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Storage Allocation and Investment Optimization for Transmission Constrained Networks Considering Losses and High Renewable Penetration

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Context and Motivation

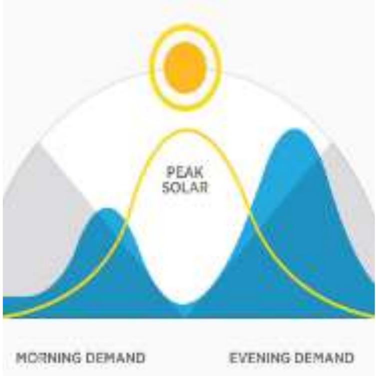
Context

Renewable Energy Sources (RES)

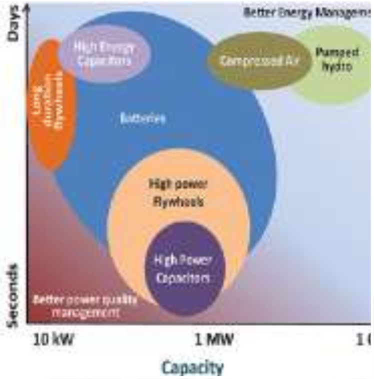
- Increase of RES share in the following years
- Intermittency issues and no output control

Energy Storage Systems (ESS)

- Promising option to soften renewable intermittency and increase flexibility
- New developments are reducing the costs, especially for electrical ESS



Motivation



Wide number of ESS technologies and characteristics

- Different energy/power ratios
- Multiple services: time shifting, ramping etc.

Real Power System characteristics

- Network Congestion
- Transmission Losses

Research Questions

- What is the impact of network congestion or transmission losses on ESS allocation/ investment decisions?
- How does the level of renewable penetration in a power system change the ESS investment decisions?

Optimization Model and Metrics

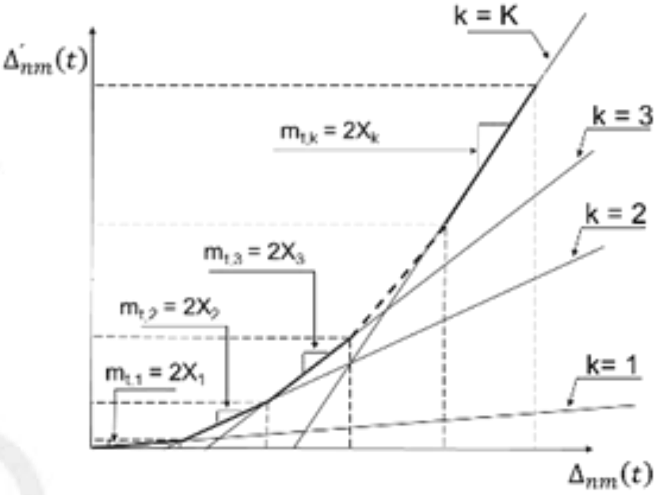
Optimization Model General Description

Objective Function:

- Minimize production costs

Subject to:

- Power balance constraint
- Storage balance constraint
- Charge/discharge limits
- Storage limits
- Final storage level condition
- Thermal units limits
- Ramp limits for thermal units
- Maximum Storage to be installed
- Transmission network constraints (DC-OPF)
- Piecewise Linear Approximation for transmission losses



Metrics

Metric	Purpose	Equation
Overall Capacity Metric (OM)	To compare the maximum storage level in MWh attained over the time horizon to the actual amount of capacity of that technology installed at each node	$OM_{jn} = 1 - \frac{max_t\{s_{jn}(t)\}}{k_{jn}}$
Cycling Metric (CM)	To keep tracking of how many full charging cycles a technology goes through over the total time horizon at each node	$CM_{jn} = \frac{\sum_{t \in T}\left[r_{jn}^{c}(t) \cdot \Delta t\right]}{k_{jn}}$
Overall Storage Level Metric (OSL)	To provide an idea of how much energy each technology stores throughout a day for each scenario in comparison to the base case of an unconstrained network	$OSL_j = \frac{\sum_{n,t} s_{jn}(t)}{\sum_{n,t} s\_BaseCase_{jn}(t)}$

