Benefits of transmission switching and energy storage in power systems with high renewable energy penetration*

Energy Discussion Group in EME, The University of Edinburgh
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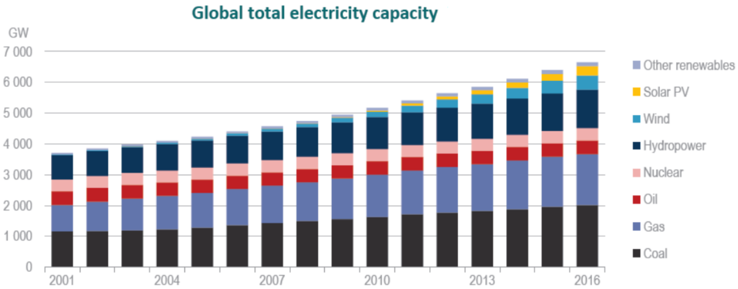
Introduction

- **Power system planning and operations** is a decision making process to supply sufficient and continuous power to consumers and determines a minimum cost strategy for operating the system.
- The problem is a challenging due to its complexity, dimensionality and nonlinearity.
- Complexity of the problem increases due to
  - Load growth
  - Increase generation from renewable energy sources (RES)
  - Forecast errors
  - Unexpected failures of components

Introduction

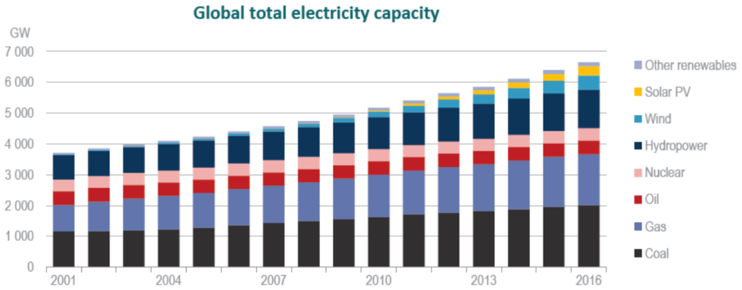
Load growth



Source: IEA, Renewables 2017

- About 40% increase in the last 15 years

Introduction
Load growth



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Introduction

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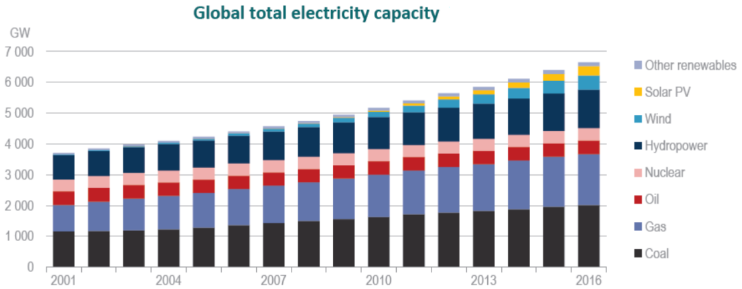

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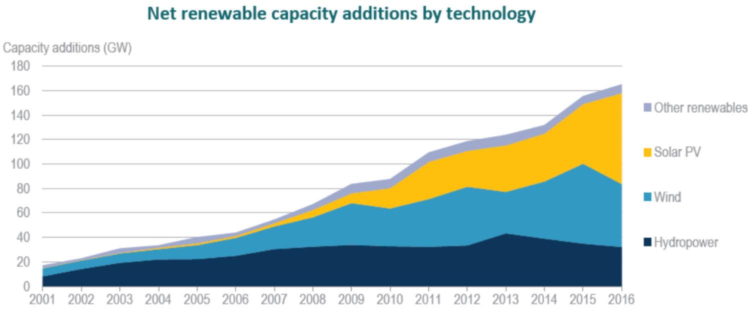
- About 40% increase in the last 15 years
- Mostly dependent on fossil fuels
- Increase in renewable energy sources in the last decade

Introduction

Penetration of RES in supply



Source: IEA, Renewables 2017

- Share of RES in supply increases from 19% to 24%*
- The share is expected to be 31% in 2040*

