Frequency Response Study process: metrics and modelling and potential solutions if threshold is breached

The impact of renewable penetration on the inertial and primary frequency response[47,] (Figure TA-26, Figure TA-27), BAL-003 obligations of MISO (Figure TA-28, Figure TA-29) were studied through dynamic simulation of 60 seconds length, and key Frequency Response metrics studied in RIIA are listed in Table TA-42. Historical large generation loss events informed the assessment of frequency response (Figure TA-29). Renewable resources were initially assumed to have no headroom thus were non-responsive to the under-frequency events. At higher penetrations of renewable energy resources, modeling of their frequency response was investigated and modified in order to evaluate what, if any, changes need to be made to meet the appropriate frequency obligations. Changes included maintaining head-room in renewable resources to provide frequency response for under-frequency type events (refer to page 131).

#	Performance Criteria	Threshold	Significance	Potential Solutions (if threshold is breached)
I-I	Eastern Interconnection Frequency Response Obligation	-1002 MW/0.1Hz	NERC BAL-003 Standard[48]	Install fast response resources, such as flywheels, capable renewable resources, batteries or demand response. Reserve headroom of traditional and renewable generation.
I-II	MISO's Frequency Response Obligation	~ -200 MW/0.1Hz		
I-III	Frequency nadir	59.5 Hz	Under Frequency Load Shedding (UFLS), NERC PRC-006	
I-IV	Rate of Change of Frequency (RoCoF)	-	Single largest contingency to initiate UFLS	

Table TA-42: Key Frequency Response Metrics Studied in RIIA

[47] NERC, "Essential Reliability Services Task Force Measures Framework Report", page -20, available online: https://www.nerc.com/comm/Other/essntlrlbltysrvcstskfrcDL/ERSTF%20Framework%20Report%20-%20Final.pdf,

[48] NERC BAL-003-1 Standard, page 13, available online: https://www.nerc.com/pa/Stand/Project%20200712%20Frequency%20Response%20DL/BAL-003-1_clean.pdf

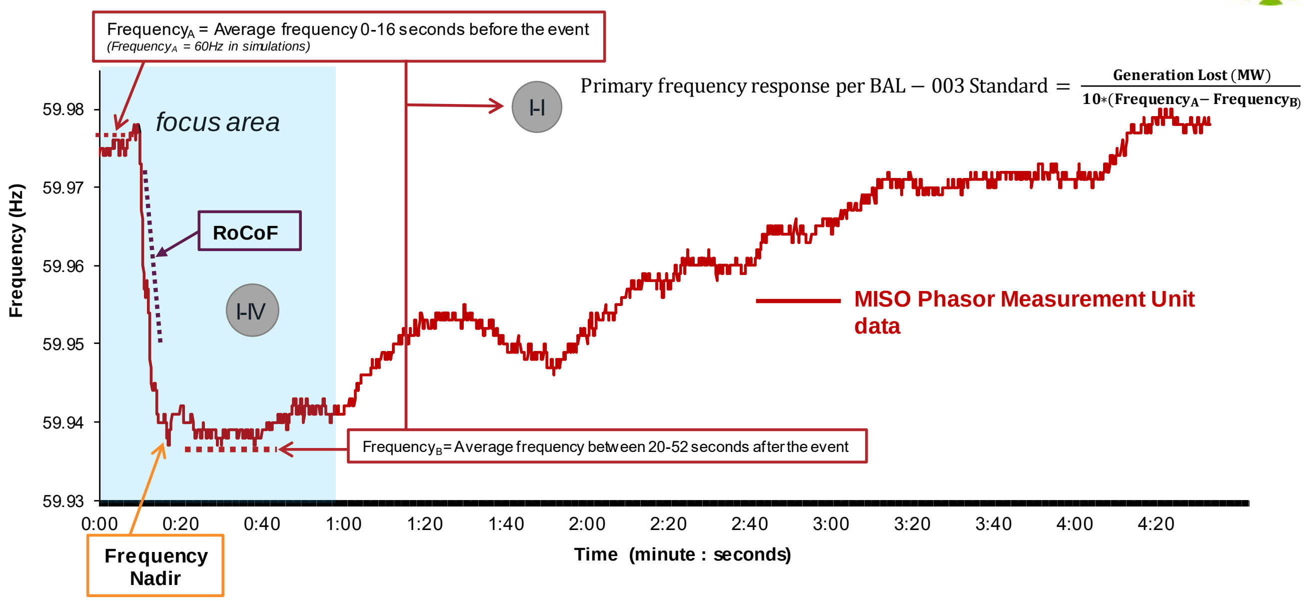


Figure TA-27: Key Frequency Response Metrics: Frequency Nadir, Rate of Change of Frequency (RoCoF), NERC BAL-003 Obligations

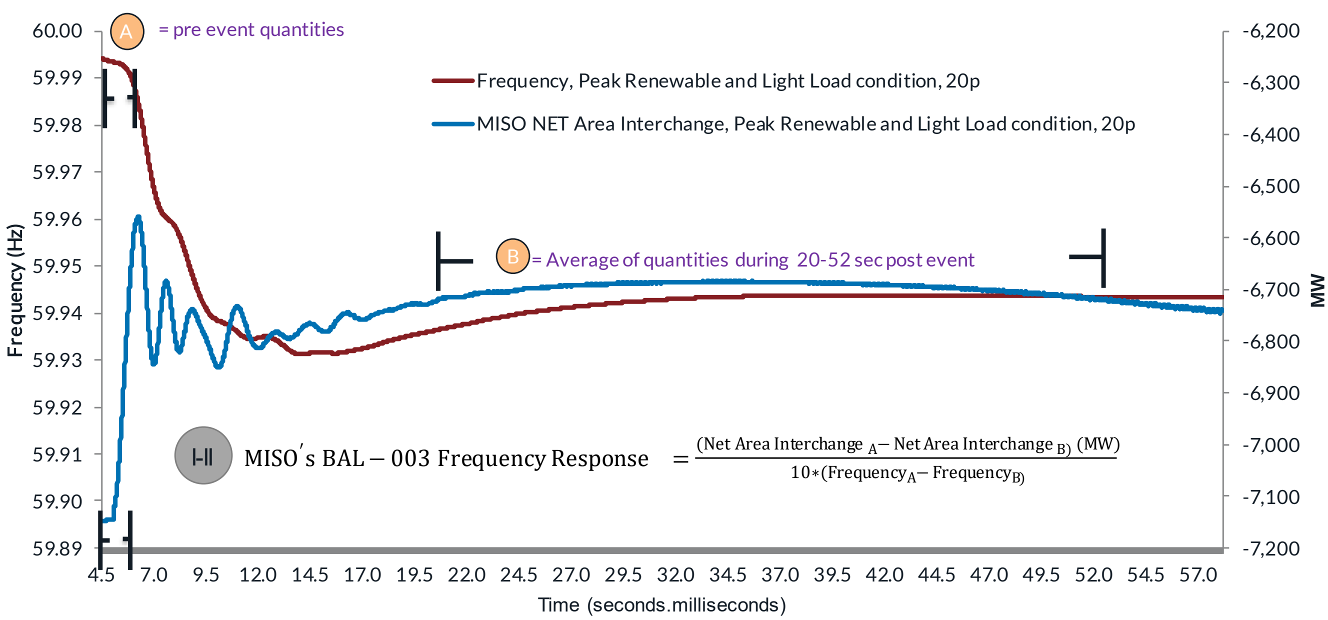


Figure TA-28: MISO's BAL-003-1 obligations are calculated based on Net Area Interchange and Frequency profile

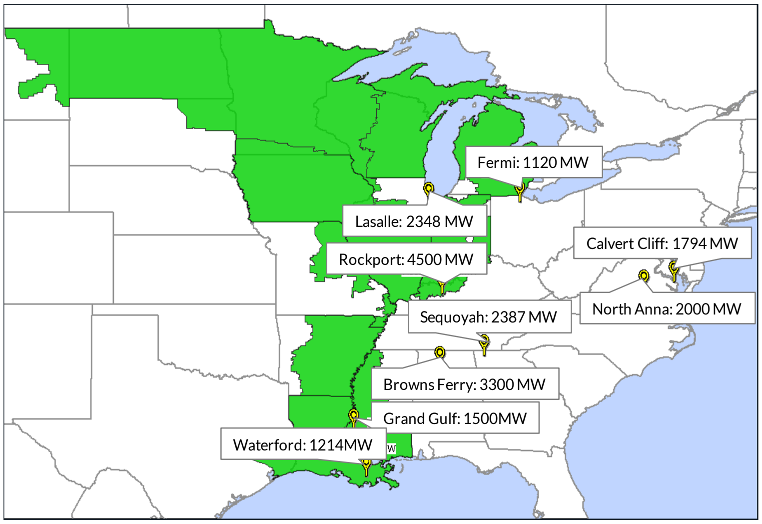


Figure TA-29: Historical large generation loss events are to evaluate frequency response

Benchmarking of models for frequency response study

Through previous model validation efforts, MISO has observed that Eastern Interconnection (EI) wide dynamic models are highly optimistic[49] and do not capture system response realistically, hence MISO incorporated model updates such as modeling asymmetrical dead-bands in existing governor models with generic values (Figure TA-30), removal of governor models for any unit that remain non-response to frequency events (Figure TA-31), and model withdrawal of frequency support by certain units (especially gas unit by utilizing LCFB1[50] model). The base dynamic models were validated against actual system disturbances by utilizing Phasor Measurement Data (PMU) to benchmark against actual system response (Figure TA-30).