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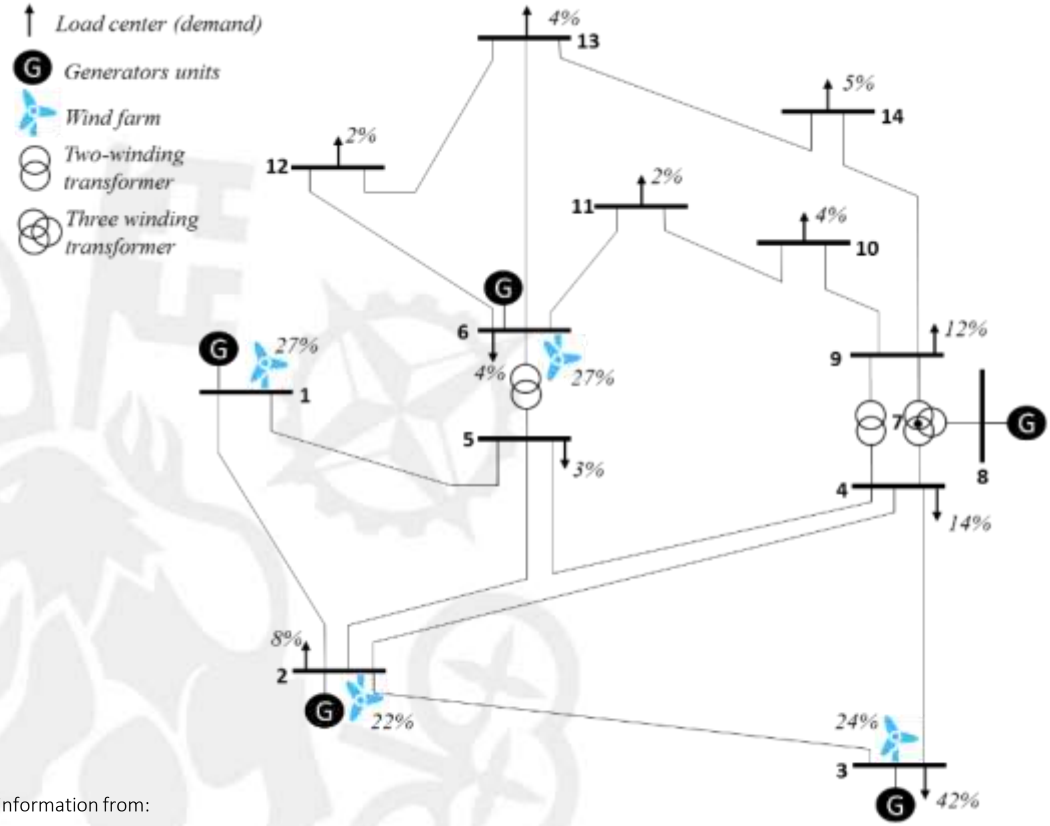
Case Study

Modified IEEE 14 Bus System



Data information from:

S. Wogrin y D. F. Gayme, «Optimizing Storage Siting, Sizing, and Technology Portfolios in Transmission-Constrained Networks», IEEE Trans. Power Syst., vol. 30, n.o 6, pp. 3304-3313, nov. 2015.

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Storage Allocation Results

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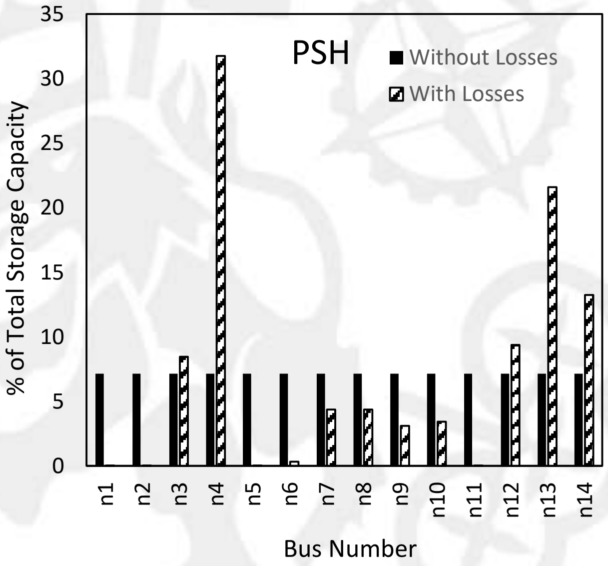
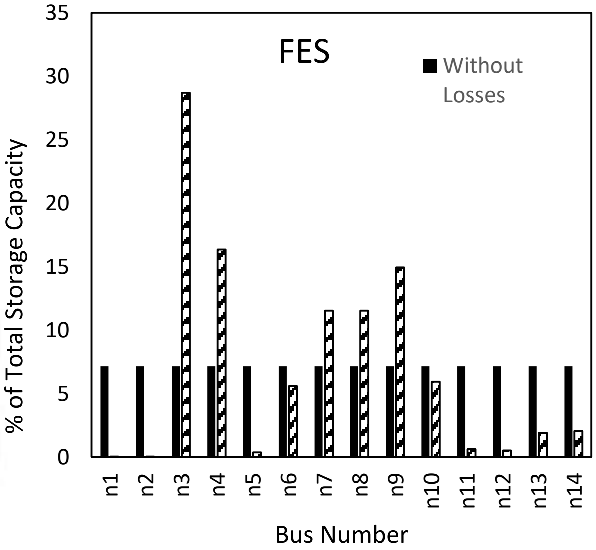
Impact of Transmission Losses