*Source: IEA, World Energy Outlook, 2017

Renewable Energy Sources

- *Advantages:* - Sustainable
  - Clean

Reduce carbon emission and dependence on fossil fuels

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  - Variable
  - Dependent on spatial locations

  Affect power system reliability and stability

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Control Mechanisms

- Demand-Side Management (DSM)
- Renewable Energy Curtailment (REC)
- Energy Storage Systems (ESS)
- Transmission Switching (TS)

Control Mechanisms

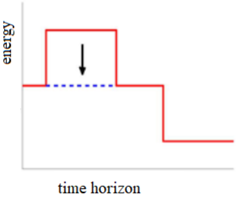
Demand-Side Management (DSM)

- Group of activities to increase overall efficiency in systems

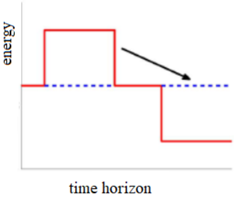
Control Mechanisms

Demand-Side Management (DSM)

- Group of activities to increase overall efficiency in systems
- **Demand response (DR)** reshapes consumers' load profiles
  - **Load-shedding:** Reduces energy consumption at peak periods
  - **Load-shifting:** Shifts energy consumption from peak periods to off-peak periods



Load-shedding

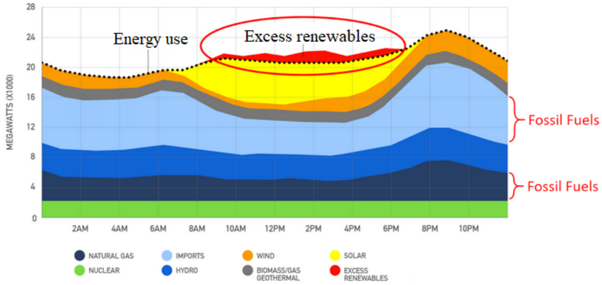


Load shifting

Control Mechanisms

Renewable Energy Curtailment (REC)

- Curtails renewable energy due to technical and operational reasons
  - To maintain system voltage and frequency levels
  - To satisfy minimum generation requirements from thermal sources

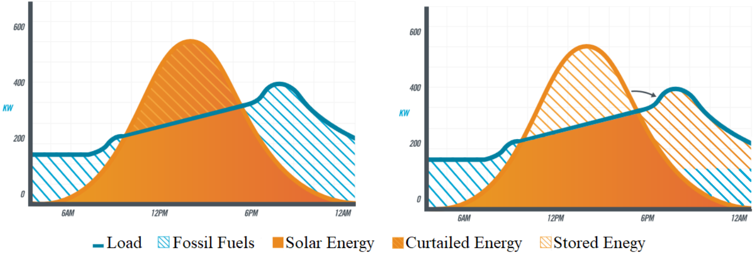


Source: https://sandiego350.org/ab-813-renewable-energy-curtailment/

Control Mechanisms

Energy Storage Systems (ESS)

- Stores electrical energy generated at off-peak hours to use at peak hours
- Smooths variability and intermittency of RES



Source: https://www.essinc.com/energy-storage-applications/utility/

Control Mechanisms

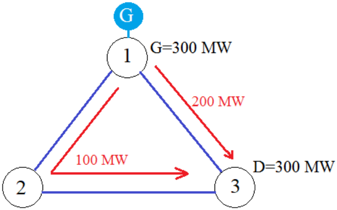
Transmission Switching (TS)

- Identifies the branches that should be taken out of service
- Decreases transmission congestion

Control Mechanisms

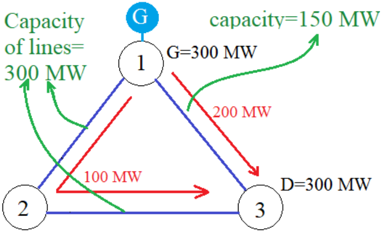
Transmission Switching (TS)

- Identifies the branches that should be taken out of service
- Decreases transmission congestion
- Flow in power networks is special:
  - Power flows on all lines in proportion to the electrical characteristics of the lines
  - If all lines are identical, the flows should be as follows:



Control Mechanisms
Transmission Switching (TS)

If switching is not allowed and capacity between nodes 1 and 3 is less than 200 MW, then system turns out to be infeasible!