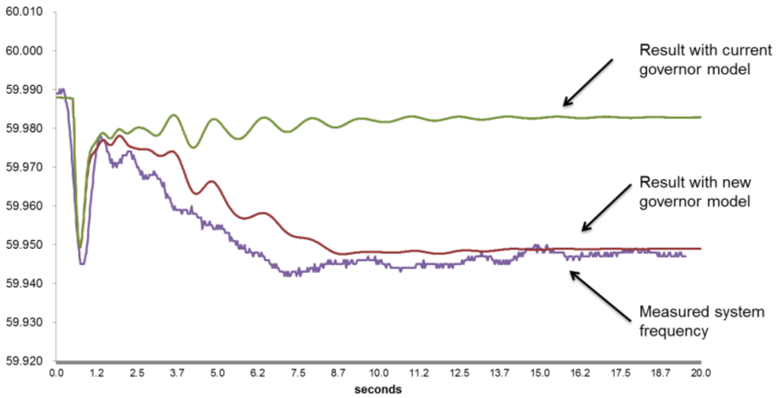
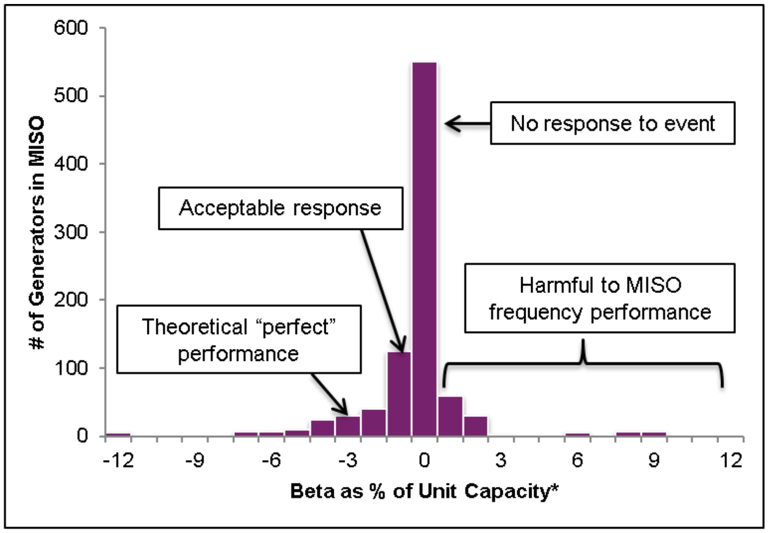


Figure TA-30: Validation results after implementing governor dead-band modeling improvements in dynamics models

[49] N. Mohan, "Governor Modeling improvement", MISO MUGforum, 2017, https://cdn.misoenergy.org/20171003%20MUG%20Item%2003f%20MISO%20Frequency%20Response%20Recommendation199031.pdf

[50] WECC Thermal governor Modeling, https://www.wecc.org/Reliability/WECC%20MVWG%20Thermal%20Governor%20Model%20Revision%202012-06-20.pdf



*Based on real-time MISO data.

Figure TA-31: Non-responsive units were identified through Real-Time Operations and accordingly modelled

Issue identified during the frequency response analysis per NERC 2019 report

The *NERC Reliability Guideline Report*[51] released on June 2019 indicated that some optimism, due to inaccurate individual unit parameters, is observed in units' response (Figure TA-32). Impact of optimism was studied and discussed in the127.

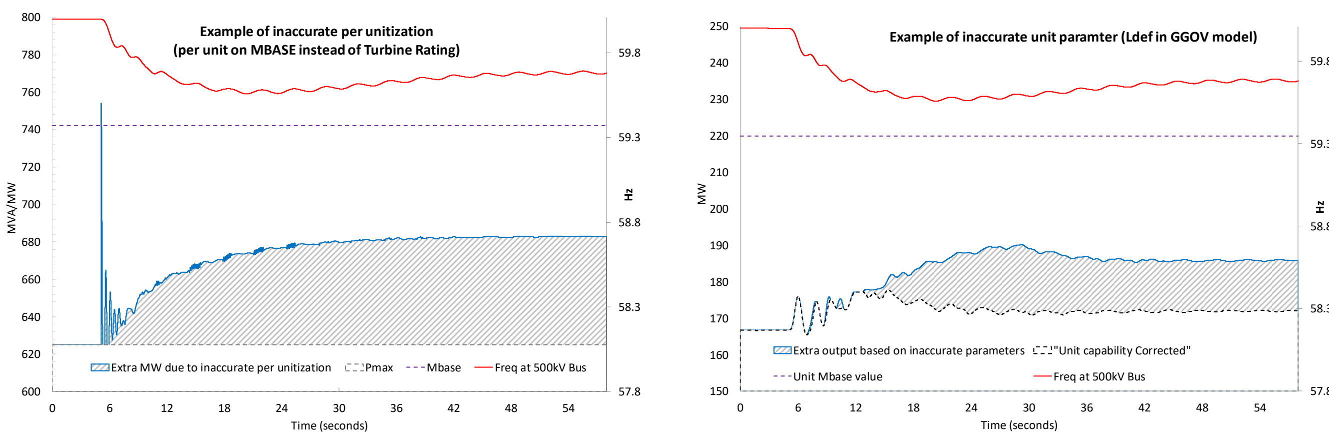


Figure TA-32: Additional optimism in frequency response model due to inaccurate per-unitization and inaccurate unit parameters

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[51] NERC Reliability Guideline : "Application Guide for Modeling Turbine-Governor and Active Power Frequency Controls in Stability Studies", June 2019 available online here

Rotor Angle Stability: Critical Clearing Time Analysis

Historically known stability issues and any new issues identified through other focus areas were studied in this analysis. Local and regional planning criteria were applied for all disturbances simulated. These criteria monitor first swing transient stability, angular oscillation, damping characteristics, line relays, and voltage recovery. The generic PRC-024 frequency and voltage ride-through capability was monitored for all generators with the exception of renewable energy plants or other generating plants that had detailed frequency and voltage capabilities already specified. Generic distance relays were modeled on all lines 100 kV and above with the exception of lines that have detailed relays already specified.

Model REGCAU1; regc_a : RE Converter Model A	PSSE Translation	Parameter Name	Type 3 WTG	Type 4 WTG	Grid Scale PV	Grid Scale Battery
Lvplsw (Low Voltage Power Logic) switch (0: LVPL not present, 1: LVPL present)	M	1	1	1	1	1
Tg, Converter time constant (s)	J	Tg	0.02	0.02	0.02	0.02
Rrpwr, Low Voltage Power Logic (LVPL) ramp rate limit (pu)	J+1	Rrpwr	10	10	10	10
Brkpt, LVPL characteristic voltage 2 (pu)	J+2	Brkpt	0.9	0.9	0.9	0.1
Zerox, LVPL characteristic voltage 1 (pu)	J+3	Zerox	0.5	0.5	0.5	0.05
Lvpl1, LVPL gain (pu)	J+4	Lvpl1	1.22	1.22	1.22	1.22
Volim, Voltage limit (pu) for high voltage reactive current management	J+5	Vtmax	1.2	1.2	1.2	1.2
Lvpnt1, High voltage point for low voltage active current management (pu)	J+6	Lvpnt1	0.8	0.8	0.8	0.2
Lvpnt0, Low voltage point for low voltage active current management (pu)	J+7	Lvpnt0	0.4	0.4	0.4	0.05
Iolim, Current limit (pu) for high voltage reactive current management (specified as a negative value)	J+8	qmin	-1.3	-1.3	-1.3	-1.3
Tfltr, Voltage filter time constant for low voltage active current management (s)	J+9	Tfltr	0.02	0.02	0.02	0.02
Khv, Overvoltage compensation gain used in the high voltage reactive current management	J+10	accel	0.7	0.7	0.7	0.7
Iqrmax, Upper limit on rate of change for reactive current (pu)	J+11	iqrmax	999	999	999	99
Iqrmin, Lower limit on rate of change for reactive current (pu)	J+12	iqrmin	-999	-999	-999	-99
Accel, acceleration factor (0 < Accel ≤ 1)	J+13		0.7	0.7	0.7	0.7

Table TA-43: regc_a Model parameters

WTPTAU1, wtgp_a : Wind Turbine Pitch Controller	PSSE Translation	wtgp_a	Type 3 WTG	Type 4 WTG	Grid Scale PV	Grid Scale Battery
Kiw, Pitch-control Integral Gain (pu)	J	Kiw	25	Do not use this model		
Kpw, Pitch-control proportional gain (pu)	J+1	Kpw	150			
Kic, Pitch-compensation integral gain (pu)	J+2	Kic	30			
Kpc, Pitch-compensation proportional gain (pu)	J+3	Kpc	3			
Kcc, Gain (pu)	J+4	Kcc	0			
Tp, Blade response time constant (s)	J+5	Tpi	0.3			
TetaMax, Maximum pitch angle (degrees)	J+6	Pimax	30			
TetaMin, Minimum pitch angle (degrees)	J+7	Pimin	-5			
RTetaMax, Maximum pitch angle rate (degrees/s)	J+8	Piratmx	10			
RTetaMin, Minimum pitch angle rate (degrees/s) (< 0)	J+9	Piratmn	-10			

Table TA-44: wtgp_a model parameter

WTDTAU1, wtgt_a: Generic Drive Train Model for Type 3 wind machine	PSSE Translation	wtgt_a	Type 3 WTG	Type 4 WTG	Grid Scale PV	Grid Scale Battery
H, Total inertia constant constant (s) (>0)	J	Ht+Hg	5	Do not use this model		
DAMP, Machine damping factor (pu)	J+1	0	0			
Htfrac, Turbine inertia fraction (Ht/H)	J+2	Ht/Hg	0.86			
Freq1, First Shaft Torsional resonant frequency (Hz)	J+3	K	1.7162 +- 0.5 Hz			
Dshaft, Shaft damping factor (pu)	J+4	Dshaft	1.5			
WTARAU1, wtga_a : Generic Aerodynamic Model for Type 3 wind machine	**PSSE Translation**	**wtga_a**	**Type 3 WTG**			
Ka, Aerodynamic gain factor (pu/degrees)	J	Ka	0.007			
Theta 0 Initial pitch angle (degrees)	J+1	Theta0	10			

Table TA-45: Generic drive train wtgt_a and Generic Aerodynamic wtga_a models used for Type-3 wind machines

