Indirect Mechanism Design for Efficient Integration of Uncertain Resources in Power System Operations

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Background

- Solving multi-stage multi-period SCUC and SCED in the presence of uncertain resources (renewables, DERs, EVs…)
  - Deterministic optimization: employ point forecasts of randomness.
    - Not accurately capturing the uncertainties.
  - Stochastic optimization: employ “scenarios” that represent randomness
    - Computational complexity drastically increases.
    - Unknown uncertainties.
  - Robust optimization: employ uncertainty sets and worst-case assumptions.
    - Conservative

Motivation

- Can we reach the **social optimum** defined by the stochastic optimization, without having the ISO actually solving this computationally challenging problem?

- Goals
  – **Practicality:** Design a "sufficiently simple" market mechanism where the ISO solves a **computationally tractable** problem, and yet
  – **Efficiency:** the market reaches social efficiency at its equilibria granted **strategic behaviors** of the participants.

Approach

- Indirect mechanism design: **Resources as market participants**
  - Information collection
  - System operation
  - Payment allocation

Approach

- Indirect mechanism design: Existing example: Energy market
  - Information collection
    - Generators submit their cost functions and constraints
  - System operation
    - SCUC and SCED
  - Payment allocation
    - Multi-settlement payments with LMPs

Approach

- Indirect mechanism design: With uncertain resources
  - Information collection
    - What information should we elicit from uncertain resources?
  - System operation
    - What optimization problems should we solve given these info?
  - Payment allocation
    - How should we pay each uncertain resource?

- Key question: how would the market **equilibrium** perform re: **social efficiency,** granted the market participants act *strategically*, not assuming perfect competition or truthfulness?

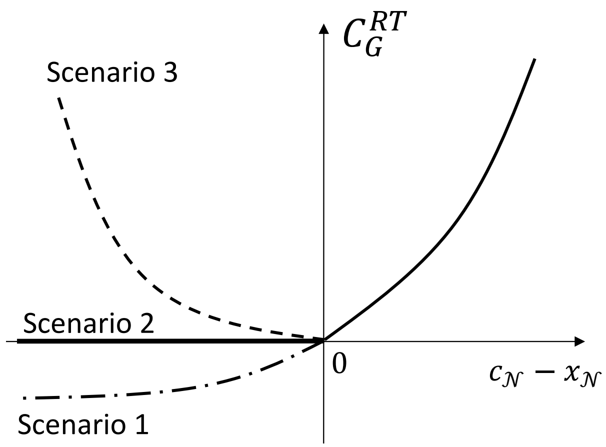
Related Work

- Grid operation and planning with uncertain renewables
  - [Varaiya, Wu, Bialek 11], [DeJonghe, Hobbs, Belmans 12]
- Market equilibrium in deterministic settings
  - Single stage: [Hu & Ralph 07] [Ruiz et al. 14] [Anderson & Philpott 02] [Joahri & Tsitsiklis 11] [Lin & Bitar 17]
  - Multi-stage: [Allaz & Vila 93] [Yao, Adler, Oren 08]
- Renewables bidding and payments in power markets
  - Single RPP [Bitar et al. 12] [Morales, Conejo, Pérez-Ruiz 10] [Baringo & Conejo 13, 16]
  - Many RPPs / aggregation [Baeyens et al. 13], [Nayyar et al. 13], [Lin & Bitar 14], [Z. et al. 15] [Khazaei & Z. 17, 18], [Zhang Rajagopal Johari 15].

Integrating Renewables: Uncongested Case

[Khazaei and Z. 18]

- Model: A two-stage (DA-RT) single-period problem
  - Two sets of conventional generators,
    - DA generators:
      - Can be slow but cheap
    - RT generators:
      - Can be Fast but expensive



There can be an arbitrary overlap between the two sets.

  - *N* Renewable Power Producers (RPPs)
  - Not yet considering UC, security constraints, etc.
  - Focus on the behaviors of strategic RPPs.