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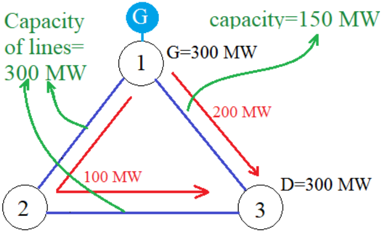

- New lines/units should be added to make it feasible

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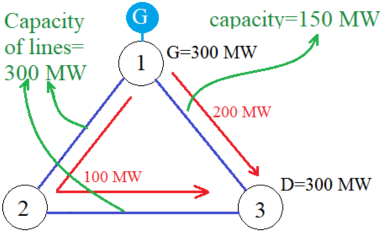
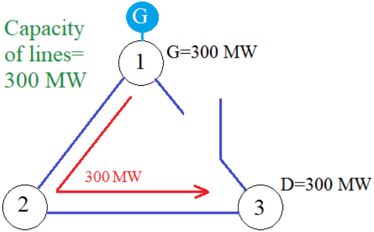


• New lines/units should be added to make it feasible

If the line is opened or switched, then system becomes feasible!



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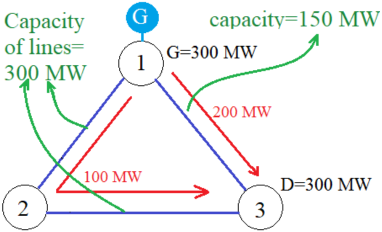

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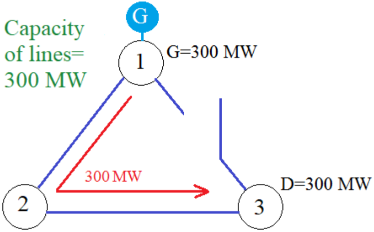

- No need for new lines/units

Objective

Although renewable energy sources have many advantages, they affect power system reliability and stability due to their disadvantages (e.g. intermittency, variability).

Control mechanisms could be utilized for integrating RES into power systems and decreasing disadvantages of them.

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Although renewable energy sources have many advantages, they affect power system reliability and stability due to their disadvantages (e.g. intermittency, variability).

Control mechanisms could be utilized for integrating RES into power systems and decreasing disadvantages of them.

Aim of this study

To discuss value of control mechanisms to handle the variability and intermittency of RES.

Literature Review

- ESS
  - Siting
  - Sizing
    Pandzic et al. (2015), Wogrin and Gayme (2015), Fernandez-Blanco et al. (2017), Go et al. (2016), Xiong and Singh (2016), Qiu et al. (2017)

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- ESS and TS
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Literature Review

- DSM (Load-shedding - LS)
  - Penalty cost for its impact on quality of life
- REC
  - Penalty cost for compensation of revenue losses from renewable energy generators

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- DSM (Load-shedding - LS)
  - Penalty cost for its impact on quality of life
- REC
  - Penalty cost for compensation of revenue losses from renewable energy generators

Penalty costs are important...

Operational and/or tactical plans may be affected by penalty costs.

Contribution

- ESS and TS

	investment costs	LS	REC	sizing
Nikoobakht et al. (2016)	✗	✗	✗	✗
Aghaei et al. (2018)	✗	penalty cost	penalty cost	✗
Dehghan and Amjady (2016)	line, ESS	penalty cost	✗	✗

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Our study	line, ESS	constraint	constraint	✓

Our study

• fills a gap in the literature by simultaneously considering TS, ESS siting and sizing decisions
• examines the value of co-optimizing control mechanisms to handle variability of RES.

Contribution

- ESS and TS

	investment costs	LS	REC	sizing
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Our study

• fills a gap in the literature by simultaneously considering TS, ESS siting and sizing decisions

• examines the value of co-optimizing control mechanisms to handle variability of RES.