REECAU1, reec_a : Generic Renewable Electrical Control Model	PSSE Translation	reec_a	Type 3 WTG	Type 3 WTG	Type 4 WTG	Grid Scale PV	Grid Scale Battery
Bus number for voltage control; local control if 0	M	PSSE Remote BUS	<RB>	<RB>	<RB>	<RB>	Do not use this model, used reec_c
PFFLAG (Power factor control flag): 1 if power factor control 0 if Q control (which can be controlled by an external signal)	M+1	pfflag	0	0	0	0	
VFLAG: 1 if Q control 0 if voltage control	M+2	vflag	0	0	0	0	
QFLAG: 1 if voltage or Q control 0 if constant pf or Q control	M+3	qflag	0	0	1	0	
PFLAG: 1 if active current command has speed dependency 0 for no dependency	M+4	pflag	0	0	0	0	
PQFLAG, P/Q priority flag for current limit: 0 for Q priority 1 for P priority	M+5	pqflag	0	0	0	0	
Vdip (pu), low voltage threshold to activate reactive current injection logic	J	vdip	-1	-1	-1	-1	
Vup (pu), Voltage above which reactive current injection logic is activated	J+1	vup	2	2	2	2	
Trv (s), Voltage filter time constant	J+2	Trv	0.02	0.02	0.02	0.02	
dbd1 (pu), Voltage error dead band lower threshold (<=0)	J+3	dbd1	-1	-1	-1	-1	
dbd2 (pu), Voltage error dead band upper threshold (>=0)	J+4	dbd2	1	1	1	1	
Kqv (pu), Reactive current injection gain during over and undervoltage conditions	J+5	kqv	0	0	0	0	
Iqhl (pu), Upper limit on reactive current injection Iqinj	J+6	iqh1	0.001	0.001	0.001	0.001	
Iqll (pu), Lower limit on reactive current injection Iqinj	J+7	iql1	-0.001	-0.001	-0.001	-0.001	
Vref0 (pu), User defined reference (if 0, model initializes it to initial terminal voltage)	J+8	vref0	1	1	1	1	
Iqfrz (pu), Value at which Iqinj is held for Thld seconds following a voltage dip if Thld > 0	J+9	iqfrz	0	0	0	0	
Thld (s), Time for which Iqinj is held at Iqfrz after voltage dip returns to zero	J+10	thld	0	0	0	0	
Thld2 (s) (>=0), Time for which the active current limit (IPMAX) is held at the faulted value after voltage dip returns to zero	J+11	thld2	0	0	0	0	
Tp (s), Filter time constant for electrical power	J+12	Tp_	0.05	0.05	0.05	0.05	
QMax (pu), limit for reactive power regulator	J+13	Qmax_	0.33	0.33	0.33	0.33	
QMin (pu) limit for reactive power regulator	J+14	Qmin_	-0.33	-0.33	-0.33	-0.33	
VMAX (pu), Max. limit for voltage control	J+15	Vmax	1.1	1.1	1.1	1.1	

REECAU1, reec_a : Generic Renewable Electrical Control Model	PSSE Translation	reec_a	Type 3 WTG	Type 3 WTG	Type 4 WTG	Grid Scale PV	Grid Scale Battery
VMIN (pu), Min. limit for voltage control	J+16	Vmin	0.9	0.9	0.9	0.9	
Kqp (pu), Reactive power regulator proportional gain	J+17	kqp	0	0	0	0	
Kqi (pu), Reactive power regulator integral gain	J+18	kqi	0.2	0.2	0.2	0.2	
Kvp (pu), Voltage regulator proportional gain	J+19	kvp	0	0	0	0	
Kvi (pu), Voltage regulator integral gain	J+20	kvi	5 +-2	40 +-10	5 +-2	5 +-2	
Vbias (pu), User-defined bias (normally 0)	J+21	vref1	0	0	0	0	
Tiq (s), Time constant on delay s4	J+22	tiq	0.02	0.02	0.02	0.02	
dPmax (pu/s) (>0) Power reference max. ramp rate	J+23	dpmax	1	1	1	1	
dPmin (pu/s) (<0) Power reference min. ramp rate	J+24	dpmin	-1	-1	-1	-1	
PMAX (pu), Max. power limit	J+25	Pmax_	1.05	1.05	1.05	1.05	
PMIN (pu), Min. power limit	J+26	Pmin_	0.05	0.05	0.05	0.05	
Imax (pu), Maximum limit on total converter current	J+27	imax	1.8	1.8	1.5	1.5	
Tpord (s), Power filter time constant	J+28	Tpord	0.05	0.05	0.05	0.05	
Vq1 (pu), Reactive Power V-I pair, voltage	J+29	vq1	0	0	0	0	
Iq1 (pu), Reactive Power V-I pair, current	J+30	iq1	1.4	1.4	1.4	1.4	
Vq2 (pu) (Vq2>Vq1), Reactive Power V-I pair, voltage	J+31	vq2	0.1	0.1	0.1	0.1	
Iq2 (pu) (Iq2>Iq1), Reactive Power V-I pair, current	J+32	iq2	1.4	1.4	1.4	1.4	
Vq3 (pu) (Vq3>Vq2), Reactive Power V-I pair, voltage	J+33	vq3	0.5	0.5	0.5	0.5	
Iq3 (pu) (Iq3>Iq2), Reactive Power V-I pair, current	J+34	iq3	1.4	1.4	1.4	1.4	
Vq4 (pu) (Vq4>Vq3), Reactive Power V-I pair, voltage	J+35	vq4	1	1	1	1	
Iq4 (pu) (Iq4>Iq3), Reactive Power V-I pair, current	J+36	iq4	1.4	1.4	1.4	1.4	
Vp1 (pu), Real Power V-I pair, voltage	J+37	vp1	0	0	0	0	
Ip1 (pu), Real Power V-I pair, current	J+38	ip1	1.1	1.1	1.1	1.1	
Vp2 (pu) (Vp2>Vp1), Real Power V-I pair, voltage	J+39	vp2	0.1	0.1	0.1	0.1	
Ip2 (pu) (Ip2>Ip1), Real Power V-I pair, current	J+40	ip2	1.1	1.1	1.1	1.1	
Vp3 (pu) (Vp3>Vp2), Real Power V-I pair, voltage	J+41	vp3	0.5	0.5	0.5	0.5	
Ip3 (pu) (Ip3>Ip2), Real Power V-I pair, current	J+42	ip3	1.1	1.1	1.1	1.1	
Vp4 (pu) (Vp4>Vp3), Real Power V-I pair, voltage	J+43	vp4	1	1	1	1	
Ip4 (pu) (Ip4>Ip3), Real Power V-I pair, current	J+44	ip4	1.1	1.1	1.1	1.1	

Table TA-46: Generic Renewable Electrical Control Model for wind and solar models

REECCU1, reec_c : Battery Renewable Electrical Control Model	***PSSE Translation***	***reec_c***	***Grid Scale Battery***
Bus number for voltage control; local control if 0	M	PSSE Remote BUS	<RB>
PFFLAG (Power factor control flag): 1 if power factor control 0 if Q control (which can be controlled by an external signal)	M+1	pfflag	0
VFLAG: 1 if Q control 0 if voltage control	M+2	vflag	1
QFLAG: 1 if voltage or Q control 0 if constant pf or Q control	M+3	qflag	0
PQFLAG, P/Q priority flag for current limit: 0 for Q priority 1 for P priority	M+4	pqflag	0
Vdip (pu), low voltage threshold to activate reactive current injection logic	J	vdip	-99
Vup (pu), Voltage above which reactive current injection logic is activated	J+1	vup	99
Trv (s), Voltage filter time constant	J+2	Trv	0.01
dbd1 (pu), Voltage error dead band lower threshold (<=0)	J+3	dbd1	-0.05
dbd2 (pu), Voltage error dead band upper threshold (>=0)	J+4	dbd2	0.05
Kqv (pu), Reactive current injection gain during over and undervoltage conditions	J+5	kqv	15
Iqhl (pu), Upper limit on reactive current injection Iqinj	J+6	iqh1	0.75
Iqll (pu), Lower limit on reactive current injection Iqinj	J+7	iql1	-0.75
Vref0 (pu), User defined reference (if 0, model initializes it to initial terminal voltage)	J+8	vref0	1
Tp (s), Filter time constant for electrical power	J+9	Tp	0.05
QMax (pu), limit for reactive power regulator	J+10	Qmax	0.75
QMin (pu) limit for reactive power regulator	J+11	Qmin	-0.75
VMAX (pu), Max. limit for voltage control	J+12	Vmax	1.1
VMIN (pu), Min. limit for voltage control	J+13	Vmin	0.9
Kqp (pu), Reactive power regulator proportional gain	J+14	kqp	0
Kqi (pu), Reactive power regulator integral gain	J+15	kqi	1
Kvp (pu), Voltage regulator proportional gain	J+16	kvp	0
Kvi (pu), Voltage regulator integral gain	J+17	kvi	1
Tiq (s), Time constant on delay s4	J+18	tiq	0.017
dPmax (pu/s) (>0) Power reference max. ramp rate	J+19	dpmax	99
dPmin (pu/s) (<0) Power reference min. ramp rate	J+20	dpmin	-99
PMAX (pu), Max. power limit	J+21	Pmax_	1
PMIN (pu), Min. power limit	J+22	Pmin_	-0.667
Imax (pu), Maximum limit on total converter current	J+23	imax	1.11

REECCU1, reec_c : Battery Renewable Electrical Control Model	*PSSE Translation*	*reec_c*	*Grid Scale Battery*
Tpord (s), Power filter time constant	J+24	Tpord	0.017
Vq1 (pu), Reactive Power V-I pair, voltage	J+25	vq1	0
Iq1 (pu), Reactive Power V-I pair, current	J+26	iq1	0.75
Vq2 (pu) (Vq2>Vq1), Reactive Power V-I pair, voltage	J+27	vq2	0.2
Iq2 (pu) (Iq2>Iq1), Reactive Power V-I pair, current	J+28	iq2	0.75
Vq3 (pu) (Vq3>Vq2), Reactive Power V-I pair, voltage	J+29	vq3	0.2
Iq3 (pu) (Iq3>Iq2), Reactive Power V-I pair, current	J+30	iq3	0.75
Vq4 (pu) (Vq4>Vq3), Reactive Power V-I pair, voltage	J+31	vq4	1
Iq4 (pu) (Iq4>Iq3), Reactive Power V-I pair, current	J+32	iq4	0.75
Vp1 (pu), Real Power V-I pair, voltage	J+33	vp1	0.2
Ip1 (pu), Real Power V-I pair, current	J+34	ip1	1.11
Vp2 (pu) (Vp2>Vp1), Real Power V-I pair, voltage	J+35	vp2	0.5
Ip2 (pu) (Ip2>Ip1), Real Power V-I pair, current	J+36	ip2	1.11
Vp3 (pu) (Vp3>Vp2), Real Power V-I pair, voltage	J+37	vp3	0.75
Ip3 (pu) (Ip3>Ip2), Real Power V-I pair, current	J+38	ip3	1.11
Vp4 (pu) (Vp4>Vp3), Real Power V-I pair, voltage	J+39	vp4	1
Ip4 (pu) (Ip4>Ip3), Real Power V-I pair, current	J+40	ip4	1.11
T, battery discharge time (s) (>0)	J+41	T	999
SOCini (pu), Initial state of charge	J+42	SOCini	0.5
SOCmax (pu), Maximum allowable state of charge	J+43	SOCmax	0.8
SOCmin (pu), Minimum allowable state of charge	J+44	SOCmin	0.2

