Evaluating the Impact of Smart Grid Technologies on Generation Expansion Planning Under Uncertainties

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Outline

- Motivation
- Deterministic problem formulation
- Robust optimization modeling
  - Model 1: Uncertainty on right-hand side of the constraint
  - Model 2: Uncertainty on the objective function
- Numerical studies
- Conclusions

1. Motivation

Uncertain factors in smart grids：

- Aging of the electrical infrastructure
- Stochastic generation (wind $ solar)
- New smart grid technology
- Uncertain demand growth

Key issues need to be considered:

- Decision making under uncertainty
- Medium-term planning horizon

1. Motivation

The infrastructure needs to be
built to withstand the
Worst
Operating condition

- ❖But, what is the worst condition?
- ❖We don’t know!
- ❖Hence, the need of robust sets

Robust sets are regarded as the support of data distribution, and represent “uncertain-but-bounded” perturbations.

1. Motivation

- Robust optimization modeling
  - Step 1: Establishing optimization objective
  - Step 2: Robust sets based on worst uncertain realization
  - Step 3: Operating to mitigate negative effects in the best manner

- Robust optimization versus Stochastic programming
  - Robust opt. makes sense for infrastructure planning
  - Robust sets → No scenarios (no probability distribution)
  - Computational tractability

1. Motivation

- The traditional generation expansion planning problem is a problem of determining the following major objectives:
  - When to invest?
  - How much capacity to be installed?
  - What type of generation is needed?
  - Where to build new generating units?

- Mathematically, generation expansion planning can be considered as a large-scale highly nonlinear constrained multi-stage and multi-objective mathematical programming problem.

What is the robust generation expansion planning problem under uncertainties?

2. Deterministic problem formulation

❑ Nomenclature

- Indices and Sets

  S – Set of all prospective generating units

  K – Set of all existing generation units

  T – Set of planning horizons

  Λ– Set of all units generating carbon emission

- Constants

  a_{ts} – Investment cost of new unit *s* ($/MW)

  m_{ts} – Operational and maintenance cost of new unit *s* ($/MW)

  g_{tk} – Operational and maintenance cost of existing unit *k* ($/MW)

  f_{ts} – Generation cost for new unit *s* per MW ($/MW)

  d_{tk} – Generation cost for existing unit *k* per MW ($/MW)

  v_t – Unmet cost for a unit per MW ($/MW)

  l_t – Amount of load loss (MW)

  B_{tnk}– Amount of carbon emission for existing unit *k* (ton/MW)

  E_{tns}– Amount of carbon emission for new unit *s* (ton/MW)

2. Deterministic problem formulation

❑ Nomenclature

- Constants

  r – Discount rate

  l_{td} – Maximum load demand (MW)

  h_t – Revenue obtained from the generation capability benefit ($/MW)

  b_{tk_max} – Size of the kth existing generation unit (MW)

  e_{ts_max} – Size of the sth new generation unit (MW)

- Variables

  x_{ts} – Total power capacity of unit of type s to be installed in time period t (MW)

  e_{ts} – Power output of new generator s during the demand interval t (MW)

  b_{tk} – Power output of existing generator k during the demand interval t (MW)

2. Deterministic problem formulation

❑ Cost

- Investment cost

$$C_1 = \sum_{t=1}^{T} (1+r)^{-t} \sum_{s=1}^{S} a_{ts} x_{ts}$$

- Fixed operational and maintenance cost

$$C_2 = \sum_{t=1}^{T} (1+r)^{-t} \sum_{s=1}^{S} m_{ts} x_{ts} + \sum_{t=1}^{T} (1+r)^{-t} \sum_{k=1}^{K} g_{tk} q_{tk}$$

New generation units   Existing generation units

- Generation cost

$$C_3 = \sum_{t=1}^{T} (1+r)^{-t} \sum_{s=1}^{S} e_{ts} f_{ts} + \sum_{t=1}^{T} (1+r)^{-t} \sum_{k=1}^{K} b_{tk} d_{tk}$$