Optimal Dispatch (Uncongested)

- Stochastic optimization (assuming RPPs' variable costs are zero)

$$\min_{q_G^{DA}} \quad C_G^{DA}\left(q_G^{DA}\right) + \mathbb{E}_{X_{\mathcal{N}}}\left[C_G^{RT}\left(L - q_G^{DA} - x_{\mathcal{N}}\right)\right]$$

- DA and RT Prices --- Marginal Cost of Generation

$$p^f = \left.\frac{dC_G^{DA}(q)}{dq}\right|_{q_G^{DA}}, \quad p^r = \left.\frac{dC_G^{RT}(q)}{dq}\right|_{q_G^{RT}}$$

- Lemma (Optimal Dispatch, Uncongested)
  - The DA dispatch is optimal iff $p^f = \mathbb{E}_{X_{\mathcal{N}}}\left[p^r\right]$.

Proposed Market Mechanism

- Information collection
  - At DA, each RPP *i* submits a "commitment", c_i, to the ISO.
- System operation
  - At DA, the ISO takes the commitment as "firm", and dispatch the DA generators: $q_G^{DA} = L - c_{\mathcal{N}}$.
  - At RT, the renewables are realized, the RT generators are dispatched to balance the system: $q_G^{RT} = c_{\mathcal{N}} - x_{\mathcal{N}}$.
- Payment allocation to RPPs according to the DA and RT Prices

$$\mathcal{P}_i = p^f(c_{\mathcal{N}}) \cdot c_i - p^r(c_{\mathcal{N}} - x_{\mathcal{N}}) \cdot (c_i - x_i)$$

  - A price-making environment $p^f = \left.\frac{dC_G^{DA}(q)}{dq}\right|_{q_G^{DA}}, \quad p^r = \left.\frac{dC_G^{RT}(q)}{dq}\right|_{q_G^{RT}}$

Benefits for the ISO

- ISO's dispatch problem is much simpler.

$$q_G^{DA} = L - c_{\mathcal{N}}$$

$$q_G^{RT} = c_{\mathcal{N}} - x_{\mathcal{N}}$$

  - The uncertainty of renewables are hidden from the ISO, but taken on by the RPPs.

- ISO only elicits one number, c_i, from each RPP.
  - Very simple to implement.

Outcome of the Proposed Mechanism

- A Non-Cooperative Game of RPPs
  - When submitting its DA commitment c_i, a strategic RPP i will maximize its expected profit, given by

$$\pi_i(c_i, c_{-i}) = p^f(c_{\mathcal{N}}) \cdot c_i - \mathbb{E}\left[p^r(c_{\mathcal{N}} - x_{\mathcal{N}}) \cdot (c_i - x_i)\right]$$

    - The expected profit depends on others' commitments, the conventional generators' cost functions and production levels, and the joint distribution of the renewables.

  - **The Game among the RPPs in the DA market**
    - Players: the N RPPs
    - Strategies: Each RPP's firm power commitment at DA
    - Payoffs: Each RPP's expected profit

Outcome of the Proposed Mechanism (cont.)

- The outcome of the commitment game – **Nash Equilibrium**
  - NE: a set of commitments $c_1, c_2, \ldots, c_N$, such that each c_i optimally solves its best response problem, simultaneously,

$$\forall i,\ \ c_i \in \underset{c_i}{\operatorname{argmax}}\, \pi_i(c_i, c_{-i})$$

- Questions
  - Does NE induces the optimal operation decisions by the ISO fully considering the RPPs' uncertainties?
    In other words, is the NE "efficient"?

Main Results (Uncongested)

- Theorem (Asymptotic Efficiency of Pure NE)

  The social efficiency is achieved at any pure NE as $N \to \infty$,

$$\lim_{N \to \infty} c_{\mathcal{N}}^{\star,ne} = c_{\mathcal{N}}^{o}$$

  Moreover, the gap between the NE and the social optimum has a closed-form characterization,

$$p^f\left(c_{\mathcal{N}}^{\star,ne}\right) - \mathbb{E}_{X_{\mathcal{N}}}\left[p^r\left(c_{\mathcal{N}}^{\star,ne} - x_{\mathcal{N}}\right)\right] = -\frac{\left.\frac{d\mathbb{E}_{X_{\mathcal{N}}}[\mathcal{P}_{\mathcal{N}}]}{dc_{\mathcal{N}}}\right|_{c_{\mathcal{N}}^{\star,ne}}}{N-1}$$

Remarks

- To compute the NE solution, each RPP *i* only needs the two-dimensional joint pdf of X_i *and* X_N, not the joint pdf of all RPPs.

