Towards Energy Equity in Interconnected Systems: An Energy Burden Criteria-Constrained Tie-line Scheduling Model

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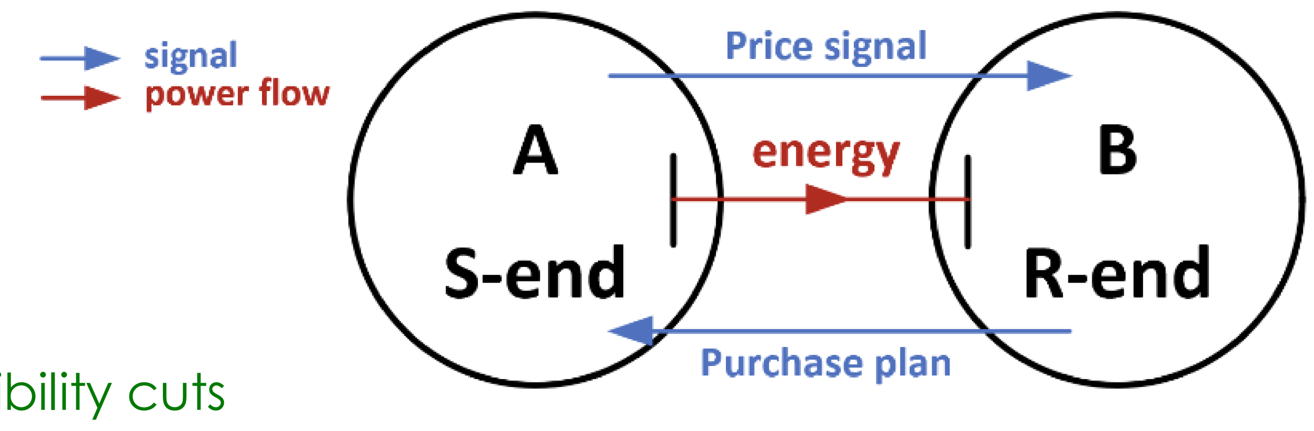
Background & Motivation

- Energy equity requires the fair and just distribution of benefits in the energy system through intentional design of systems, **technology, procedures and policies**
- Global circumstances, including geopolitical conflict, the COVID-19 pandemic, and world-wide inflation, have resulted in an energy crisis driving **soaring energy prices**
- In interconnected systems, the **tie-line schedule** has a significant impact on the prices in each individual system, and consequently, also on energy burden for vulnerable households

Problem Formulation



Upper operation model

$$\min_{\mathbf{y},\mathbf{P}} \mathbf{a}^{\mathrm{T}}\mathbf{y} + \mathbf{c}^{\mathrm{T}}\mathbf{P}$$

s.t.

$$\mathbf{BP} \le \mathbf{d} \quad :\boldsymbol{\rho}$$
$$\mathbf{Cy} \le \mathbf{g}$$
$$\mathbf{y} + \mathbf{1}^T\mathbf{P} = \mathbf{1}^T\mathbf{D} \quad :\boldsymbol{\lambda}$$
$$\mathbf{Gy} + \mathbf{JP} + \mathbf{HD} \le \mathbf{f} \quad :\boldsymbol{\mu}$$

Dual variables

Feasibility cuts

$$R_k = eb^{thd}\boldsymbol{\delta}_k + \mathbf{h}^{\mathrm{T}}\boldsymbol{\varepsilon}_k + \mathbf{d}^{\mathrm{T}}\boldsymbol{\varphi}_k + \left(\mathbf{1}^T\mathbf{D} - \mathbf{y}\right)^{\mathrm{T}}\boldsymbol{\gamma}_k + (\mathbf{f} - \mathbf{HD} - \mathbf{Gy})^{\mathrm{T}}\boldsymbol{\eta}_k + (\mathbf{b}_\rho - \mathbf{M}_\rho\bar{\mathbf{z}}_\rho)^{\mathrm{T}}\boldsymbol{\pi}_k + (\mathbf{b}_\mu - \mathbf{Gy} - \mathbf{M}_\mu\bar{\mathbf{z}}_\mu)^{\mathrm{T}}\boldsymbol{\sigma}_k \le 0$$

Lower relaxed market clearing model

Purchase plan → $\mathbf{y} \in \Phi$

$$\Phi := \{\mathbf{y} | \min_{\boldsymbol{\lambda},\boldsymbol{\mu},\mathbf{s}} \mathbf{1}^{\mathrm{T}}\mathbf{s} = 0$$

s.t.