New generation units   Existing generation units

- Reliability cost

$$C_4 = \sum_{t=1}^{T} (1+r)^{-t} l_t v_t$$

- Environment cost

$$C_5 = \sum_{t=1}^{T} \sum_{n \in L} \left(\sum_{k=1}^{K} b_{tnk} B_{tnk} + \sum_{s=1}^{S} e_{tns} E_{tns} \right)$$

Emission of existing generation units   Emission of new generation units

2. Deterministic problem formulation

❑ **Model description**

Total cost

$$\min \ q = \sum_{i=1}^{5} w_i \bar{C}_i$$

Planning and Operation constrains

$$s.t. \ \sum_{k=1}^{K} b_{tk} + \sum_{s=1}^{S} e_{ts} \geq l_{td} + l_t$$

$$e_{ts} \leq e_{ts\_\max}$$

$$b_{tk} \leq b_{tk\_\max}$$

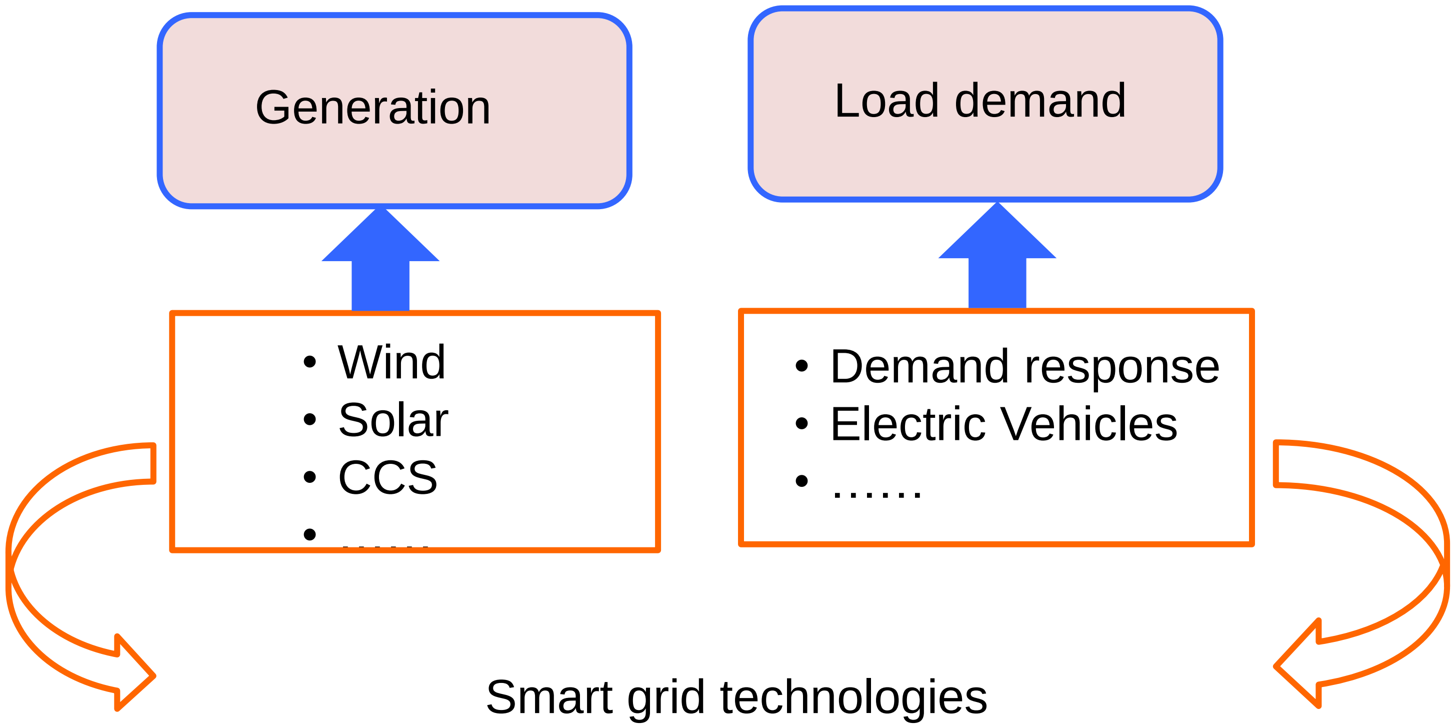
Index standardization

$$\bar{C}_i = \frac{C_i - C_i^{\min}}{C_i^{\max} - C_i^{\min}}$$

Expected value

3. Robust optimization modeling

A generation expansion plan problem is generally affected by two aspects, generation technology and demand shifting .