- The mechanism offers a justified way for paying the RPPs.

$$\mathcal{P}_i = p^f(c_{\mathcal{N}}^{ne}) \cdot c_i^{ne} - p^r(c_{\mathcal{N}}^{ne} - x_{\mathcal{N}}) \cdot (c_i^{ne} - x_i)$$

Numerical Experiments

- Simulation setting
  - Generators' parameters

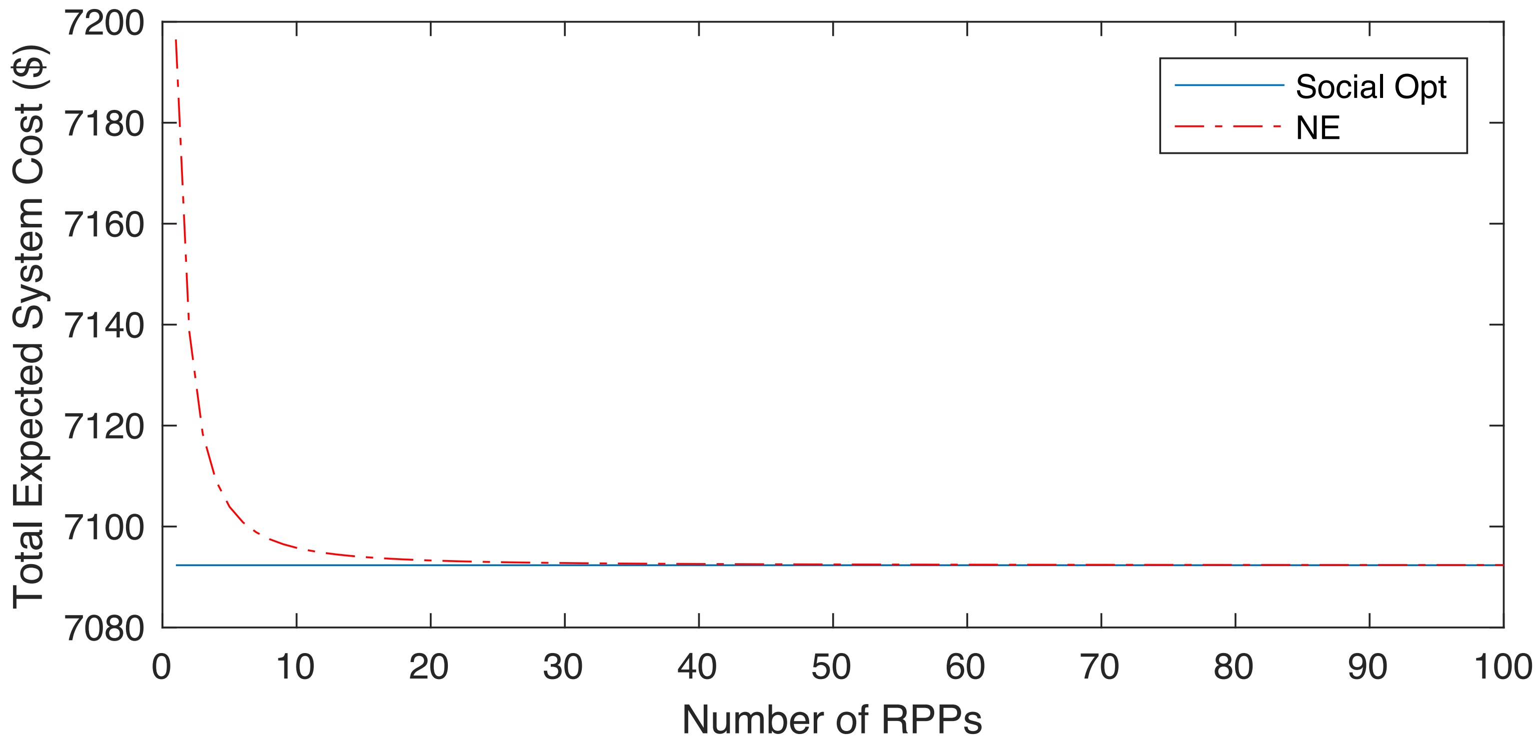
$$C_G^{DA}(q) = \frac{1}{2}\alpha_G^{DA} \cdot q^2 + \beta_G^{DA} \cdot q,$$
$$C_G^{RT}(q) = \frac{1}{2}\alpha_G^{RT} \cdot q^2 + \beta_G^{RT} \cdot q.$$