Energy equity constraints:

$$(\boldsymbol{\lambda}^{\mathrm{T}} \circ \mathbf{1}^{\mathrm{T}} + \boldsymbol{\mu}^{\mathrm{T}}\mathbf{H} + \mathbf{s}^{\mathrm{T}})\mathbf{D} \le eb^{thd}$$
$$\mathbf{Ls} \le \mathbf{h}$$
$$\boldsymbol{\lambda}, \boldsymbol{\mu} \in \Theta$$
$$\Theta := \{\ (29), (31), (32)$$

KKT conditions:

$$\mathbf{BP} + \mathbf{K}_\rho\boldsymbol{\rho} + \mathbf{M}_\rho\mathbf{z}_\rho \le \mathbf{b}_\rho$$
$$\mathbf{Gy} + \mathbf{JP} + \mathbf{K}_\mu\boldsymbol{\mu} + \mathbf{M}_\mu\mathbf{z}_\mu \le \mathbf{b}_\mu$$
$$\mathbf{c}^{\mathrm{T}} + \boldsymbol{\rho}^{\mathrm{T}}\mathbf{B} + \boldsymbol{\lambda}^{\mathrm{T}}\mathbf{1}^{\mathrm{T}} + \boldsymbol{\mu}^{\mathrm{T}}\mathbf{J} = \mathbf{0}\}\}$$

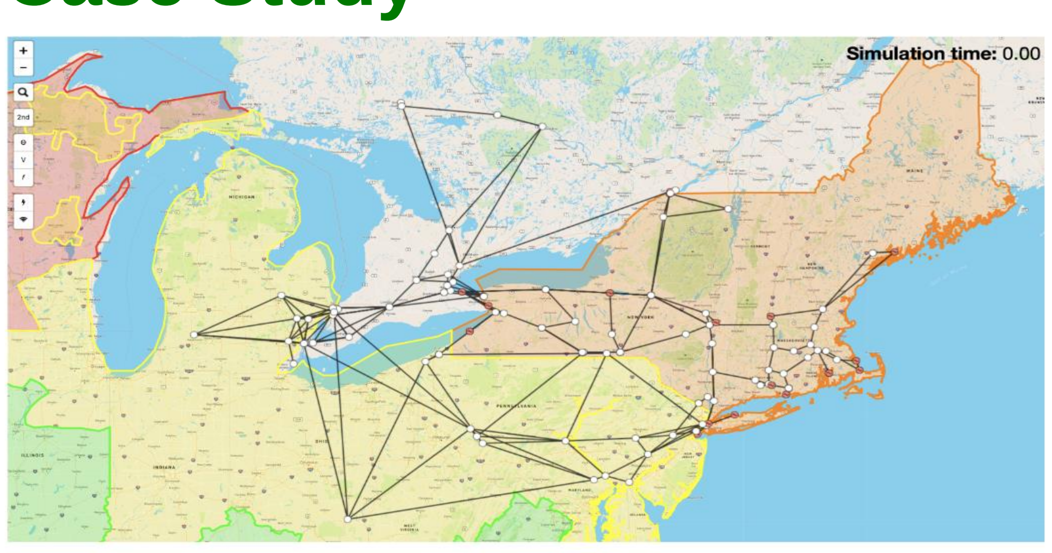
Dual model

$$\max_{\boldsymbol{\delta},\boldsymbol{\varepsilon},\boldsymbol{\varphi},\boldsymbol{\gamma},\boldsymbol{\eta},\boldsymbol{\pi},\boldsymbol{\sigma},\boldsymbol{\zeta}} R = eb^{thd}\boldsymbol{\delta} + \mathbf{h}^{\mathrm{T}}\boldsymbol{\varepsilon} + \mathbf{d}^{\mathrm{T}}\boldsymbol{\varphi} + \left(\mathbf{1}^T\mathbf{D} - \mathbf{y}\right)^{\mathrm{T}}\boldsymbol{\gamma} + (\mathbf{f} - \mathbf{HD} - \mathbf{Gy})^{\mathrm{T}}\boldsymbol{\eta} + (\mathbf{b}_\rho - \mathbf{M}_\rho\bar{\mathbf{z}}_\rho)^{\mathrm{T}}\boldsymbol{\pi} + (\mathbf{b}_\mu - \mathbf{Gy} - \mathbf{M}_\mu\bar{\mathbf{z}}_\mu)^{\mathrm{T}}\boldsymbol{\sigma}$$