We propose a two-stage stochastic programming model.

• First stage:

Investment decisions: ESS and lines

• Second stage:

Operational decisions: flow, generation amount, status of line

Problem Formulation
Parameters

Parameters	Explanation
c_g^{om}	Operation cost of unit g (\$/MWh)
c_a^{line}	Annualized inv. cost of candidate line a (\$)
c^E	Annualized inv. cost of ESS for energy capacity (\$/MWh)
c^P	Annualized inv. cost of ESS for power rating (\$/MW)
c^d	Discharging cost (\$/MW)
$\overline{E}$, $\underline{E}$	Maximum and minimum energy capacity of ESS (MWh)
$\overline{P}$, $\underline{P}$	Maximum and minimum power rating of ESS (MW)
η	Charging/Discharging efficieny of ESS
α	Energy-power ratio of ESS
E_0	Initial energy level at ESS
$\overline{F}_a$	Capacity of line a (MW)
$\overline{G}_{igts}$ ($\underline{G}_{igts}$)	Max (Min) generation limits from unit g in bus i at hour t of scenario s (MW)
R_g^{up} (R_g^{down})	Ramp-up (ramp-down) rate of generation unit g
D_{its}	Demand of bus i at hour t of scenario s (MW)
φ_a	Susceptance of line a (p.u.)
τ	Maximum number of switchable lines
p^{ls}	Ratio of load that can be shed to total load
p^{rec}	Ratio of renewable generation that can be curtailed to total generation
σ_s	Probability of scenario s
NS	Number of days in the target year

Problem Formulation
Decision Variables

Dec. Var.	Explanation
Y_i	1 if ESS is built at node *i*, 0 o.w.
Y_i^E	Energy capacity of ESS at node *i*
Y_i^P	Power rating of ESS at node *i*
L_a	1 if candidate line *a* is built, 0 o.w.
P_{its}^c	Charging rate of ESS at node *i* at hour *t* of scenario *s*
P_{its}^d	Discharging rate of ESS at node *i* at hour *t* of scenario *s*
X_{its}	Status of ESS at bus *i* at hour *t* of scenario *s*, 1 is for charging/0 is for discharging
E_{its}	State of charge of ESS at bus *i* at hour *t* of scenario *s*
f_{ats}	Power flow on line *a* at hour *t* of scenario *s*
Z_{ats}	1 if line *a* is closed at hour *t* of scenario *s*, 0 if it is open
G_{igts}	Power generation of unit *g* in node *i* at hour t of scenario s
DS_{its}	Load shedding amount at bus *i* at hour *t* of scenario *s*
θ_{its}	Voltage angle of node *i* at hour *t* of scenario *s*

Problem Formulation
Mathematical Model

$$\min \quad z_{line} + z_{storage} + z_{om} \tag{1}$$

total investment cost

$$z_{line} = \sum_{a \in A \setminus EA} c_a^{line} L_a$$

$$z_{storage} = \sum_{i \in B} (c^E Y_i^E + c^P Y_i^P)$$

total operational cost

$$z_{om} = \sum_{s \in S} NS\sigma_s \sum_{i \in B} \sum_{t \in T} \{ \sum_{g \in C \setminus C_R} c_g^{om} G_{igts} + c^d P_{its}^d \}$$

Problem Formulation

Mathematical Model

s.t

power balance

$$\sum_{g \in C} G_{igts} + \sum_{a \in A\Psi^{-}(a)=i} f_{ats} - \sum_{a \in A\Psi^{+}(a)=i} f_{ats} + - P^{c}_{its} + P^{d}_{its} = D_{its} - DS_{its} \quad \forall i \in B, t \in T, s \in S \quad (2)$$

generation dispatch

$$G_{igts} \leq \overline{G}_{igts} \quad \forall i \in B, g \in C_r, t \in T, s \in S \quad (3)$$