	α_G $\left(\$/(MWh)^2\right)$	β_G $(\$/(MWh))$
DA	0.01	15
RT	0.02	30

  - Renewables' parameters
    - For a variety of *N*, consider *N* i.i.d RPPs.
    - Consider a fixed expectation (500MW) and standard deviation (30MW) for the *total* renewable generation.

Numerical Experiments (cont.)

- Total Expected System Cost: Optimum vs. NE



Integrating Renewables: Congested Case

[Khazaei, Z. and Sun 19]

- A two-stage (DA-RT) single-period problem
  - Conventional generators and RPPs at arbitrary locations in a power network.
  - Not yet considering UC, security constraints, etc.

- The optimal DA dispatch requires solving a **two-stage** stochastic optimization problem with power network constraints.

Proposed Market Mechanism

- Information collection
  - At DA, each RPP *i* submits a "commitment", c_i, to the ISO.
- System operation
  - At DA, the ISO takes the commitments as "firm", and solves a deterministic OPF for DA dispatch to balance the system.
  - At RT, the renewables $\{X_i\}$ are realized, the ISO solves a deterministic OPF for RT dispatch to balance the system.
- Payment allocation according to the DA and RT **LMPs (price making)**

$$p_m^{DA} \cdot c_i - p_m^{RT} \cdot (c_i - X_i)$$

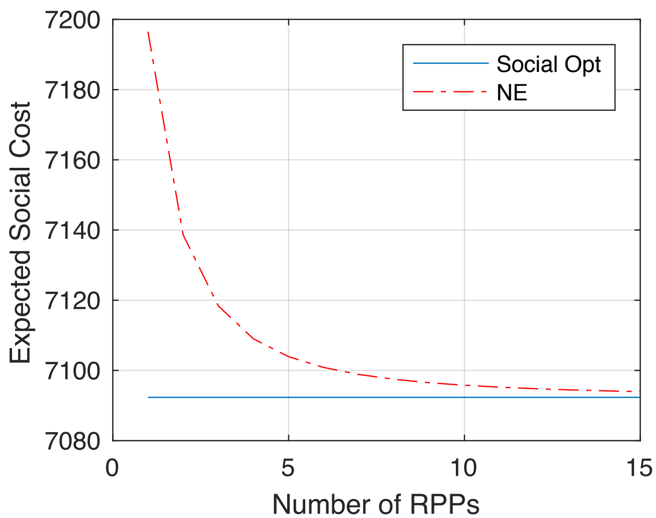
Benefits for the ISO

- ISO's only solves a deterministic DA dispatch, and hence can directly apply existing software/solvers.
  - The uncertainty of renewables are hidden from the ISO, but taken on by the RPPs.

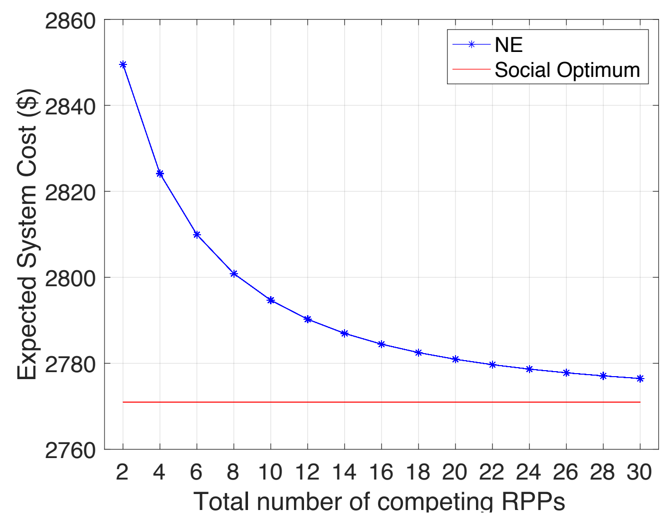
- ISO only elicits one number, c_i, from each RPP.
  - Very simple to implement.