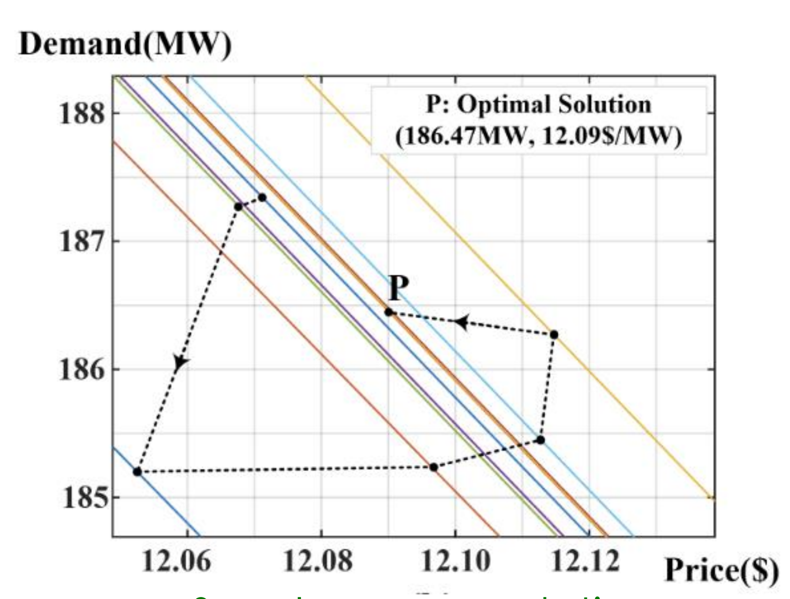
s.t.

$$\mathbf{B}^{\mathrm{T}}(\boldsymbol{\varphi} + \boldsymbol{\pi}) + \mathbf{1} \circ \boldsymbol{\gamma} + \mathbf{J}^{\mathrm{T}}(\boldsymbol{\eta} + \boldsymbol{\sigma}) = \mathbf{0}$$
$$\mathbf{K}_\rho^{\mathrm{T}}\boldsymbol{\pi} + \mathbf{B}\boldsymbol{\zeta} = \mathbf{0}$$
$$\mathbf{D}\boldsymbol{\delta} + \boldsymbol{\zeta} = \mathbf{0}$$
$$\mathbf{H}\boldsymbol{\delta} + \mathbf{K}_\mu^{\mathrm{T}}\boldsymbol{\sigma} + \mathbf{J}\boldsymbol{\zeta} = \mathbf{0}$$
$$\mathbf{D}\boldsymbol{\delta} + \mathbf{L}^{\mathrm{T}}\boldsymbol{\varepsilon} = \mathbf{1}^{\mathrm{T}}$$

Case Study



NPCC 140-bus test system



Supply curve updating

eb^{thd} ($)	S-end Cost($)	R-end Cost ($)				Social Cost($)
		Operation	Import	Subsidy	Total	
47,000	111,540	66,412	45,874	0	112,286	177,952
45,000	111,540	66,412	45,875	0	112,287	177,952
43,000	118,300	59,932	53,907	0	113,839	178,232
41,000	126,980	52,133	64,761	0	116,894	179,113
39,000	131,560	48,284	70,468	706	119,458	179,844
37,000	131,560	48,284	70,467	2707	121,458	179,844

Economic results in different thresholds

Conclusions

- The proposed model provides the guidelines for operators who need to implement Energy Burden principles, for the potential **energy equity programs**
- Effectiveness of the proposed energy burden-constrained tie-line scheduling model is verified, and the **sustainability** of the Energy Burden implementation is validated in the model

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