Table TA-47: Generic Renewable Electrical Control Model for grid scale battery

REPCAU1, repc_a : Generic Renewable Plant Control Model: All plant modelled with Voltage Control at POI + Primary Frequency Response	PSSE Translation	repc_a	Type 3 WTG (1st type) 5% droop 36mHz dead-band	Type 3 WTG : (2nd Type) 5% droop 36mHz dead-band	Type 4 WTG 5% droop 36mHz dead-band	Grid Scale PV 5% droop 36mHz dead-band	Grid Scale Battery with High Droop, 5mHz dead-band
Difference in PSSE dyr format			IBUS, 'USRMDL', ID, 'REPCTAU1', 107, 0, 7, 27, 7, 9,	IBUS, 'USRMDL', ID, 'REPCTAU1', 107, 0, 7, 27, 7, 9,	IBUS, 'USRMDL', ID, 'REPCAU1', 107, 0, 7, 27, 7, 9,	IBUS, 'USRMDL', ID, 'REPCAU1', 107, 0, 7, 27, 7, 9,	IBUS, 'USRMDL', ID, 'REPCAU1', 107, 0, 7, 27, 7, 9,
Bus number for voltage control; local control if 0	M	<Remote bus (RB)>	<RB>	<RB>	<RB>	<RB>	<RB>
Monitored branch FROM bus number for line drop compensation (if 0 generator power will be used)	M+1	<Low side of Interconnecting Transformer to BES BUS>	<Low side of Interconnecting Transformer to BES BUS>	<Low side of Interconnecting Transformer to BES BUS>	<Low side of Interconnecting Transformer to BES BUS>	<Low side of Interconnecting Transformer to BES BUS>	<Low side of Interconnecting Transformer to BES BUS>
Monitored branch TO bus number for line drop compensation (if 0 generator power will be used)	M+2	<High side of Interconnecting Transformer to BES BUS>	<High side of Interconnecting Transformer to BES BUS>	<High side of Interconnecting Transformer to BES BUS>	<High side of Interconnecting Transformer to BES BUS>	<High side of Interconnecting Transformer to BES BUS>	<High side of Interconnecting Transformer to BES BUS>
Branch circuit id for line drop compensation (enter in single quotes) (if 0 generator power will be used)	M+3	<Interconnecting Transformer ckt ID>	<Interconnecting Transformer ckt ID>	<Interconnecting Transformer ckt ID>	<Interconnecting Transformer ckt ID>	<Interconnecting Transformer ckt ID>	<Interconnecting Transformer ckt ID>
VCFlag (droop flag): 0: with droop if power factor control 1: with line drop compensation	M+4	vcmpflg	0	0	0	0	1
RefFlag (flag for V or Q control): 0: Q control 1: voltage control	M+5	refflg	1	1	1	1	1
Fflag (flag to disable frequency control): 1: Enable control 0: disable	M+6	frqflg	1	1	1	1	1
Tfltr, Voltage or reactive power measurement filter time constant (s)	J	Tfltr_	0.02	0.02	0.02	0.02	0.02
Kp, Reactive power PI control proportional gain (pu)	J+1	Kp	10 +- 10%	4 +- 10%	10 +- 10%	10 +- 10%	0
Ki, Reactive power PI control integral gain (pu)	J+2	Ki	5 +- 10%	2 +- 10%	5 +- 10%	5 +- 10%	0.0001
Tft, Lead time constant (s)	J+3	Tft	0	0	0	0	0
Tfv, Lag time constant (s)	J+4	Tfv	0.05	0.05	0.05	0.05	0.05
Vfrz, Voltage below which State s2 is frozen (pu)	J+5	vfrz	0.7	0.7	0.7	0.7	0
Rc, Line drop compensation resistance (pu)	J+6	rc	0	0	0	0	0
Xc, Line drop compensation reactance (pu)	J+7	xc	0	0	0	0	0
Kc, Reactive current compensation gain (pu)	J+8	Kc	0.02 (in the range 0.02 - 0.04)	0.02 (in the range 0.02 - 0.04)	0.02 (in the range 0.02 - 0.04)	0.02 (in the range 0.02 - 0.04)	0

REPCAU1, repc_a : Generic Renewable Plant Control Model: All plant modelled with Voltage Control at POI + Primary Frequency Response	PSSE Translation	repc_a	Type 3 WTG (1st type) 5% droop 36mHz dead-band	Type 3 WTG : (2nd Type) 5% droop 36mHz dead-band	Type 4 WTG 5% droop 36mHz dead-band	Grid Scale PV 5% droop 36mHz dead-band	Grid Scale Battery with High Droop, 5mHz dead-band
emax, upper limit on deadband output (pu)	J+9	emax	0.1	0.1	0.1	0.1	0.1
emin, lower limit on deadband output (pu)	J+10	emin	-0.1	-0.1	-0.1	-0.1	-0.1
dbd1, lower threshold for reactive power control deadband (<=0)	J+11	dbd	0	0	0	0	0
dbd2, upper threshold for reactive power control deadband (>=0)	J+12	dbd	0	0	0	0	0
Qmax, Upper limit on output of V/Q control (pu)	J+13	Qmax	0.33	0.33	0.33	0.33	0.75
Qmin, Lower limit on output of V/Q control (pu)	J+14	Qmin__	-0.33	-0.33	-0.33	-0.33	-0.75
Kpg, Proportional gain for power control (pu)	J+15	kpg	0.2-.27	0.2-.27	0.2-.27	0.2-.27	1
Kig, Proportional gain for power control (pu)	J+16	kig	0.2-.27	0.2-.27	0.2-.27	0.2-.27	0
Tp, Real power measurement filter time constant (s)	J+17	Tp	0.05	0.05	0.05	0.05	0.25
fdbd1, Deadband for frequency control, lower threshold (<=0)	J+18	fdbd1	-0.0006	-0.0006	-0.0006	-0.0006	-0.0000833
Fdbd2, Deadband for frequency control, upper threshold (>=0)	J+19	fdbd2	0.0006	0.0006	0.0006	0.0006	0.0000833
femax, frequency error upper limit (pu)	J+20	femax	0.05	0.05	0.05	0.05	99
femin, frequency error lower limit (pu)	J+21	femin	-0.05	-0.05	-0.05	-0.05	-99
Pmax, upper limit on power reference (pu)	J+22	pmax	1.05	1.05	1.05	1.05	1
Pmin, lower limit on power reference (pu)	J+23	pmin	0.05	0.05	0.05	0.05	-0.667
Tg, Power Controller lag time constant (s)	J+24	tlag	0.1	0.1	0.1	0.1	0.1
Ddn, reciprocal of droop for over-frequency conditions (pu)	J+25	ddn	20	20	20	20	126
Dup, reciprocal droop for under-frequency conditions (pu)	J+26	dup	20	20	20	20	126

Table TA-48: Generic Renewable Plant Control Model

Background and Outside Studies

The scope for RIIA was developed based on the lessons learned and conclusions from past studies both performed by MISO and other industry groups. RIIA seeks to overcome limitations seen in previous studies and provide a more complete understanding of integration issues for the MISO region as well as create a more complete and comprehensive study process. Even with this view, limitations exist in RIIA that require additional considerations that were only lightly touched or were outside the scope entirely as discussed below in Gaps in Analysis.

Background Studies

Minnesota Renewable Energy Integration and Transmission Study (MRITS)

https://mn.gov/commerce/industries/energy/distributed-energy/mrits.jsp

Relevant Findings:

- 40-50% Renewable in Minnesota
- 20% MISO wide

Regional Generation Outlet Study (RGOS)

A multi-year study on how to integrate state-mandated wind into MISO

https://www.misoenergy.org/Planning/Pages/RegionalGenerationOutletStudy.aspx

Relevant Finding:

- ~20% Renewable MISO Midwest

Eastern Wind Integration and Transmission Study (EWITS)

https://www.nrel.gov/docs/fy11osti/47078.pdf

Relevant Finding:

- 20% Renewable Eastern Interconnect

Eastern Renewable Generation Integration Study (ERGIS)

https://www.nrel.gov/grid/ergis.html

Relevant Finding:

- 30% Renewable Eastern Interconnect

Western Wind and Solar Integration Study (WWSIS)

https://www.nrel.gov/grid/wwsis.html

Relevant Finding:

- 35% Renewable Western Interconnect

PJM Renewable Integration Study (PRIS)

http://www.pjm.com/committees-and-groups/subcommittees/irs/pris.aspx

Relevant Finding:

- 30% Renewable PJM

2016 SPP Wind Integration Study

https://www.spp.org/documents/34200/2016%20wind%20integration%20study%20(wis)%20final.pdf

Relevant Finding:

- Looked at 60% peak renewable rather than % of energy.

Minnesota Solar Pathways

http://mnsolarpathways.org/

Relevant Finding:

- Studied 10% Solar by 2030 in Minnesota and 70% Renewables by 2050 in Minnesota

External Resources

Other resources were reviewed to inform the design of this assessment.