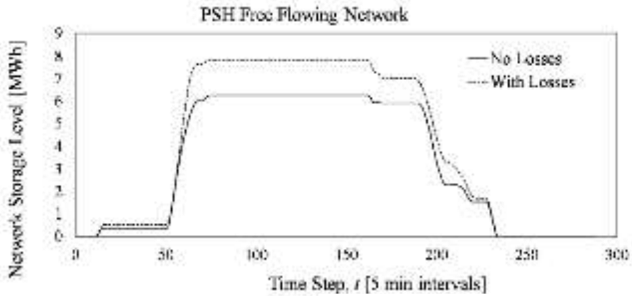
The introduction of losses into the model led to changes in the *spatial distribution of storage capacity* and the temporal usage of each technology



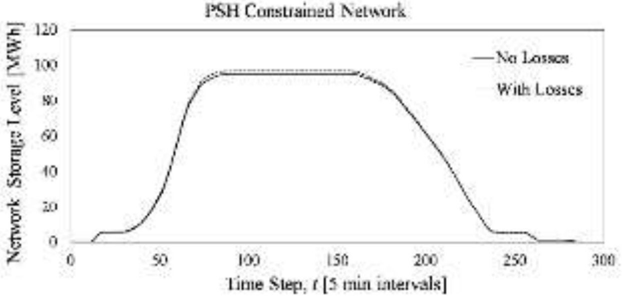


Impact of Transmission Congestion

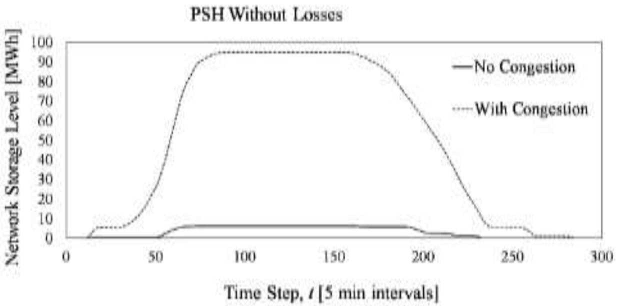
No Congestion



Congestion

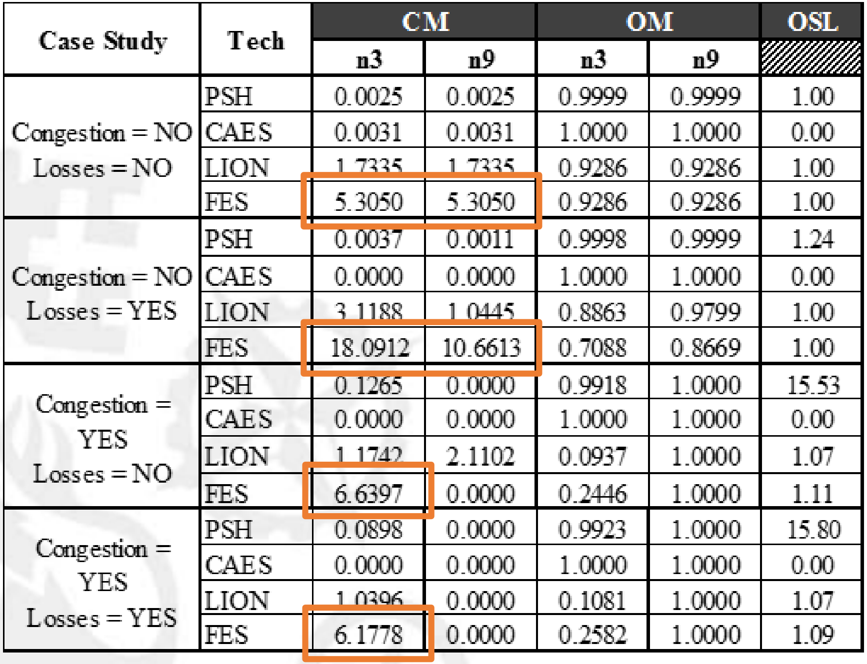


Comparison



While it may be important to consider transmission losses in a free-flowing network, in a congested network they will not significantly impact how a storage system should be integrated