$$\underline{G}_{igts} \leq G_{igts} \leq \overline{G}_{igts} \quad \forall i \in B, g \in C \backslash C_r, t \in T, s \in S \quad (4)$$

$$R^{down}_{g} \leq G_{igts} - G_{igt\text{-}1s} \leq R^{up}_{g} \quad \forall i \in B, g \in C \backslash C_r, t \in T, s \in S \quad (5)$$

network limitations

$$-\overline{F}_a Z_{ats} \leq f_{ats} \leq \overline{F}_a Z_{ats} \quad \forall a \in A, t \in T, s \in S \quad (6)$$

$$f_{ats} = \varphi_a Z_{ats}(\theta_{its} - \theta_{jts}) \quad \forall a \in AS_{ij}, t \in T, s \in S \quad (7)$$

$$Z_{ats} \leq L_a \quad \forall a \in A, t \in T, s \in S \quad (8)$$

$$\sum_{a \in A} L_a \leq \sum_{a \in A} Z_{ats} + \tau \quad \forall t \in T, s \in S \quad (9)$$

LS restriction

$$\sum_{i \in B} \sum_{t \in T} DS_{its} \leq p^{ls} \sum_{i \in B} \sum_{t \in T} D_{its} \quad \forall s \in S \quad (10)$$

REC restriction

$$\sum_{i \in B} \sum_{g \in C_R} \sum_{t \in T} G_{igts} \geq (1 - p^{rec}) \sum_{i \in B} \sum_{g \in C_R} \sum_{t \in T} \overline{G}_{igts} \quad \forall s \in S \quad (11)$$

Problem Formulation

Mathematical Model

energy related constraints for storages:

$$E_{its} = E_{it\text{-}1s} + \Delta t(\eta P^c_{its} - \frac{1}{\eta} P^d_{its}) \quad \forall i \in B, t \in T, s \in S \quad (12)$$

$$\underline{E} Y_i \leq E_{its} \leq Y^E_i \quad \forall i \in B, t \in T, s \in S \quad (13)$$

$$\underline{E} Y_i \leq Y^E_i \leq \overline{E} Y_i \quad \forall i \in B, t \in T, s \in S \quad (14)$$

$$E_{i0s} = E_{iTs} = E_0 Y_i \quad \forall i \in B, s \in S \quad (15)$$

power related constraints for storages:

$$\underline{P} Y_i \leq Y^P_i \leq \overline{P} Y_i \quad \forall i \in B, t \in T, s \in S \quad (16)$$

$$P^c_{its} \leq Y^P_i \quad \forall i \in B, t \in T, s \in S \quad (17)$$

$$P^d_{its} \leq Y^P_i \quad \forall i \in B, t \in T, s \in S \quad (18)$$

$$P^c_{its} \leq \overline{P} X_{its} \quad \forall i \in B, t \in T, s \in S \quad (19)$$

$$P^d_{its} \leq \overline{P}(1 - X_{its}) \quad \forall i \in B, t \in T, s \in S \quad (20)$$

$$\alpha Y^P_i \leq Y^E_i \quad \forall i \in B, t \in T, s \in S \quad (21)$$

$$+ \, DomainConstraints$$

Problem Formulation
Mathematical Model

- Constraint (7) is nonlinear: $f_{ats} = \varphi_a Z_{ats}(\theta_{its} - \theta_{jts})$
- Generally used linearization technique:

$$-M_a(1 - Z_{ats}) + \varphi_a(\theta_{its} - \theta_{jts}) \leq f_{ats} \leq M_a(1 - Z_{ats}) + \varphi_a(\theta_{its} - \theta_{jts})$$

Problem Formulation
Mathematical Model

- Constraint (7) is nonlinear: $f_{ats} = \varphi_a Z_{ats}(\theta_{its} - \theta_{jts})$
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- We define these equations:

$$f_{ats} = f^+_{ats} - f^-_{ats} \qquad \theta_{its} - \theta_{jts} = \Delta\theta^+_{ats} - \Delta\theta^-_{ats}$$
$$f^+_{ats}, f^-_{ats} \geq 0 \qquad \Delta\theta^+_{ats}, \Delta\theta^-_{ats} \geq 0$$