Outcome of the Proposed Mechanism

- A Non-Cooperative Game of RPPs
- The crux of the work is **efficient computation of the NE**.
- We develop a method for efficiently computing the NE based on **finding the congestion pattern at NE**.



Uncongested



congested, IEEE 14-bus

Finding NE in the Congested Case

- Observations
  - No analytical form of LMPs.
    - For each RPP, the best response condition, while can be evaluated numerically, does not enjoy an analytical form.
    - The results from the uncongested case do not hold.

Finding NE in the Congested Case

- Observations
  - No analytical form of LMPs.
    - For each RPP, the best response condition, while can be evaluated numerically, does not enjoy an analytical form.
    - The results from the uncongested case do not hold.
- Idea
  - If, for some reason, the ***congestion pattern*** **at NE** is known:
    - Finding the NE becomes much simplified, and in fact reduces to solving a set of linear equations when generators have quadratic generation costs.

Finding NE assuming a Congestion Pattern

– DA market clearing

$$\min_{\boldsymbol{q}^D} \sum_{i \in S_G^D} C_i^D\left(q_i^D\right) = \sum_{i \in S_G^D} \left(\frac{1}{2}\alpha_i^D \cdot (q_i^D)^2 + \beta_i^D q_i^D\right)$$

$$\text{s.t.} \sum_{i \in S_G^D} q_i^D = \sum_{u \in \mathcal{N}} L_u^D - \sum_{k \in S_R} c_k, \quad \tilde{q}_u^D = \sum_{i \in S_{G,u}^D} q_i^D + \sum_{k \in S_{R,u}} c_k - L_u^D,$$

$$\left| \sum_{u \in \mathcal{N}} PTDF_{u,o}^{(m,n)} \cdot \tilde{q}_u^D - \sum_{v \in \mathcal{N}} PTDF_{v,o}^{(m,n)} \cdot \tilde{q}_v^D \right| \leq T^{(m,n)}, \quad \forall (m,n) \in S_T,$$

– RT market clearing

$$\min_{\boldsymbol{q}^R} \sum_{j \in S_G^R} C_j^R\left(\hat{q}_j^R\right) = \sum_{j \in S_G^R} \left(\frac{1}{2}\alpha_j^R \cdot (\hat{q}_j^R)^2 + \beta_j^R \hat{q}_j^R\right)$$

$$\text{s.t.} \sum_{j \in S_G^R} q_j^R = \sum_{k \in S_R} \left(c_k - x_k\right), \quad \tilde{q}_u^R = \sum_{j \in S_{G,u}^R} q_j^R + \sum_{i \in S_{G,u}^D} q_i^D + \sum_{k \in S_{R,u}} x_k - L_u^D,$$

$$\left| \sum_{u \in \mathcal{N}} PTDF_{u,o}^{(m,n)} \cdot \tilde{q}_u^R - \sum_{v \in \mathcal{N}} PTDF_{v,o}^{(m,n)} \cdot \tilde{q}_v^R \right| \leq T^{(m,n)}, \quad \forall (m,n) \in S_T,$$

Finding NE assuming a Congestion Pattern (cont.)

– DA market clearing assuming a congestion pattern

Theorem 1: For an assumed DA congestion pattern in the DA market, the optimal solution of the DA economic dispatch in (1a)-(1c) is a linear function of the DA commitments of the RPPs as

$$\boldsymbol{q}^D = G_1^D \boldsymbol{c} + G_2^D. \tag{8}$$

Similarly, the DA-LMPs at the DA market is a linear function of the DA commitments of the RPPs as

$$\boldsymbol{\lambda}^D = H_1^D \boldsymbol{c} + H_2^D. \tag{9}$$

– RT market clearing assuming a congestion pattern

Theorem 2: For an assumed RT congestion pattern in the RT market, a given set of power dispatches of DA conventional generators in the DA market, the optimal solution of the RT economic dispatch in (3a)-(4) is a linear function of the RPPs' DA commitments and RT realizations as

$$\boldsymbol{q}^R = G_1^R \boldsymbol{c} + G_2^R \boldsymbol{x} + G_3^R. \tag{10}$$