Results obtained for the Metrics

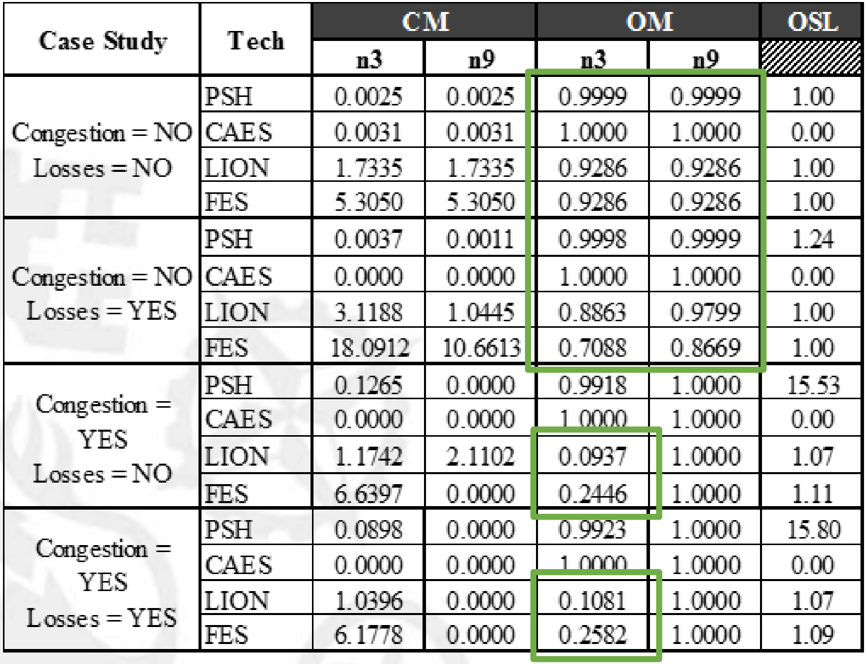


Case Study	Tech	CM		OM		OSL
		n3	n9	n3	n9	
Congestion = NO Losses = NO	PSH	0.0025	0.0025	0.9999	0.9999	1.00
	CAES	0.0031	0.0031	1.0000	1.0000	0.00
	LION	1.7335	1.7335	0.9286	0.9286	1.00
	FES	5.3050	5.3050	0.9286	0.9286	1.00
Congestion = NO Losses = YES	PSH	0.0037	0.0011	0.9998	0.9999	1.24
	CAES	0.0000	0.0000	1.0000	1.0000	0.00
	LION	3.1188	1.0445	0.8863	0.9799	1.00
	FES	18.0912	10.6613	0.7088	0.8669	1.00
Congestion = YES Losses = NO	PSH	0.1265	0.0000	0.9918	1.0000	15.53
	CAES	0.0000	0.0000	1.0000	1.0000	0.00
	LION	1.1742	2.1102	0.0937	1.0000	1.07
	FES	6.6397	0.0000	0.2446	1.0000	1.11
Congestion = YES Losses = YES	PSH	0.0898	0.0000	0.9923	1.0000	15.80
	CAES	0.0000	0.0000	1.0000	1.0000	0.00
	LION	1.0396	0.0000	0.1081	1.0000	1.07
	FES	6.1778	0.0000	0.2582	1.0000	1.09

The CM indicates that FES goes through the most full cycles of any technology in the portfolio. This is likely attributed to its short ramp time which allows it to fully charge and discharge within a single timestep.

When losses are introduced, the number of cycles more than triples at node 3 and doubles at node 9 even though the overall capacity remains unchanged.