NERC Essential Reliability Services Sufficiency Guideline Report

http://www.nerc.com/comm/Other/essntlrlbltysrvcstskfrcDL/ERSWG_Sufficiency_Guideline_Report.pdf

NERC Essential Reliability Services Task Force Measures Framework Report

http://www.nerc.com/comm/Other/essntlrlbltysrvcstskfrcDL/ERSTF%20Framework%20Report%20-%20Final.pdf

2011 Wind Technologies Market Report

https://emp.lbl.gov/sites/all/files/lbnl-5559e.pdf

Relevant Finding: Figure AC-1.

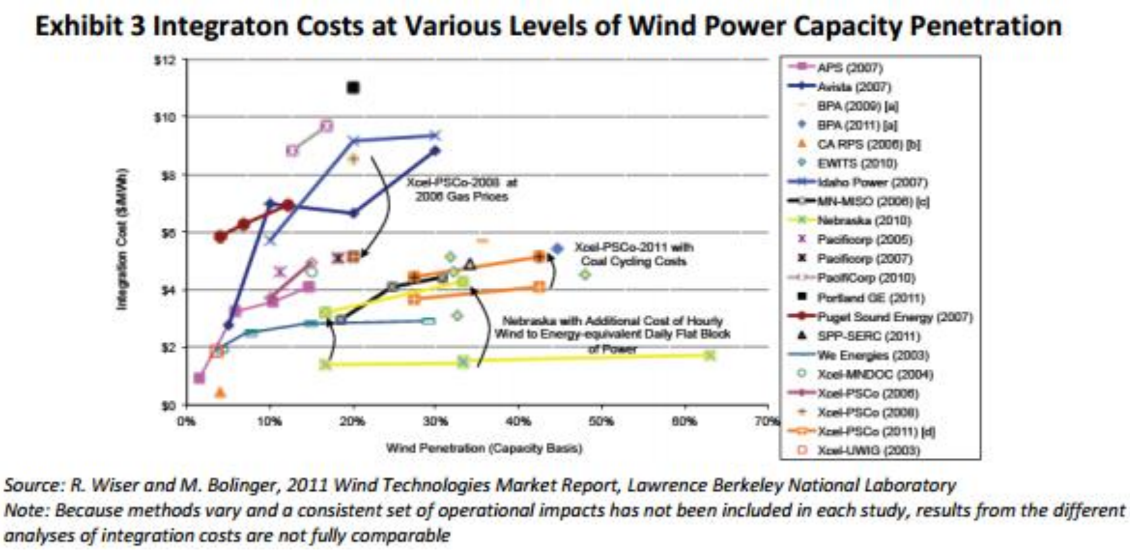

Figure AC-1: Inflection Point Example from the 2011 *Wind Technologies Market Report* (Page 64))

Gaps In Analysis

To fully understand the impacts of the increasing amounts of wind and solar generation in a specific electrical area, a broad suite of models and views must be examined. For RIIA, the same models and assumptions were used across the entire geographic and time scales. However, assumptions and compromises were made to keep consistency and to conduct the work in a reasonable time frame.

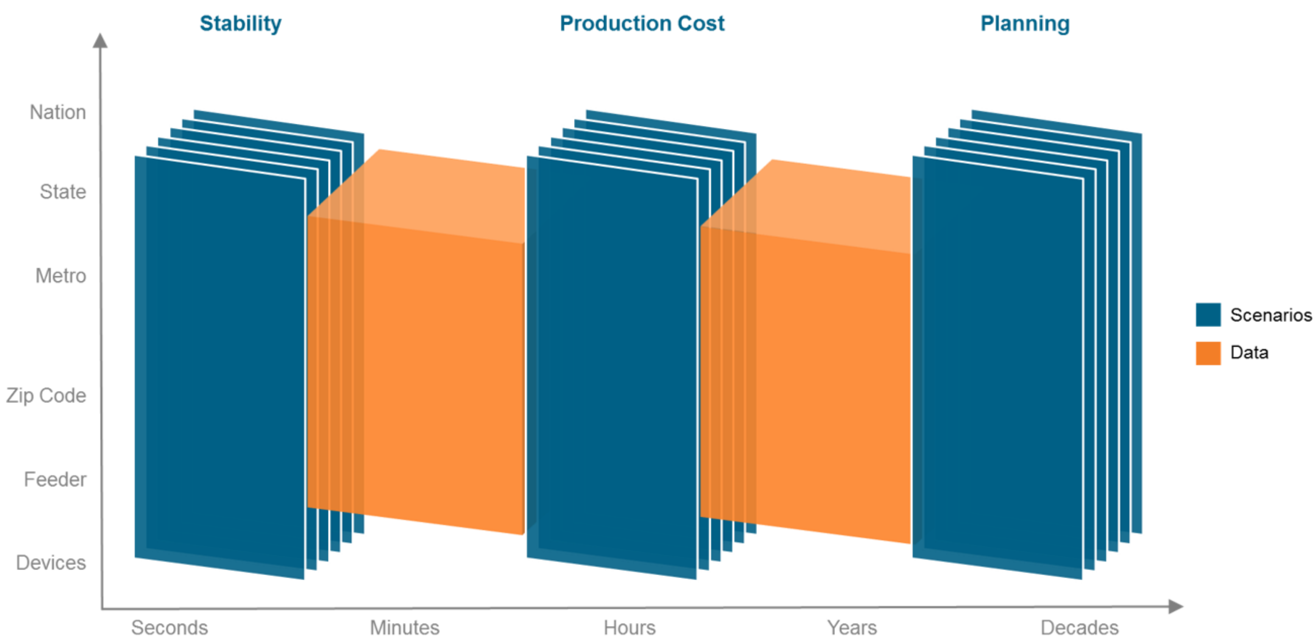

Figure AC-2: Variety models for different geographic and temporal resolutions (Source: *NREL)*

The majority of the analysis was conducted on a single planning scenario to keep consistency between the detailed geographic and time scale modeling and the more general modeling. This limitation was addressed by examining the impacts of technology, at different penetration levels, on specific geographic areas (Figure AC-2). In addition, analyses were done to understand the effects key assumptions had on the results. Sensitivity analysis was also conducted in the energy market modeling and resource adequacy areas to look at other scenario combinations.

The majority of the analysis was based on a single weather year (2012). Other analyses found this to be the most recent representative weather year when the RIIA began in 2017; however, this limited the ability to see weather outliers and their effect on the results. This shortcoming was partially addressed by using a series of weather years from 2007-2017 for the Resource Adequacy analysis. Data analytics was also used to understand ramping and other behavior across the years.

Limited analysis was conducted for the timeframe between 1 and 60 minutes. This was primarily due to the lack of good data, models and the difficulties of performing the analysis. This was partially addressed through data analytics of 5-minute time series data and studying select 5-minute periods. Additional work is needed to look at 5-minute energy market performance over an entire year and generator performance when responding to Ancillary Service calls.

Work outside of MISO has addressed some of these limitations, looking at different power systems and wind and solar penetration scenarios. Lessons can be learned to inform future work by comparing RIIA findings and other industry work products.

Frequently Asked Questions (FAQ)

General

(Q1) **How is RIIA different than other renewable studies in North America?**

- RIIA employed highly detailed siting of renewable generation in a way to mimic the way actual renewable generation may be sited in the future. Other studies have sited renewable generation in a more clustered way. For instance, some studies examined only clustered renewable generation around retired coal and other thermal plants.
- RIIA studied actual dispatch & load levels generated from a production cost model. A process was used to identify the expected most stressful 3 hours (snapshots) from the 8760 hours simulated; then those snapshots were studied in the Operating Reliability realm to identify facility upgrades needed for a secure system with the high level of renewable generation added, up to the 50% milestone; in those snapshots, the renewable penetration rose as high as 89% of load being served by renewable power.
- In the Operating Reliability realm, studies examined reliability for thermal, voltage, frequency, rotor angle stability, and small-signal inter-area issues. Facilities were added to the models to mitigate any reliability standards not met.

(Q2) **What do the percentage penetrations mean?**

The calculated penetrations in this study are done on a regional basis for MISO or the EI, as specified in this report. The percentage values mean two things.

- The milestone values, like 40%, represent the proportion of MISO load energy served annually by renewable energy resources. Any percentage paired with “milestone” can be interpreted in this way.
- In some parts of the work, analyses examine the so-called “instantaneous” penetration, which represents the portion of MISO load demand (MW) served by renewable resources at a particular moment in time. The instantaneous penetration at a specific day and hour of a milestone may be much higher than overall annual energy penetration. The calculated penetrations in this study are done on a regional basis for MISO or the EI, as specified in this report.

(Q3) **Will MISO post transmission constraints and solicit for transmission solutions to ensure cost-effective solutions are identified?**

The purpose of RIIA isn’t to identify individual constraints or lines. Rather it is to show the general types, locations and risks seen in order to help frame future work. For this reason, MISO will not publish detailed solution data and costs.

(Q4) **Which states belong to each subregion?**

MISO North comprises North and South Dakota, Minnesota, Wisconsin, and Iowa. MISO Central includes Illinois, Indiana, Michigan, Missouri, and Kentucky. MISO South consists of Arkansas, Louisiana, Mississippi, and Texas. Several states, including Texas, have utilities that are not a part of MISO.
Is the complexity metric basically equal to the cost of integrating renewables into the MISO system? Is it quantitative or qualitative? Has the complexity been scaled at all?
Understanding Renewable Complexity describes the quantitative complexity in creating the chart. MISO attempted to quantify the cost of solutions for each focus area. Given that there is subjectivity in the quantitative exercise of developing costs, it makes more sense to focus on the relative scale rather than the specific numbers. Using the relative scale also allows for consideration of other issues. For example,

unexpected difficulties in siting, routing, procuring materials and construction crew availability could also be considered. The complexity has not been scaled.

(Q5) **Why hasn't MISO released the underlying data for the complexity chart?**

MISO has chosen not to release the specific data, as MISO believes it distracts from the purpose of the work. The purpose is not to develop specific plans or give specific costs, although they were necessary to create the conclusions and graphics. The purpose is to understand the implications of increasing renewable penetration in the MISO region and to highlight the specific causes and timing of challenges; inform ongoing focus; and plans needed to address them. MISO decided to not disclose the detailed solutions, because RIIA is not a transmission planning study. It is a proof-of-concept study to show how the MISO system could operate reliably up to 50% renewable energy with existing technology. The section *Solutions* includes the general cost assumptions and types of technologies considered when analyzing options.