3. Robust optimization modeling—*Uncertainty on the right-hand side of the constraint*

Total cost

$$\min \ q = \sum_{i=1}^{5} w_i \bar{C}_i$$

Planning and Operation constrains

$$s.t. \ \sum_{k=1}^{K} b_{tk} + \sum_{s=1}^{S} e_{ts} \geq \boxed{l_{td}} + l_t$$

$$e_{ts} \leq e_{ts\_\max}$$

$$b_{tk} \leq b_{tk\_\max}$$

Expected “worst” value of uncertain parameters

Index standardization

$$\bar{C}_i = \frac{C_i - C_i^{\min}}{C_i^{\max} - C_i^{\min}}$$

3. Robust optimization modeling—*Uncertainty on the right-hand side of the constraint*

- The original formulation of this problem with uncertainty on the right-hand side of the constraint.

$$\begin{cases} \min \ cx \\ s.t. \quad Ax \geq b_0 + z\hat{b} \\ \qquad x \geq 0 \end{cases}$$

Considering parameter *b* is uncertain,

$$b \rightarrow b_0 + z\hat{b}$$

- The dual formulation of the original problem.

$$\begin{cases} \max \ b'y \\ s.t. \quad A'y \leq c' \\ \qquad y \geq 0 \end{cases}$$

"V Gabrel,C Murat. Robustness and duality in linear programming. The Journal of the Operational Research Society, Vol. 61, No. 8, 2010, pp. 1288-1296. "

3. Robust optimization modeling—*Uncertainty on the right-hand side of the constraint*

- The dual problem is equivalent to the following representation.

$$
\begin{aligned}
\max\ & b_0' y + z'\hat{b}y \\
s.t.\ & A'y \le c' \\
& z \le \Gamma_0 \\
& 0 \le z \le 1 \\
& y \ge 0
\end{aligned}
$$

- The prime-dual problem is formulated as follows.

$$
\begin{aligned}
\min\ & cx \\
s.t.\ & Ax \ge b_0' + z'\hat{b} \\
& z \le \Gamma_0 \\
& 0 \le z \le 1 \\
& x \ge 0
\end{aligned}
$$

3. Robust optimization modeling—*Uncertainty on the right-hand side of the constraint*

- The original problem of generation expansion planning with uncertain l_{td}

$$\min \; \theta = \sum_{i=1}^{5} w_i \bar{C}_i$$

$$s.t. \; \sum_{k=1}^{K} b_{tk} + \sum_{s=1}^{S} e_{ts} \geq l_{td} + l_t$$

$$e_{ts} \leq e_{ts\_\max}$$

$$b_{tk} \leq b_{tk\_\max}$$

$$\bar{C}_i = \frac{C_i - C_i^{\min}}{C_i^{\max} - C_i^{\min}}$$

$$l_{td} \in [l_{td\_\min}, l_{td\_\max}]$$

- The robust counterpart of the original problem

$$\begin{cases} \min \; \theta(x_{ts}, b_{tk}, e_{ts}) \\ s.t. \; \sum_{k=1}^{K} b_{tk} + \sum_{s=1}^{S} e_{ts} - l_t \geq \frac{1}{2}[(l_{td\_\min} + l_{td\_\max})' + z'\hat{b}_{lt}], \forall t \\ \sum_{i=1}^{V} z_i \leq \Gamma_0 \\ 0 \leq z_i \leq 1, \; \forall i = 1, \cdots, V \\ e_{ts} \leq e_{ts\_\max}, \forall t \\ b_{tk} \leq b_{tk\_\max}, \forall t \\ (\hat{b}_{lt})_{ii} = (l_{td\_\max})_i - (l_{td\_\min})_i, \; \forall i = 1, \cdots, V \end{cases}$$

The problem can then be handled by the traditional linear programming technique.