Results obtained for the Metrics



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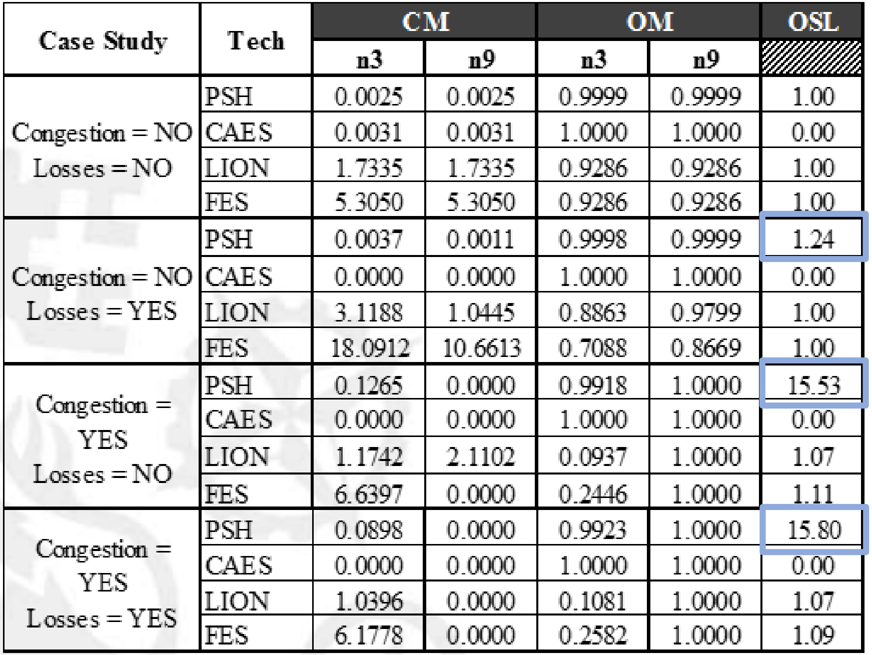
The OM indicates that in a non-congested network, the capacity allocated in node 3 is almost fully used for all the technologies. However, when the network is congested, the allocation of FES capacity is not used due to the transmission constraints, and OM metrics shows how almost 75% of this capacity is unused.

Results obtained for the Metrics



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The OSL illustrates this trend with an increase of 24% in PSH storage usage midday, allowing a system operator to dissipate stored energy at the evening peaks.

For PSH storage network congestion increased the OSL fifteen-fold system-wide from the base case. However, considering losses yielded no significant changes.

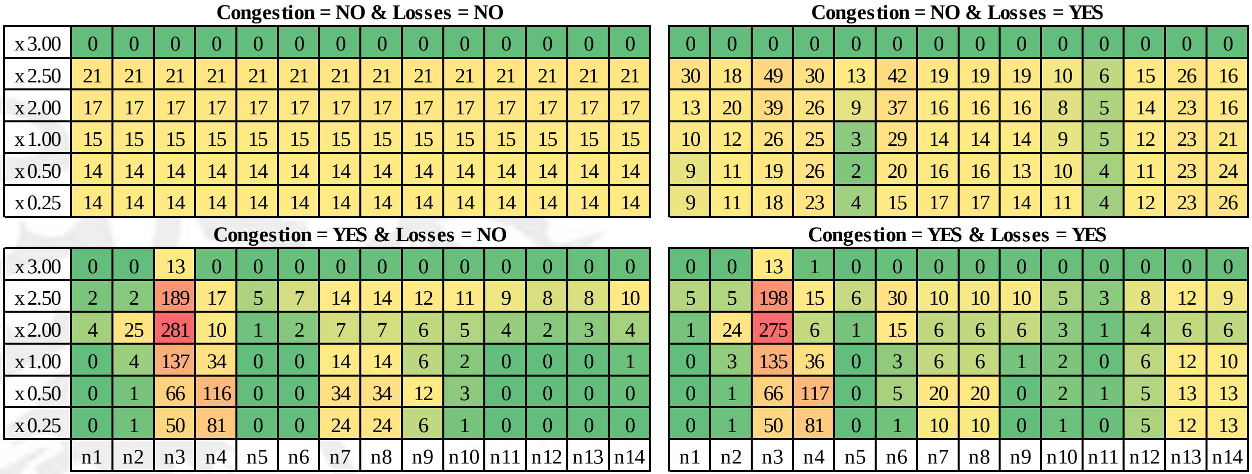
Storage Investment Results

Impact of Renewable Penetration on Investment per Technology [MWh]