(Q6) **Does the system break at 30% and cause the need for rolling blackouts? Where is the "Houston, we have a problem" point?**

RIIA found the challenges to integrate renewables increase as the penetration increases, with a stark escalation occurring between the 30-40% penetration levels. However, even at the 50% milestone, the system can still operate reliably once solutions utilizing existing technology are deployed. MISO did not find any milestones of the system being inoperable, up to the 50% milestone studied.

(Q7) **Is the inflection point near 30% caused by issues distributed throughout the MISO footprint, or are the issues localized to a particular region?**

The challenges at 30% penetration are spread across an extensive area. Although there are local pockets with higher penetrations of renewables (some at 60% of the local load energy), the risk is associated with a wide area.

(Q8) **What is the specific starting point for each milestone's models?**

The starting point for each milestone model (for instance, the 40% milestone models), unless otherwise noted, is the prior milestone models (for instance, the 30% milestone models) including all transmission solutions needed to securely meet the 30% energy penetration.

(Q9) **What is the difference between Phase 1, Phase 2, Phase 2s, and Phase 3?**

Phases 1 through 3 reflect the progress of RIIA, in which:

- Phase 1 includes the completion of Resource Adequacy from 10% to 100% milestone, and completion of Energy Adequacy and Operation Reliability from 10% to 30% milestone
- Phase 2 includes completion of Energy Adequacy and Operational Reliability from 40% to the 50% milestone
- Phase 2s examines Sensitivities of the Phase 2 models by altering key model assumptions
- Phase 3 combines multiple Sensitivities and creates the final Energy Adequacy and Resource Adequacy models, again from 10% to 50% milestone.

For the purpose of this report the Phase terminology was not used as it was meant to mark progress during the analysis rather than mark distant parts of the work.

(Q10) **Does MISO believe the insights gained from the RIIA may be impacted by the difference between the siting of MISO RIIA analysis and where project developers will ultimately choose to site their projects?**

In RIIA, the siting sought a balance between good resource areas, proximity to load, available transmission capacity and actions taken by developers (i.e. interconnection activity). MISO views the RIIA siting as a reasonable representation of future developer activity but recognizes that renewable siting is very difficult to predict. MISO does not believe that the differences between its siting assumptions and actual renewable development will impact the insights described.

(Q11) **How has the RIIA work already been integrated into other MISO studies?**

MISO is referencing RIIA simulation results of hourly wind and solar generation to evaluate key assumptions in the Reliability Planning Models. Model assumptions and findings in RIIA Resource Adequacy and Energy Adequacy focus areas also serve as valuable references for MISO to explore future challenges to Resource Availability and Need (RAN) in market operation, given continued shifts in resource mix.

(Q12) **Has MISO thought of doing localized transmission solutions?**

Local and regional transmission solutions were employed as deemed necessary to meet reliability standards.

Next Steps

(Q13) **Where will the results of this study be used?**

RIIA assessed the broad implications of increasing amounts of wind and solar in the MISO footprint. The work looks at broad areas such as resource availability and variability, transmission, and stability. RIIA is actively other areas and studies as applicable. MISO expects several future studies will build on the insights from RIIA. Some of the processes developed in RIIA are currently being utilized in MISO planning processes as part of the Long-Range Transmission Plan (LRTP); for example, RIIA aided in determining ways wind and solar units should be dispatched in MTEP reliability models. Areas of future focus are discussed in the Executive Summary.

(Q14) **Given that the demand forecast and baseline generation assumptions used in RIIA, based on MTEP19, are very different than those used in MTEP21, will MISO re-perform the RIIA study with updated assumptions from MTEP?**

RIIA was designed to understand the risks of increasing wind and solar levels in the MISO footprint and to help shape the scope of future work related to those risks. Analyses included several sensitivities to test input assumptions. Thus, MISO believes the results and recommendations are robust for that purpose. MISO has no plans to redo the RIIA work to align with different input assumptions from other MISO studies.

(Q15) **The optimization process used by MISO in RIIA considered approximately 11,000 transmission project candidates between major high voltage substations across the MISO footprint. Some projects must have demonstrated superior adjusted production cost (APC) benefits to others. There are also significant differences in load forecasts between MTEP19 and MTEP21. Does MISO intend to introduce these projects into the MTEP21 process? If yes, as what type of project?**

RIIA is not a transmission planning study. Transmission solutions have been shared to inform other MISO planning processes, such as the Long-Range Transmission Plan (LRTP), but each will have to perform according to the requirements of the individual study and its use in RIIA will not play a role.

(Q16) **Are the issues only regional or interregional? Can MISO post information about interregional issues to supplement LRTP discussions?**

Some issues are regional, and some are interregional. For example, some reliability issues (thermal and voltage) are regional, while some of issues (frequency and small-signal inter-area oscillation) are interregional. The regional and interregional violations and mitigations have been covered in this report and in the RIIA workshops and presentations.

(Q17) **Will MISO develop the transmission projects identified by RIIA?**

The purpose of RIIA is not to identify actionable solutions. Instead, MISO determined the timing and nature of transmission or storage needs in a future system with a high penetration of renewables. MISO expects that the actual development of generation and transmission will differ from the assumptions and solutions of RIIA, but thinks the study is representative of the needs of a high renewable future.

Siting and System Assumptions

(Q18) **Why does MISO examine renewable integration over the entire Eastern Interconnection?**

It is important to model the renewable expansion expected in the entire Eastern Interconnection, because this study specifically examines the addition of renewables to find out when the existing system is stressed. If renewables were only added within the MISO footprint, the study might understate the potential complexity because MISO would be able to easily export low-cost energy to areas outside of MISO and take advantage of the ramping capabilities of the thermal units of MISO's less-stressed neighbors in simulations of system behavior.

(Q19) **How diverse is wind output across MISO?**

Wind diversity is quite large. Some areas of the MISO footprint have wind capacity factors nearing 50%, while others have capacity factors less than 10%.

(Q20) **Did RIIA use existing grid topology and conditions, and were studies done considering batteries as solutions, as opposed to transmission?**

RIIA starts with the system as it was in late 2017 (with a 5-year-out transmission model representing the 2022 expected transmission topology) and builds forward from that starting point. Generation and topology were changed as needed to achieve the analysis targets. The energy storage sensitivity analysis examined the ability of batteries to aid in enabling renewable energy to serve load.

(Q21) **Were other resources added beyond renewables?**

Some units were "un-retired" for stability purposes. No other resources were added.

(Q22) **Does MISO plan to examine the potential for adding more gas and thermal capacity, and how to rely on those units in the transition to a system with a high penetration of renewable energy?**

The focus of the RIIA study is to look at renewable generation development within MISO. Siting new gas and thermal generation was not considered, though the analysis does look at how thermal units support the transition through flexibility.

(Q23) **Why initially use the 75:25 wind to solar ratio? And would the results change significantly from a different ratio of wind to solar?**

When the RIIA study was initiated, the 3:1 capacity ratio between wind and solar aligned with historic and near-term MISO generation interconnection queue. In the subsequent years, solar technology has rapidly decreased in cost, leading to a higher proportion of solar in the MISO interconnection queue. The sensitivity analysis examined the relative mix of wind and solar capacity by modifying the siting assumptions, such that the wind and solar capacity mix reached an even split by the 50% milestone. That work did not demonstrate significantly different performance than the original work with 3:1 capacity ratio. Additional work has shown the general conclusions hold.

(Q24) **What study year and season was used for the study? Are the wind profiles and solar profiles for a specific year?**

For the Resource Adequacy work, the years were 2007 through 2012 and all seasons, based on the best data availability. In addition, some sensitivities used 2014 through 2018. For the Energy Adequacy work, 2012 was selected as the most representative weather year, so the wind, solar, and load profile shapes from 2012 were used.

(Q25) **Did MISO study multi-day, low-wind periods?**

MISO studied both high and low wind periods, based on historical weather.

(Q26) **Do the wind farms in MISO North generally peak at the same time because they see weather systems at the same time?**

No, due to the large geographic area of the region. As weather fronts move through the MISO footprint, there is a wide variety of wind output.

(Q27) **Does MISO assume uniform penetrations across the footprint?**

The penetration and impact are different at certain locations — wind-rich or solar-rich. The solar irradiance values and wind speed values come from industry hourly data at a granular level by geography across the study area.

(Q28) **What were the renewable energy targets and to where was the energy delivered?**

The purpose of RIIA is to understand higher renewable penetrations in MISO and to determine the system risk. As such, analysis target milestones were set in 10% increments of annual renewable energy serving MISO-wide load, rather than examining targets set by states or utilities. Renewable generation within MISO was targeted to serve load within MISO, but some interchange with MISO's neighbors was permitted. The study stopped at the 50% milestone due to stakeholder feedback and indicated that MISO would need to make significantly different assumptions beyond that point.

(Q29) **Is there more exploration of non-traditional solutions?**

Phase 3 of the RIIA studies explored battery storage.

(Q30) **Will RIIA consider more demand-side resources?**

RIIA's scope did not include considering demand-side resources other than limited DER and demand-side storage.

(Q31) **Were hybrid plants studied?**

Hybrid plants were studied in Phase 3 of RIIA.

(Q32) **Has MISO thought about replacing renewables with nuclear units, since they are comparable from a decarbonization perspective?**

RIIA was not a decarbonization study.

Resource Adequacy

(Q33) **When considering ELCC for solar, solar does a good job of addressing gross peak of solar, but not so much at net peak. How can that be communicated?**

Similar to other studies, RIIA indicates that as renewable penetration increases, the risk of losing load shifts to later in the day i.e. from noon to later in the evening. It should be noted that these periods of risk are not necessarily the period of highest gross load but are periods of highest net-load (gross load minus total renewable output).This shift in risk is therefore primarily driven by adding more solar to the system which moves the net-load peak to later hours of the day. ELCC as measure of capacity contribution looks at the availability of a resource to meet load during the period of highest risks, which as more solar is added becomes less coincident with peak solar output. This phenomenon drives the ELCC of solar to decline. Thus, the current process leads to a situation where solar gets lower ELCC numbers, even though it is available during the period of the gross load.