- We linearize as follows:

$$f^+_{ats} \leq \varphi_a \Delta\theta^+_{ats} \qquad f^-_{ats} \leq \varphi_a \Delta\theta^-_{ats}$$
$$f^+_{ats} \geq \varphi_a \Delta\theta^+_{ats} - M_a(1 - Z_{ats}) \qquad f^-_{ats} \geq \varphi_a \Delta\theta^-_{ats} - M_a(1 - Z_{ats})$$

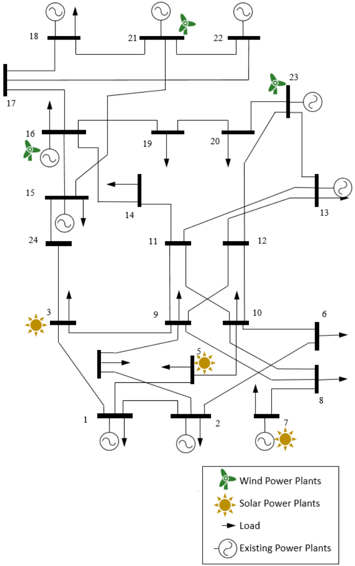
Computational Study

Data Set

IEEE 24-bus power system

- 34 transmission lines
- 10 existing generation nodes

90% of them thermal sources
Installed capacity: 3405 MW
Load: 2850 MW



Computational Study
Data Set

IEEE 24-bus power system

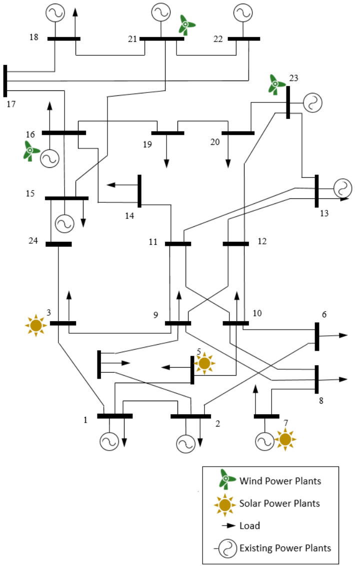
- 34 transmission lines
- 10 existing generation nodes

90% of them thermal sources
Installed capacity: 3405 MW
Load: 2850 MW

Modified IEEE 24-bus power system

- Line capacity: -50%
- Thermal sources capacity: -75%
- New solar sources*: 1500 MW/bus
- New wind sources*: 1000 MW/bus

*Each has a different profile



Computational Study
Data Set

- Time horizon: 1 year (365 days)
- By *K-means algorithm*, 5 representative days are selected
- Number of days in each cluster of K-means algorithm determines the probability of that day
- p^{ls} : 0.0 - 1.0
- p^{rec}: 0.0 - 1.0

To observe the effect of TS, we compare two cases:

- $\tau = 0$ (ESS case)
- $\tau = 5$ (ESS-TS case)

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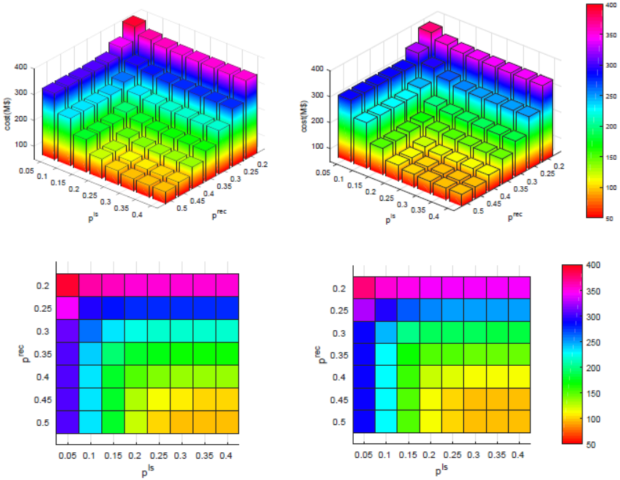
We discuss effect of TS on