Case Study	Tech	Wind production					
		x 0.25	x 0.50	x 1.0	x 2.0	x 2.5	x 3.0
Congestion = NO Losses = NO	PSH	0	0	0	0	9	206
	CAES	0	0	0	0	103	535
	LION	0	0	0	0	0	55
	FES	200	200	211	237	298	0
Congestion = NO Losses = YES	PSH	0	0	0	0	19	211
	CAES	0	1	0	0	123	538
	LION	0	0	0	0	0	57
	FES	204	204	217	257	312	0
Congestion = YES Losses = NO	PSH	0	0	0	0	49	398
	CAES	1	1	0	0	209	965
	LION	0	0	0	0	14	116
	FES	188	266	212	363	309	16
Congestion = YES Losses = YES	PSH	0	0	0	0	53	373
	CAES	0	1	0	0	204	818
	LION	0	0	0	0	13	117
	FES	184	262	221	361	326	17

- For the cases at or below standard wind production, FES was the only storage technology invested in. This implies that the need for FES capacity may primarily be to provide general load balance as opposed to just dealing with fluctuations from volume of wind generation.
- However, when wind production rose there grew a need for large-scale energy reservoirs instead of fast energy storage technology such as FES.

FES investment per node [MWh]



Congestion = NO & Losses = NO

	n1	n2	n3	n4	n5	n6	n7	n8	n9	n10	n11	n12	n13	n14
x 3.00	0	0	0	0	0	0	0	0	0	0	0	0	0	0
x 2.50	21	21	21	21	21	21	21	21	21	21	21	21	21	21
x 2.00	17	17	17	17	17	17	17	17	17	17	17	17	17	17
x 1.00	15	15	15	15	15	15	15	15	15	15	15	15	15	15
x 0.50	14	14	14	14	14	14	14	14	14	14	14	14	14	14
x 0.25	14	14	14	14	14	14	14	14	14	14	14	14	14	14

Congestion = NO & Losses = YES

	n1	n2	n3	n4	n5	n6	n7	n8	n9	n10	n11	n12	n13	n14
x 3.00	0	0	0	0	0	0	0	0	0	0	0	0	0	0
x 2.50	30	18	49	30	13	42	19	19	19	10	6	15	26	16
x 2.00	13	20	39	26	9	37	16	16	16	8	5	14	23	16
x 1.00	10	12	26	25	3	29	14	14	14	9	5	12	23	21
x 0.50	9	11	19	26	2	20	16	16	13	10	4	11	23	24
x 0.25	9	11	18	23	4	15	17	17	14	11	4	12	23	26

Congestion = YES & Losses = NO

	n1	n2	n3	n4	n5	n6	n7	n8	n9	n10	n11	n12	n13	n14
x 3.00	0	0	13	0	0	0	0	0	0	0	0	0	0	0
x 2.50	2	2	189	17	5	7	14	14	12	11	9	8	8	10
x 2.00	4	25	281	10	1	2	7	7	6	5	4	2	3	4
x 1.00	0	4	137	34	0	0	14	14	6	2	0	0	0	1
x 0.50	0	1	66	116	0	0	34	34	12	3	0	0	0	0
x 0.25	0	1	50	81	0	0	24	24	6	1	0	0	0	0

Congestion = YES & Losses = YES

	n1	n2	n3	n4	n5	n6	n7	n8	n9	n10	n11	n12	n13	n14
x 3.00	0	0	13	1	0	0	0	0	0	0	0	0	0	0
x 2.50	5	5	198	15	6	30	10	10	10	5	3	8	12	9
x 2.00	1	24	275	6	1	15	6	6	6	3	1	4	6	6
x 1.00	0	3	135	36	0	3	6	6	1	2	0	6	12	10
x 0.50	0	1	66	117	0	5	20	20	0	2	1	5	13	13
x 0.25	0	1	50	81	0	1	10	10	0	1	0	5	12	13

- The transmission losses help to distinguish among the nodes for investment decisions in energy storage.
- However, if the network is congested then the investment decision are mainly driven by the network constraints. In this case, the network losses help to distinguish among the areas of the network that are not congested.

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Conclusions and Future Research

Summary…

In an area with no congestion problems, losses are important to distinguish among the nodes in order to allocate ESS

Congestion is more relevant than losses and drives the allocation and investment decisions

Level of renewable penetration alters the optimal ESS technology investment decisions

Future work…

Use a more detailed model, such as Second Order Cone Programming (SOCP), in order to consider reactive and active power.

Stochastic model for uncertainty representation of multiple renewable profiles as scenarios in the future operation.

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