3. Robust optimization modeling—*Uncertainty on the objective function*

Total cost

$$\min\ q=\sum_{i=1}^{5} w_i \bar{C}_i$$

→ Expected "worst" value of uncertain parameters

Planning and Operation constrains

$$s.t.\ \sum_{k=1}^{K} b_{tk} + \sum_{s=1}^{S} e_{ts} \geq l_{td} + l_t$$

$$e_{ts} \leq e_{ts\_\max}$$

$$b_{tk} \leq b_{tk\_\max}$$

Index standardization

$$\bar{C}_i = \frac{C_i - C_i^{\min}}{C_i^{\max} - C_i^{\min}}$$

3. Robust optimization modeling—*Uncertainty on the objective function*

Considering the impact of demand response, the benefit will be reflected by the reduction of generation capacities. The generation cost C_3 is transformed into the following presentation:

$$C_3' = \left[\sum_{t=1}^{T} (1+r)^{-t} \sum_{s=1}^{S} e_{ts} f_{ts} + \sum_{t=1}^{T} (1+r)^{-t} \sum_{k=1}^{K} b_{tk} d_{tk}\right] - p_t b_t h_t$$

$$b_t = \sum_{k=1}^{K} b_{tk} + \sum_{s=1}^{S} e_{ts}$$

Substituted generation capacity from the usage of demand response resources

- p_t is the substitution percentage of generation capacity from the usage of demand response resources.
- $p_t b_t$ is equivalent to generation substituted capacity due to demand response.

3. Robust optimization modeling—*Uncertainty on the objective function*

Considering the parameter p_t is uncertainty which is on the objective.

$$\min_{X_t}\sup_{z\in U} q(X_t, p_t) = \min_{X_t}\max_{z\in U} q(X_t, \bar{p}_t + z)$$

$$= \min_{X_t}\max_{z\in U}\Big[\sum_{\substack{i=1,\\ i\neq 3}}^{5} w_i \bar{C}_i + w_3 \bar{C}'_3(e_{ts}, b_{tk}, \bar{p}_t + z)\Big]$$

Uncertain set

F(X)

$$F(X_t) = \max\Big[\sum_{\substack{i=1,\\ i\neq 3}}^{5} w_i \bar{C}_i + w_3 \bar{C}_3 - \sum_{t=1}^{T}(1+r)^{-t}\sum_{k=1}^{K}\bar{p}_t b_{tk} h_t\Big] - \max_{z\in U}\left[\sum_{t=1}^{T}(1+r)^{-t}\sum_{k=1}^{K} z b_{tk} h_t\right]$$

Uncertainty is considered by ζ.

"Ben-Tal A, Nemirocski A. Robust solutions of uncertain linear programs. Oper. Res. Lett., Vol. 25,1999, pp. 1-13. "

3. Robust optimization modeling—*Uncertainty on the objective function*

For the uncertain term of *F(X)*, $\max_{z \in U}\left[\sum_{t=1}^{T}(1+r)^{-t}\sum_{k=1}^{K} z b_{tk} h_t\right]$

The Lagrangian function can be established:

$$L(z,\lambda,\delta,\gamma) = z^T b h' - \lambda e^T z + \delta^T(\underline{z} - z) + \gamma^T(z - \bar{z})$$

$$\frac{\partial L}{\partial z} = b_k h' - \lambda e - \delta + \gamma = 0$$

$$\min_{(\lambda,\delta,\gamma)} \max_{z} L(z,\lambda,\delta,\gamma) = \min_{(\lambda,\delta,\gamma)}[\delta^T \underline{z} - \gamma^T \bar{z}]$$

$$s.t.\ \ b_k h' - \lambda e - \delta + \gamma = 0$$

$$\delta,\gamma \geq 0$$

3. Robust optimization modeling—*Uncertainty on the objective function*

The robust counterpart of the original problem can be obtained with the following representation.

$$\min_{X_t}\sup_{z\in U}\theta(X_t,p_t)=\min_{(X_t,\lambda,\delta,\gamma)}\Big[\sum_{\substack{i=1,\\ i\neq 3}}^{5} w_i\bar{C}_i+w_3\bar{C}_3-\sum_{t=1}^{T}(1+r)^{-t}\sum_{k=1}^{K}\bar{p}_t b_{tk}h_t\Big]-[\delta^T\underline{z}-\gamma^T\bar{z}]$$

$$\begin{aligned} s.t.\quad & b_k+e_s\geq l_d+l\\ & b_k\leq b_{k\_\max}\\ & e_s\leq e_{s\_\max}\\ & b_k h'-\lambda e-\delta+\gamma=0\\ & \delta,\gamma\geq 0 \end{aligned}$$

The modified part of original objective

New added constraints

This problem can be handled by the traditional linear programming technique.