- Total system cost
- ESS siting and sizing
- LS and REC

Computational Study

Effect of TS on total system cost



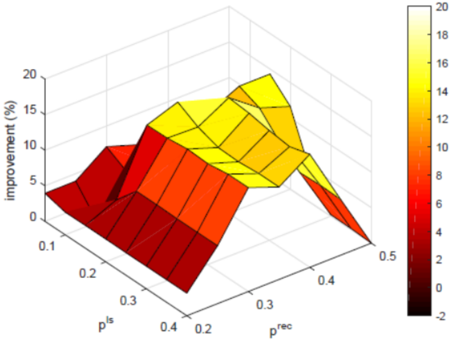
ESS case

ESS-TS case

(p^{ls}, p^{rec})= $(0.05, 0.2)$ - $(0.4, 0.5)$

Reducing p^{ls} and/or p^{rec} increases total cost in both cases

Computational Study
Effect of TS on total system cost



- TS substantially decreases total cost for medium p^{ls} and p^{rec} values
- Total system cost savings:
  - Maximum= 16.27%
  - Average= 8.5%

Computational Study

Effect of TS on ESS siting and sizing

		ESS case							ESS-TS case						
		p^{rec}							p^{rec}						
		0.20	0.25	0.30	0.35	0.40	0.45	0.50	0.20	0.25	0.30	0.35	0.40	0.45	0.50
p^{ls}	0.05	11	8	7	6	6	6	6	11	8	6	6	6	6	6
	0.10	11	9	6	5	4	4	4	10	8	6	4	4	4	4
	0.15	11	9	6	5	3	1	1	10	8	6	5	2	1	1
	0.20	11	9	6	5	3	1	—	10	8	6	5	2	—	—
	0.25	11	9	7	5	3	1	—	10	8	6	5	2	—	—
	0.30	11	9	7	5	3	1	—	10	8	6	5	2	—	—
	0.35	11	9	7	5	3	1	—	10	8	6	4	2	—	—
	0.40	11	9	7	5	3	1	—	10	8	6	4	2	—	—

- Increasing p^{ls} and/or p^{rec} reduces number of storage units
- TS decreases number of storage units

Computational Study

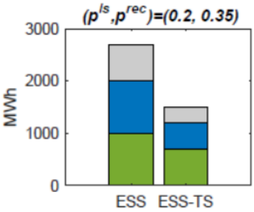
Effect of TS on ESS siting and sizing

		Improvement in energy capacity (%)							Improvement in power rating (%)						
		p^{rec}							p^{rec}						
		0.20	**0.25**	**0.30**	**0.35**	**0.40**	**0.45**	**0.50**	**0.20**	**0.25**	**0.30**	**0.35**	**0.40**	**0.45**	**0.50**
	0.05	3.06	5.08	13.33	5.43	5.43	5.43	5.43	6.53	4.77	17.55	8.27	8.27	8.27	8.27
	0.10	2.30	11.47	17.42	33.10	20.43	20.43	20.43	6.00	15.88	15.26	27.70	16.70	16.70	16.70
	0.15	2.25	10.55	2.29	16.21	30.84	3.86	3.86	5.99	14.89	3.89	15.10	27.26	4.28	4.28
p^{ls}	**0.20**	2.27	7.32	2.59	25.28	50.02	100.00	–	6.01	10.67	3.34	30.68	57.52	100.00	—
	0.25	3.17	7.19	14.82	24.51	50.69	100.00	–	7.73	10.52	13.94	30.72	56.80	100.00	—
	0.30	3.17	7.20	13.77	25.15	50.35	100.00	–	7.73	10.52	13.58	31.18	56.38	100.00	—
	0.35	3.17	7.19	14.52	26.90	48.61	100.00	–	7.73	10.52	14.30	31.44	54.56	100.00	—
	0.40	3.17	7.19	14.52	26.90	51.40	100.00	–	7.73	10.52	14.30	31.44	57.55	100.00	—