Similarly, the RT-LMPs is a linear function of the RPPs' DA commitments and RT realizations as

$$\boldsymbol{\lambda}^R = H_1^R \boldsymbol{c} + H_2^R \boldsymbol{x} + H_3^R. \tag{11}$$

– RPPs best responses assuming a congestion pattern - a set of linear equations

$$\boldsymbol{\pi} = \text{diag}\left((E_R)^\top \boldsymbol{\lambda}^D\right) \boldsymbol{c} + \mathbb{E}\left[\text{diag}\left((E_R)^\top \boldsymbol{\lambda}^R\right)(\boldsymbol{x} - \boldsymbol{c})\right].$$

$$\left.\frac{d\pi_k}{dc_k}\right|_{(c_1,\cdots,c_K)=(c_1^\star,\cdots,c_K^\star)} = 0,\ \forall k \in S_R. \quad \Rightarrow \quad \begin{aligned} &\left(\text{diag}\left(\text{diag}\left((E_R)^\top\left(H_1^D - H_1^R\right)\right)\right) + (E_R)^\top\left(H_1^D - H_1^R\right)\right)\boldsymbol{c} \\ &+ (E_R)^\top\left(H_2^D - H_2^R\boldsymbol{\mu} - H_3^R\right) + \text{diag}\left(\text{diag}\left((E_R)^\top H_1^R\right)\right)\boldsymbol{\mu} = 0. \end{aligned}$$

Finding NE in the Congested Case

- Observations
  - No analytical form of LMPs.
    - For each RPP, the best response condition, while can be evaluated numerically, does not enjoy an analytical form.
    - The results from the uncongested case do not hold.
- Idea
  - If, for some reason, the ***congestion pattern* at NE** is known:
    - Finding the NE becomes much simplified, and in fact reduces to solving a set of linear equations when generators have quadratic generation costs.
  - *How do we find the congestion pattern at NE?*

Finding NE in the Congested Case (cont.)

- Solution Algorithm
  - *Assuming* a congestion pattern:
    - Find the set of RPP's commitments $\{c_i\}$ at NE under this **assumed congestion**: This provides a **candidate** for the true NE.

Finding NE in the Congested Case (cont.)

- Solution Algorithm
  - *Assuming* a congestion pattern:
    - Find the set of RPP's commitments $\{c_i\}$ at NE under this **assumed congestion**: This provides a **candidate** for the true NE.
    - Assuming the set of commitments at this candidate NE, solve the ISO's problem of optimal deterministic dispatch. Observe the **resulting congestion** at the optimal solution.

Finding NE in the Congested Case (cont.)

- Solution Algorithm
  - *Assuming* a congestion pattern:
    - Find the set of RPP's commitments $\{c_i\}$ at NE under this **assumed congestion**: This provides a **candidate** for the true NE.
    - Assuming the set of commitments at this candidate NE, solve the ISO's problem of optimal deterministic dispatch. Observe the **resulting congestion** at the optimal solution.
    - **If the assumed and the resulting congestion patterns agree, the NE candidate is a true NE.**

Finding NE in the Congested Case (cont.)

- Solution Algorithm
  - *Assuming* a congestion pattern:
    - Find the set of RPP's commitments $\{c_i\}$ at NE under this **assumed congestion**: This provides a **candidate** for the true NE.
    - Assuming the set of commitments at this candidate NE, solve the ISO's problem of optimal deterministic dispatch. Observe the **resulting congestion** at the optimal solution.
    - **If the assumed and the resulting congestion patterns agree, the NE candidate is a true NE.**
  - Otherwise, *test another congestion pattern assumption*
    - E.g., move on to test the resulting congestion from the last iteration.
    - Or employ some other search algorithm.