(Q34) **Is there an optimal mix of wind and solar?**

The goal of RIIA was not to identify the optimal mix of wind and solar. The optimal mix is highly dependent on cost assumptions and future system configuration.

(Q35) **Does the dispatch of storage get applied to the same 6-hour window, or does it adjust accordingly as the net load peak shifts?**

Referring to the LOLP curves, it can be observed that the software does apply dispatch outside the net-load peak; a flattening of the curve is seen, indicating that it applies it outside the peak.

Energy Adequacy — Market and Operation

(Q36) **How does the "must-run" assumption work in RIIA simulations?**

If a unit is must-run in the current market, then it's assumed it will still be must-run in the future. A sensitivity analysis has been done by assuming none of the units will be must-run.

(Q37) **Why are there negative prices even with solar and wind at 0 $/MWh?**

The negative prices are due to excessive energy. When online capacity is greater than load, there will be excessive energy due to the inability of some resources to ramp down in a sufficient amount of time; this will result in scarcity of downward regulation and possible negative prices.

(Q38) **How did MISO achieve 40% renewable penetration when there is 80% self-scheduled thermal?**

Must-run is a commitment concept, MISO market separates the market operation processes into commitment and energy dispatch, the 80% of must-run thermal is just commitment. When a unit is must-run, the energy MW is still being optimized instead of defaulting to maximal capacity. Energy from all thermal must-run is way lower than 80%.

(Q39) **Solar drop at sunset is very well known. If a 36-hour commitment time frame is used, why are capacity shortages seen in real time?**

Solar drops at sunset is well known but there is still uncertainty around pace and quantity. In practice, MISO often defers out-of-market commitment to the last feasible point and any unforeseen uncertainty will add flexibility pressure on that period which already consumes a lot of ramping capabilities from the fleet.

Energy Adequacy — Planning

(Q40) **How does MISO determine the sufficient amount of curtailment?**

The production cost model solves unit commitment and dispatch by fulfilling load while minimizing total production cost and honoring transmission constraints; hence renewable curtailment is the modeling result highly dependent on assumptions of renewable profile and transmission constraints. For the purpose of this study a threshold was determined to deem a maximum amount of curtailment that would be allowed. This was done since the purpose of RIIA was to measure the complexity of delivering specific percentages of renewable power.

(Q41) **Is the transmission expansion solely driven by thermal violations?**

Transmission expansion is mostly driven by the need to deliver renewable energy from remote load centers. Expansion drivers include congestion, thermal and voltage violations and stability violations.

(Q42) **Are the energy adequacy solutions transmission solutions?**

Energy adequacy solutions are primarily transmission solutions.

(Q43) **Were non-transmission solutions considered?**

The study considers non-transmission solutions, including energy storage, re-siting of renewable generation plants, un-retiring units, increased reserve requirements, or additional fast-ramping generation at various stages of the process.

(Q44) **Did MISO consider dynamic thermal ratings?**

Utilization of dynamic thermal ratings is generally considered as a tool used in operations to alleviate congestion, as it requires knowledge of ambient temperature variation to accurately calculate line ratings. Sufficient data was not available to accurately model dynamic thermal ratings.

(Q45) **Did MISO consider transmission maintenance?**

Transmission maintenance in the form of removing facilities from the models were not included. MISO also did not add increased transmission maintenance to the costs for the complexity values.

(Q46) **Can MISO quantify the cost of ramping and cycling for different fuel groups?**

RIIA study does not assume specific cost of ramping and cycling for different fuel groups. The RIIA study quantified the ramp behavior, but accurate cost data was insufficient to use.

(Q47) **Why does MISO continue to be an energy importer in all scenarios?**

RIIA assumes MISO *and* the entire Eastern Interconnection meets the renewable penetration target for each milestone, without making unrealistic thermal unit retirement assumptions. Hence excess renewable energy in the rest of the Eastern Interconnection will flow into MISO and vice versa as the objective of the simulations is to minimize total production cost of the entire Eastern Interconnect. In reality, MISO has also become a net energy importer in the Eastern Interconnection in the past few years.

(Q48) **Is MISO importing solar from SERC and TVA?**

RIIA simulation results show SERC and TVA energy also flow into MISO.

Operating Reliability — Steady State

(Q49) **Are the high-voltage areas of concern?**

Prior to mitigations being applied, simulations showed high- and low-voltage criteria violations. Both types of violations are of concern, due to the potential for equipment damage. Both types of violations are not of concern after solutions were developed to mitigate any violations.

(Q50) **What is the difference between the issues in this analysis and the issues identified in the energy adequacy analysis?**

The issues explored in the OR analysis include evaluation of voltage and thermal violations from power-flow simulations, considering the non-linear nature of electrical phenomena (AC solutions) and active and reactive power. The mitigations identified through the energy adequacy analyses are needed to be able to serve each milestone's target renewable energy levels, and involve a DC-based solution algorithm unable to capture reactive power impact on the electric grid.

(Q51) **How does the model incorporate reactive power support from inverters?**

The renewable energy generation and inverters were modeled as providing reactive power support, consistent with industry requirements and FERC directives for generator interconnection. Refer to section 3 "Technical Assumption: Operating Reliability — Steady State Focus Area" for details

(Q52) **Did MISO identify any voltage stability issues driven by line overloads?**

MISO did not perform any P-V or voltage stability study driven by the high transfer of power across the transmission lines. In RIIA, many of the overloads were mitigated by upgrading the voltage class (kV) of the line (such as 230 kV to 345 kV), so the voltage stability issues would generally have been mitigated. The required addition of many dynamic reactive power devices — STATCOMs and synchronous condensers — would also mitigate voltage stability issues.

(Q53) **Did RIIA consider additional renewable resources for voltage support?**

The renewable siting was done before the models were built and run, so adding additional renewable generation was not done to help voltage support.

(Q54) **Why doesn't the MISO Generation Interconnection process address the issues seen in this analysis?**

The MISO Generation Interconnection process does address these types of issues. The renewable generation levels modeled in RIIA are far beyond any queue cycles yet studied in the MISO Generation Interconnection process.

Operating Reliability — Dynamic Stability

(Q55) **When it comes to dynamics, how is the cost quantified?**

The costs are for the facilities needed to resolve criteria violations observed and meet reliability standards, such as NERC TPL-001.

(Q56) **As far as criteria violations from added renewable generation are dealt with in the MISO Generation Interconnection process, is there any benefit to addressing the issues in a more holistic way?**

There may be several benefits to addressing issues in a holistic process, such as building long-term, most-economic, least regret transmission solutions to address several areas, such as generator interconnection and congestion alleviation.

(Q57) **Is it possible to convert retired units into synchronous condensers to be more cost effective?**

It is possible to convert retired units into synchronous condensers. Doing so may or may not be less expensive than adding a new synchronous condenser.

(Q58) **How does one relate low Short Circuit Ratio (SCR) to power flow?**

SCR is calculated in power flow models. Low SCR causes issues in the dynamics realm. Refer to the Operating Reliability — Dynamic Stability Focus Area section under the heading: "Weak - area study process: metrics and modelling and potential solutions if threshold is breached" for detailed explanation.

(Q59) **When moving from 30% to 40% penetration, did MISO apply any corrective action for frequency response?**

No frequency-related corrective actions were identified when moving from the 30% to 40% milestone.

(Q60) **Are there specific requirements for the headroom? Can wind curtailment be used as headroom?**

There are requirements for headroom implied by NERC reliability standards (BAL-001, 003 etc.). Wind curtailment can be used for headroom, if the curtailment is attained by operating wind turbines below their maximum output levels and online. For example, wind turbine blades can be pitched to operate sub-optimally and to make turbines be able to respond quickly by re-pitching to inject power into the grid.

Storage Sensitivity Assumptions

(Q61) **Is there a block size of the energy storage? For example, in the 30 GW case, does the entire 30 GW get applied to the same block of hours, or can it be spread out?**

There is no one block size of energy storage. Different scenarios have different capacities of storage located at different sites. For example, in the co-location scenario, the 12 GW capacity is split between 41 sites. For the high capacity cases of 100 GW, the sites are scaled from the nominal value used in the 12 GW case. Other scenarios assume different block sizes and storage duration.

(Q62) **Is the heuristic approach just siting storage alone, no hybrid, and no consideration of renewables siting? Is it focused on siting near load?**

All methods are meant to address the method of siting storage only. Each deploys a unique strategy for the type and location of the storage resource.

(Q63) **Where generation is located closer to load, does the location of the battery (closer to load or generation) matter from the perspective of deliverability?**

MISO finds the wind and solar generation delivery is best aided when storage is located near generation, as storage effectively reduces curtailment of the renewable generation and mitigates some transmission constraints encountered in the other case of needing to move the renewable generation to storage sited near load.

(Q64) **Storage seems to reduce wind curtailment more than solar curtailment, but developers seem to be focused on solar-storage hybrids. Is the storage sited near more wind than solar resources?**

Solar-storage hybrids are attractive due to the economics of sizing optimization for the inverter panels and battery, energy arbitrage, or ancillary services provision, rather than installing storage as an alternative to transmission. While the RIIA work finds synergy between storage and transmission, storage is only able to reduce the amount of transmission needed on a limited basis. Storage was sited both near wind and solar resources.

(Q65) **What is the difference between "storage paired with load" and "storage paired with renewables?" Is the latter utility scale and the former distribution and retail scale?**

For the RIIA work, this distinction deals with the physical location of the storage. The installation locations were biased either near wind and solar sites or near load locations. In either case, the storage is modeled as stand-alone utility-scale batteries.

(Q66) **Should storage always be installed near generation and none at load?**

The results of RIIA are sensitive to the siting of wind and solar and are sensitive to the primary objective for adding storage. For example, the storage sensitivity addressing reducing renewable curtailment contained 60 GW of wind, mostly in MISO North and far from load centers. Storage near renewable resources serves as a reservoir to store excess renewable energy when not needed to serve load, and the stored energy can be used later at times the renewable resource has lower production. If storage is sited near load without solving transmission issues encountered in delivering renewable generation to load areas, there may still be curtailment. Application of storage to resolve other reliability issues, such as small-signal inter-area oscillation, requires detailed analysis using dynamic-analysis tools. Locations of storage may be at strategic locations neither near generators nor load centers.