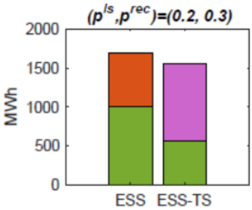
- Savings in total energy capacity:
  - Maximum: 50.69%
  - Average: 24.11%
- Savings in total power rating:
  - Maximum: 57.52%
  - Average: 26.27%

Computational Study

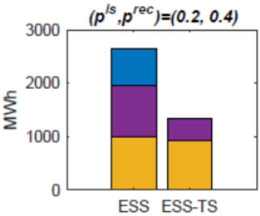
Effect of TS on ESS siting and sizing



- Decrease in total energy capacity (and power rating)



- Change locations of storage units



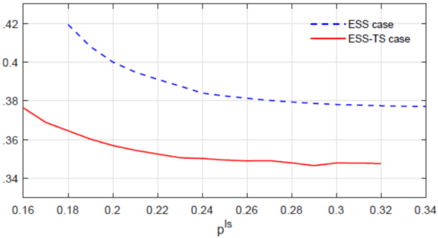
- Decrease in number of storage units

Computational Study

Effect of TS on LS and REC

- To observe effect of TS on LS and REC, pareto optimal solutions for the following model are obtained with a limited budget

$$
\begin{aligned}
min \quad & \overline{p}^{ls} \\
min \quad & \overline{p}^{rec} \\
s.t \quad & (4.2)-(4.5),(4.8)-(4.28) \\
& \sum_{i\in B}\sum_{t\in T} DS_{its} \le \overline{p}^{ls} \sum_{i\in B}\sum_{t\in T} D_{its} \\
& \sum_{i\in B}\sum_{g\in C_R}\sum_{t\in T} G_{igts} \ge (1-\overline{p}^{rec}) \sum_{i\in B}\sum_{g\in C_R}\sum_{t\in T} \overline{G}_{igts} \\
& z_{line} + z_{storage} + z_{om} \le budget
\end{aligned}
$$

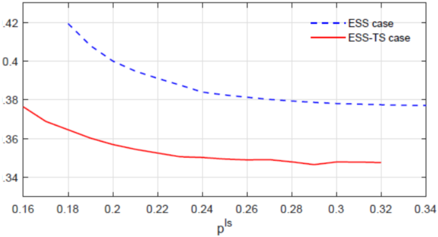


Computational Study

Effect of TS on LS and REC

- To observe effect of TS on LS and REC, pareto optimal solutions for the following model are obtained with a limited budget

$$
\begin{aligned}
min \quad & \overline{p}^{ls} \\
min \quad & \overline{p}^{rec} \\
s.t \quad & (4.2)-(4.5),(4.8)-(4.28) \\
& \sum_{i\in B}\sum_{t\in T} DS_{its} \leq \overline{p}^{ls} \sum_{i\in B}\sum_{t\in T} D_{its} \\
& \sum_{i\in B}\sum_{g\in C_R}\sum_{t\in T} G_{igts} \geq (1-\overline{p}^{rec}) \sum_{i\in B}\sum_{g\in C_R}\sum_{t\in T} \overline{G}_{igts} \\
& z_{line} + z_{storage} + z_{om} \leq budget
\end{aligned}
$$



- TS improves efficiency of the power system
  - minimum p^{ls} 0.18 –> 0.16
  - minimum p^{rec} 0.37 –> 0.35

Conclusion

- We co-optimize TS, ESS (siting and sizing) and transmission line investments.
- We analyze effect of co-optimizing control mechanisms.

Conclusion

- We co-optimize TS, ESS (siting and sizing) and transmission line investments.
- We analyze effect of co-optimizing control mechanisms.
- We conclude that
  - TS can be a more efficient and cheaper solution compared to building new lines or storages.
  - TS is noteworthy to analyze for power systems with especially renewable energy targets.
  - ESS are effective for meeting various REC limits.

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Thank you for listening

Questions & Comments?

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