Computational Complexity

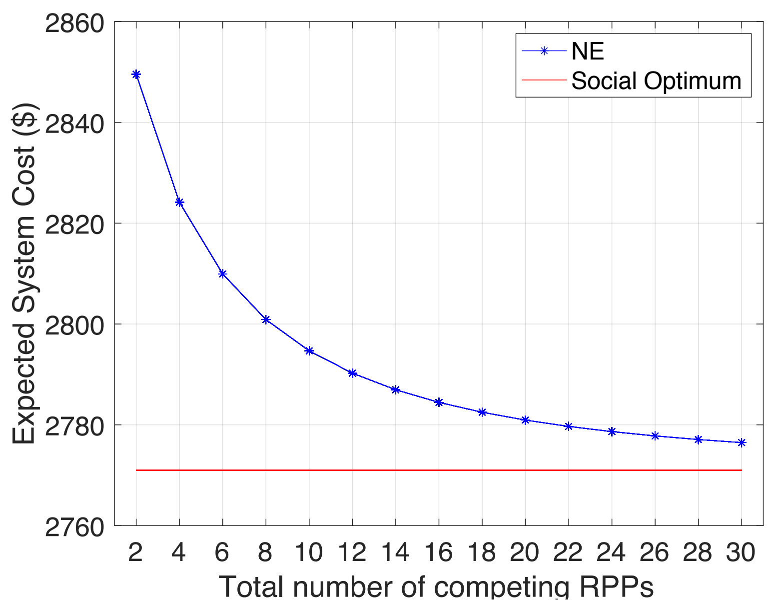
- The complexity of finding NE is decoupled into
  a) Searching over congestion patterns
  b) Computing NE candidate given a congestion pattern

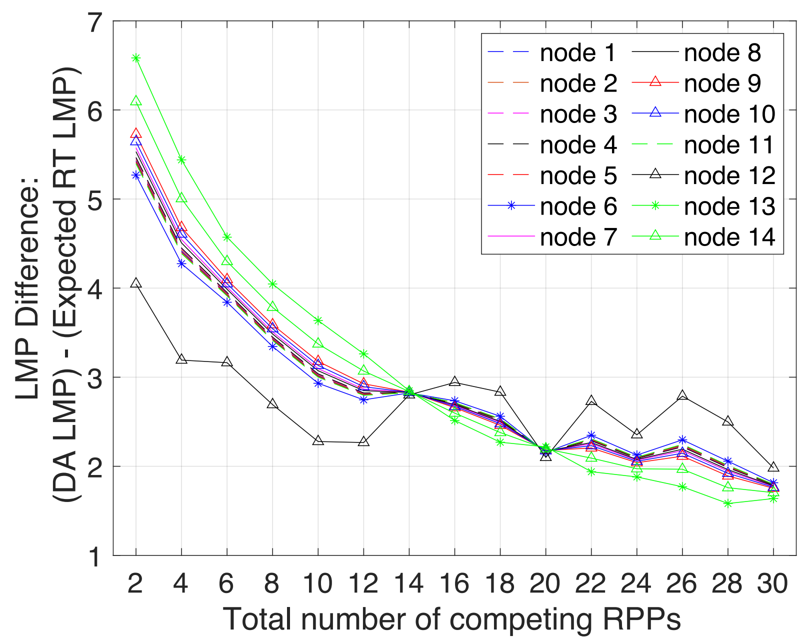
- Step b) can be efficiently performed.
  – Thus, the computation can easily be scaled to having a large number of RPPs.

- Step a) is still combinatorial
  – However, conventional wisdom in practice as well as recent works show that the congestion patterns that can actually appear are very limited [Ng et al. 18] [Misra Roald Ng 19].
  – Various heuristics can be developed.

Numerical Experiments

- Simulation setting
  - IEEE 14-bus system
    - 3 DA conventional generators, 2 RT conventional generators
    - RPPs located at 2 buses





Summary

- To reach social efficiency in the presence of renewable energies, we need not complicate the ISO's optimization problem.
- Instead, via properly designed market mechanism to engage RPPs, an ISO needs only to solve a deterministic optimization as usual.
- The competition among the participants will "push" the market equilibrium to social efficiency as if a centralized stochastic optimization is solved.
- The renewables are held responsible for their uncertainties.

Next Steps

- Extension
  - Integrating uncertain Demand Response providers

- Future work: Multi-stage and multi-period
  - UC, security constraints
  - Integrating energy storage

Thanks!