3. Robust optimization modeling—*Comparison*

Deterministic problem

$$\min c^T x + b^T y$$
$$s.t.\quad Ax + By \le Kd$$
$$c^T x \le \Pi$$

Stochastic programming problem

$$\min c^T x + b^T y$$
$$s.t.\quad \Pr\{Ax + By \le Kd \mid d \sim N(\mu, \sigma^2)\} \le \alpha$$
$$c^T x \le \Pi$$

Deterministic problem ↔ Stochastic programming problem: $d \sim N(\mu, \sigma^2)$; Uncertainty realization d^*

Robust optimization problem

$$\min_{x,y} c^T x + b^T y$$
$$s.t.\quad \max_{d \in U} Ax + By \le Kd$$
$$c^T x \le \Pi$$

Deterministic problem ↔ Robust optimization problem: $d \in U$; Uncertainty realization d^*

3. Robust optimization modeling

--Summary of solution procedure

Deterministic optimization Problem
(Linear Programming)

↓

Robust optimization modeling

- Uncertainty on the right-hand side of the constraints
- Uncertainty on the objective function

↓ ↓

Robust Counterpart of the model 1 with uncertainty on the right-hand side of the constraints

(Deterministic Linear Programming)

Robust Counterpart of the model 2 with uncertainty on the objective function

(Deterministic Linear Programming)

3. Robust optimization modeling—*Computational complexity*

Deterministic model

$$\min \ \theta = \sum_{i=1}^{5} w_i \bar{C}_i$$

$$s.t. \ \sum_{k=1}^{K} b_{tk} + \sum_{s=1}^{S} e_{ts} \ge l_{td} + l_t$$

$$e_{ts} \le e_{ts\_max}$$

$$b_{tk} \le b_{tk\_max}$$

$T \times (2S+K)$

Robust counterpart 1

$$\min \ \theta(x_{ts}, b_{tk}, e_{ts})$$

$$s.t. \ \sum_{k=1}^{K} b_{tk} + \sum_{s=1}^{S} e_{ts} - l_t \ge \frac{1}{2}[(l_{td\_min} + l_{td\_max})' + z'\hat{b}_{lt}], \forall t$$

$$\sum_{i=1}^{V} z_i \le \Gamma_0$$

$$0 \le z_i \le 1, \ \forall i = 1, \cdots, V$$

$$e_{ts} \le e_{ts\_max}, \forall t$$

$$b_{tk} \le b_{tk\_max}, \forall t$$

$$(\hat{b}_{lt})_{ii} = (l_{td\_max})_i - (l_{td\_min})_i, \ \forall i = 1, \cdots, V$$

$T \times (2S+K) + V$

Robust counterpart 2

$$\min_{X_t} \sup_{z \in U} (X_t, p_t)$$

$$s.t. \ b_k + e_s \ge l_d + l$$

$$b_k \le b_{k\_max}$$

$$e_s \le e_{s\_max}$$

$$b_k h' - \lambda e - d + g = 0$$

$$d, g \ge 0$$

$T \times (2S+K) + 3K$

Number of decision variables

4. Numerical studies—*Background*

- East China Power Grid involves Jiangsu, Anhui, Shanghai, Zhejiang and Fujian Power Grids.
- By the end of 2013, total generation capacity is 224890 MW, thermal capacity is 190410 MW, hydro capacity is 14872 MW, pump capacity is 6980 MW and renewable energy capacity is 12628 MW.
- In 2013, peak load is 209094 MW when happens on 2013.08.08.

A regional power grid planning in East China Power Grid is studied in this work.