(Q67) **Was the storage modeled at higher voltage buses?**

The co-location storage sites were located at higher voltage class buses. For co-optimization, buses of various voltage levels were considered as candidate locations for storage.

(Q68) **Does this work show that all storage will be used for ancillary services?**

The purpose of the RIIA storage work was limited to the ability of storage to help mitigate risks presented by increasing wind and solar. The analysis does not suggest that storage would only provide ancillary services. The RIIA work did not examine the optimal value stream of storage.

(Q69) **When MISO talks about pairing storage with renewables, is it referring to being physically located at the same site or simply interconnecting to the transmission system at the same point?**

MISO means the same interconnection point.

Resource Adequacy with Storage

(Q70) **What is the difference between Portfolio and Storage (with Wind + Storage)?**

"Portfolio" means the combined ELCC of a portfolio (mix) of resources which combines wind, solar, and storage, whereas "Storage (with wind+ solar)" denotes the marginal ELCC of storage alone in a system with renewables. With the base siting assumptions, there is more wind in the North, while solar is spread throughout the footprint, but with a higher concentration in the South.

(Q71) **As storage and renewables are added to the system, how does the allocation vary, and how are transmission constraints considered in the analysis?**

Allocation varies per the siting methodology and the resource mix (75:25) and differs subregionally in MISO. In Resource Adequacy, analysis on a zonal level, and per current industry standards, some of the details such as economic data and transmission topology are not included.

(Q72) **Does the location of storage vary as ICAP increases? Ditto for renewables? Or, is the sensitivity done on a zonal basis (copperplate)? What role does transmission capacity play in the storage sensitivity?**

For Resource Adequacy, the analysis is zonal (copper plate), but the location also varies, with the implication being that the availability and capacity factor of the sources change. In Resource Adequacy, PLEXOS is used with no transmission (copper plate). In Energy Adequacy, the transmission is modeled, and flow constraints are enforced.

Energy Adequacy with Storage

(Q73) **The optimal amount of storage found in RIIA is small given the large amount of storage currently proposed in the MISO interconnection queue. A significant share of that queued storage capacity appears not to be co-located with renewable generation, but instead sited to participate in energy arbitrage and ancillary services markets, subject to market conditions. Does MISO believe that incorporating a reasonable percent of the storage presently in the interconnection queue in the RIIA modeling would have significantly changed the RIIA projected transmission?**

The RIIA storage sensitivity was narrowly scoped to look at the ability of storage to help mitigate risks presented by increasing wind and solar. It is MISO's understanding that the storage and hybrids being proposed in the interconnection queue are not intended for that purpose. In the storage sensitivity modeling, large amounts of storage were added to the MISO system, but the result was a limited change to the transmission needs of the system.

(Q74) **Was the entire 100 GW of storage applied for the same six-hour period?**

Storage was modeled as smaller individual units, so each could perform differently and was free to dispatch during periods of risk.

(Q75) **It is surprising that MISO would only need 500 MW of storage. Is that an indictment of energy-arbitrage storage?**

The co-optimization expansion started with the 30% milestone transmission solutions included. The 500 MW of storage added to get to the 40% penetration level was therefore in addition to a significant amount of transmission already added to the model. The analysis suggests that although transmission would play a larger role, based on the current assumptions, there is an opportunity for storage and transmission to work well together.

Papers, Presentations and Contributors

Papers/Conference papers:

B. Heath and A.L Figueroa-Acevedo, "Potential Capacity Contribution of Renewables at Higher Penetration Levels on MISO System," in Proc. of the 2018 IEEE International Conference on Probabilistic Methods Applied to Power Systems (PMAPS) Boise, ID, 2019.

J. Bakke, M. Boese, A.L Figueroa-Acevedo, B. Heath, Y. Li, N. Mohan, J. Okullo, A. J. Prabhakar, and C.H Tsai, "Renewable Integration Impact Assessment: The MISO Experience," *IAEE Energy Forum*, First Quarter 2019, pp. 47 – 51

A.L Figueroa-Acevedo, C.H Tsai, K. Gruchalla, Z. Claes, S. Foley, J. Bakke, J. Okullo, and A. J. Prabhakar, "Visualizing the Impacts of Renewable Energy Growth in the US Midcontinent," in *IEEE Open Access Journal of Power and Energy*, vol. 7, pp. 91-99, 2020, doi: 10.1109/OAJPE.2020.2967292.

A. Figueroa-Acevedo. MISO Kaleidoscope Package. Accessed: July 12, 2019. [Online]. Available: https://github.com/al_gueroa21/MISOKaleidoscope

C.H Tsai, A.L Figueroa-Acevedo, M. Boese, Y. Li, N. Mohan, J. Okullo, B. Heath, J. Bakke, "Challenges of planning for high renewable futures: Experience in the US midcontinent electricity market, *"Renewable and Sustainable Energy Reviews,* Volume 131, 2020, https://doi.org/10.1016/j.rser.2020.109992.

Workshops:

"Renewable Integration Impact Assessment (RIIA) - Storage Sensitivity," MISO, October 27, 2020. Available: https://www.misoenergy.org/events/renewable-integration-impact-assessment-riia---october-27-2020/

"Renewable Integration Impact Assessment (RIIA) – Energy Adequacy Sensitivity," MISO, July 24, 2020. Available: https://www.misoenergy.org/events/renewable-integration-impact-assessment-riia---july-24-2020/

"Renewable Integration Impact Assessment (RIIA) Expansion/Siting and Resource Adequacy Sensitivity," MISO, June 16, 2020. Available:
https://www.misoenergy.org/events/renewable-integration-impact-assessment-riia---june-26-2020/

"Renewable Integration Impact Assessment (RIIA) Phase 2 Conclusion Workshop," MISO, November 14 - 15, 2019. Available:
https://www.misoenergy.org/events/renewable-integration-impact-assessment-riia-phase-2-conclusion-workshop---november-14---15-2019/

"RIIA 40% Penetration: Dynamics Studies Results Workshop," MISO, July 17, 2019. Available: https://www.misoenergy.org/events/riia-40-penetration-dynamics-studies-results-workshop---july-17-2019/

"Renewable Integration Impact Assessment Workshop," MISO, November 28, 2018. Available: https://www.misoenergy.org/events/renewable-integration-impact-assessment-riia-workshop---november-28-2018/

"Renewable Integration Impact Assessment Workshop - methods, assumptions, and preliminary results" MISO, June 5, 2018. Available:
https://www.misoenergy.org/events/renewable-integration-impact-assessment-riia-workshop---june-5-2018/

MISO Stakeholder Presentations:

August 16, 2017: MISO PAC - Introduce need for assessment

September 27, 2017: MISO PAC - Introduce concept behind the assessment

April 18, 2018: MISO PAC - Discuss Resource Adequacy results

June 6, 2018: Workshop - Discuss details behind work to date

October 4, 2018: MISO RSC - Discuss frequency response results 20%

November 14, 2018: MISO PAC - Discuss results 10-40%

November 28, 2018: Workshop - Discuss details behind results 10-40%

March 14, 2019: Workshop - Discuss phase III feedback and work-plan

July 17, 2019: Workshop - Discuss dynamics impacts to conclude 40%

November 13, 2019: MISO PAC - Discuss phase II conclusion

November 14 - 15, 2019: Workshop – Discuss details of phase II conclusion

June 16, 2020: Webinar – Discuss expansion/siting and resource adequacy sensitivities

July 24, 2020: Webinar – Discuss energy adequacy sensitivities

October 27, 2020: Webinar – Discuss storage sensitivities

Conferences and External Public Meetings:

October 11, 2017: UVIG - Introduction to RIIA

November 7, 2017: Iowa Utilities Board - RIIA Overview

April 27, 2018: PLEXOS User Group Meeting - RIIA overview and use of PLEXOS

March 8, 2018: Transmission Summit East (Infocast) - Discuss lessons learned to date

April 26, 2018: ND PSC Meeting - Results to date

May 21/22, 2018: GO15 Governing Board meeting - Future grid needs

June 12, 2018: Iowa Utilities Board - RIIA Results to date

June 20/21, 2018: 2018 NERC Power System Modeling Conference

June 24-29, 2018: PMAPS International

August 9, 2018: IEEE PES GM panel session

August 9, 2018: IEEE LOLE Working Group at the IEEE PES

September 11, 2018: ISU Seminar (RIIA overview)

September 13, 2018: NCEP Webinar

October 9/10, 2018: GO15 Steering Board meeting - Future grid needs

October 12, 2017: ND PSC - RIIA Overview

October 23, 2018: MRO Fall Reliability Conference - RIIA Update

November 7, 2018: INFORMS Panel on sustainable systems - RIIA overview

January 9, 2019: MN Society of Professional Engineers - RIIA overview and lessons learned

February 26, 2019: MN Senate Energy Committee - RIIA overview and lessons learned

March 20, 2019: Energy Systems Integration Group (ESIG) - RIIA overview and lessons learned

April 9, 2019: EIPC Spring Technical Workshop - RIIA implications for transmission planning

April 24-25, 2019: NERC SAMS Meeting: Renewables Impact on Frequency Response

June 26, 2019: FERC Software Conference: Discuss software needs in the context of RIIA

August 4, 2019: IEEE PES GM - Panel session on "Transmission for renewables."

August 6, 2019: IEEE PES GM - International Practices in Power System Planning

January 10, 2020: MN commission MISO 101 – RIIA

January 21, 2020: MN Center for Environmental Advocacy

January 28, 2020: NERC SAMS- Update on RIIA 50% Frequency Response

January 29, 2020: Midwest Governors Association

February 18, 2020: ND PSC RIIA

May 21, 2020: ESIG 2020 Spring Technical Workshop/System Planning Working Group

April 1, 2020: Minnesota Municipal Utilities Association

June 4, 2020: RF Board of Directors meeting

July 21-22, 2020: SERC Summer Regional Meetings

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