4. Numerical studies—*Data and assumption*

It is assumed that a 10 year planning horizon is taken into account in the simulation procedure.

In the example system, there are 32 generation units consisting of Coal/Steam, Oil/Steam, combined cycle gas turbine (CCGT), Oil/combustion turbine (CT) and nuclear in the existing network.

Table 1

Characteristics of existing generation units

Type	Capacity (MW)	Unav.	Fixed OM (M$)	Gen. cost ($/MW)	CO_2 (lbs/MW)
Coal/Steam	3´ 76	0.02	18.6352	7.07	1840
	3´ 155	0.04	38.006	7.07	1840
	1´ 350	0.08	85.82	7.07	1840
Oil/Steam	2´ 100	0.04	10.22	18.89	1638
	3´ 197	0.05	20.1334	18.89	1638
	3´ 12	0.02	1.2264	18.89	1638
CCGT	3´ 50	0.02	6.13	10.95	889
	2´ 12	0.07	1.4712	10.95	889
	2´ 20	0.07	2.452	10.95	889
	1´ 76	0.02	9.3176	10.95	889
	1´ 155	0.06	19.003	10.95	889
	1´ 100	0.06	12.26	10.95	889
CT	2´ 20	0.1	2.044	18.89	1362.5
	3´ 50	0.1	5.11	18.89	1362.5
Nuclear	2´ 400	0.12	234	0.83	0

4. Numerical studies—*Data and assumption*

We assume that the peak load in the base year is 2900 MW, and the demand will increase 6% annually. The unmet cost is assumed as 10000 $/MW. The discount rate is 0.05.

Table 2

Characteristics of candidate generation units

Type	Cap. (MW)	Unav.	Gen. cost ($/MW)	Capital cost (M$)	Fixed OM (M$)	CO_2 (lbs/MW)
Oil/Steam	197	0.05	18.89	80.573	20.13	1638
Coal/Steam	155	0.04	7.07	179	38.01	1840
Wind	50	0.05	0	69.737	11.62	0
Nuclear	400	0.12	0.83	847	234	0
CCGT	76	0.021	10.95	40.736	9.318	889
CCS	155	0.04	7.07	245.23	43.71	184

4. Numerical studies—*Data and assumption*

- Statistics from the U.S.A. showed that DR was capable of decreasing the peak load by 5.8% to 6.7%. As a result, it is assumed that the range of the annual uncertain load can be from 93.3% to 94.2% of the corresponding nominal load over the planning horizon.

- The nominal value of the substitution proportion of generation capability p_t is assumed to be 0.6% in the beginning of the planning period, and the sharing will increase by 10% annually. The ranges of the uncertainty p_t are $\pm 0.1\%$

4. Numerical studies—*Data and assumption*

For the weight combinations, two cases are proposed to show the optimal robust plans from the views of **cost-oriented** and **emission-oriented** respectively.

- Case 1 (cost-oriented): The value of each weight coefficient is 0.2.
- Case 2 (emission-oriented): The values of weight coefficient w_1~w_4 are equal to 0.1, and the weight value of w_5 is 0.6.

4. Numerical studies—*Results*

Table 3

The optimal robust plan of candidate generation technologies only considering **the uncertain load demand** for **Case 1(Cost-oriented)**

Type	*t*=1	*t*=2	*t*=3	*t*=4	*t*=5	*t*=6	*t*=7	*t*=8	*t*=9	*t*=10
Oil/Steam	-	-	-	-	-	-	-	147.8	185.4	203.5
Coal/Steam	-	-	-	-	-	-	-	-	-	-
Wind	-	72	-	62.3	-	-	-	-	-	-
Nuclear	-	-	-	-	-	-	-	-	-	-
CCGT	76.5	210	-	231	128	249.1	-	-	-	81.2
CCS	-	-	183	-	-	-	-	-	-	-

More CCGT units are built with considerations of least-cost.

- **TOTAL ADDED CAPACITY IS 1829.8 MW.**

4. Numerical studies—*Results*

Table 4

The optimal robust plan of candidate generation technologies only considering **the uncertain load demand** for **Case 2 (emission-oriented)**

Type	*t*=1	*t*=2	*t*=3	*t*=4	*t*=5	*t*=6	*t*=7	*t*=8	*t*=9	*t*=10
Oil/Steam	-	-	-	-	-	-	-	100.5	-	162
Coal/Steam	-	-	-	-	-	-	-	-	-	-
Wind	85.2	124.1	150.9	-	-	-	-	-	-	-
Nuclear	-	-	-	-	-	-	-	-	-	-
CCGT	-	71.3	79.5	-	-	176.7	135.2	-	-	-
CCS	-	-	-	162.3	141.5	-	-	-	-	-

New added clean energy generation units for least-emissions

❖ **TOTAL ADDED CAPACITY IS 1389.2 MW.**

4. Numerical studies—*Results*

Table 5

The optimal robust plan of candidate generation technologies only considering **the uncertain substitution percentage** p_t for **Case 1 (Cost-oriented)**

Type	*t*=1	*t*=2	*t*=3	*t*=4	*t*=5	*t*=6	*t*=7	*t*=8	*t*=9	*t*=10
Oil/Steam	-	-	-	-	-	-	-	154.6	127.4	-
Coal/Steam	-	-	-	-	-	-	-	-	-	-
Wind	-	-	51.7	85.9	-	-	83.3	-	-	-
Nuclear	-	-	-	-	-	-	-	-	-	-
CCGT	88.2	128.5	140.1	133.1	142.5	-	137.8	-	-	183
CCS	-	-	-	-	-	-	-	-	-	-

More CCGT units are built with considerations of least-cost.

❖ **TOTAL ADDED CAPACITY IS 1456.1MW, LESS THAN 1829.8 MW IN TABLE 3.**

4. Numerical studies—*Results*

Table 6

The optimal robust plan of candidate generation technologies only considering **the uncertain substitution percentage p_t** for **Case 2(emission-oriented)**

Type	*t*=1	*t*=2	*t*=3	*t*=4	*t*=5	*t*=6	*t*=7	*t*=8	*t*=9	*t*=10
Oil/Steam	-	-	-	-	-	-	-	139.9	-	-
Coal/Steam	-	-	-	-	-	-	-	-	-	-
Wind	76.2	72.3	75.4	-	125.6	-	-	-	-	-
Nuclear	-	-	-	-	-	-	-	-	-	-
CCGT	-	86.1	100.2	-	-	113	124.5	-	-	109.8
CCS	-	-	-	179.8	-	-	-	-	-	-

New added clean energy generation units for least-emissions

❖ **TOTAL ADDED CAPACITY IS 1202.8MW, LESS THAN 1389.2 MW IN TABLE 4.**

5. Conclusions

- The generation expansion planning problem under uncertainties can be handled based on robust optimization methodology.

  (Robust optimization models make sense for infrastructure planning).
- The uncertainties considered in the generation expansion planning mainly include load demand growth influenced by demand evolution and deregulation as well as smart grid technologies (e.g. demand response).
- Robust optimization models are computational tractable.
- Sensitivity analysis provides the advantage to analyze the impact of the uncertainty budgets and weights on the robustness of the optimization model.
- **Future work: 1) nonlinearity; 2) combined uncertainties in objective and constraints**

The Achieved Research Results:

1. Evaluating the Impact of Smart Grid Technologies on Generation Expansion Planning under Uncertainties, ***International Transactions on Electrical Energy Systems***, 2015.
2. A Two-stage Robust Stochastic Programming Approach for Generation Expansion Planning of Smart Grids under Uncertainties, ***Proceedings of TUB-SJTU Joint Workshop on Smart Cities – an Electric Engineering and Computer Science View,*** Springer Berlin Heidelberg, 2015.
3. A Robust Optimization Approach to Evaluate the Impact of Smart Grid Technologies on Generation Plans, ***2014 International Conference on Power System Technology (POWERCON)***, Chengdu, Oct. 2014, pp. 1706-1711.
4. A Distributed Robust Optimization Model for Integrated Electricity and Natural Gas Network Planning under Moment Uncertainty, ***Power System Technology***, 2015.(Special issue: Energy Internet)

Thank you!

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