Emissions-aware Electricity Network Expansion Planning via Implicit Differentiation

Anthony Degleris*

Lucas Fuentes Valenzuela

Abbas El Gamal

Ram Rajagopal

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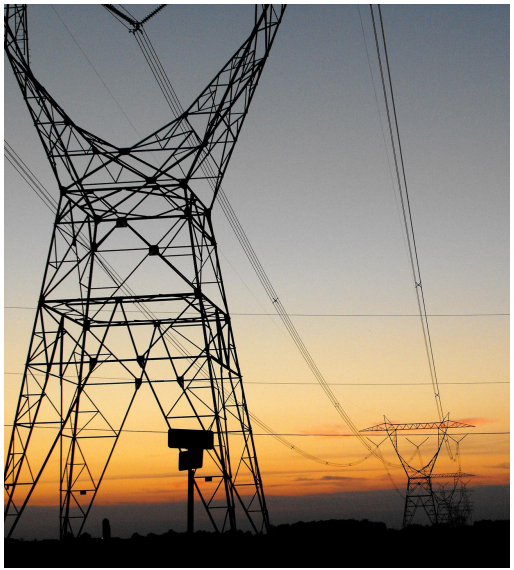
Upgrading the Electricity Grid

- Transmission upgrades
- Today
  - Renewables
  - Storage
  - EV Chargers



Transmission Line. Eddie Fouse. From Public Domain Pictures.
Solar Farm. Photon-Photos / iStock / Getty Images Plus. From Ecowatch.
Battery Farm. Reuters. From BBC.
EV Fast Chargers. From Bloomberg

Expansion Planning

Electricity Network
(transmission capacity,
storage capacity,
renewable generation, etc)

Dispatched Generation

Planning / Outer Problem

$$\text{minimize}_{\theta} \quad Q(\theta) + J(u^*(\theta))$$

Investment Cost

Operation Cost

$$u^*(\theta) = \arg\min_{u \in \mathcal{C}(\theta)} J(u)$$

Dispatch / Operation / Inner Problem

Traditional focus: monetary costs

$$J(u) = D(u)$$

Dollar Cost of Electricity

Can we use these tools
to build a low-emissions electricity grid?

Traditional Method: Carbon Tax

- Planning problem remains the same: $\text{minimize}_\theta \quad Q(\theta) + J(u^*(\theta))$
- Use operations problem $u^*(\theta)$ (electricity market) with carbon tax
- Indirectly penalizes emissions through marginal market incentives
  - Planner is still “unaware” of emissions

$$J(u) = D(u) + \tau E(u)$$

Dollar Cost of Electricity

Carbon Tax Rate

Emissions Produced

Bent, Toole. 2012.

Asgharian, Abdelaziz. 2017

Neumann, Brown. 2019

Could the planner directly reduce emissions?

New Proposal: Emissions-aware Expansion Planning

$$\text{minimize}_{\theta} \quad Q(\theta) + J(u^*(\theta)) + \lambda E(u^*(\theta))$$

Emissions Produced

Carbon *Penalty*

- Directly penalize emissions in (outer) planning problem
- $u^*(\theta)$ still defined using tax-free dispatch model

Solving the Emissions-aware Problem

$$f(\arg\min_x f(x)) = \min_x f(x)$$

Standard Formulation
(including carbon tax)

$$\text{minimize}_\theta \quad Q(\theta) + J(u^*(\theta))$$

$$u^*(\theta) = \arg\min_{u \in C(\theta)} J(u)$$

$$\text{minimize}_{\theta, u \in C(\theta)} \quad Q(\theta) + J(u)$$

Standard Optimization Tools

Emissions-aware

$$\text{minimize}_\theta \quad Q(\theta) + J(u^*(\theta)) + \lambda E(u^*(\theta))$$

$$u^*(\theta) = \arg\min_{u \in C(\theta)} J(u)$$

?

Implicit Differentiation + Gradient Descent

Gribik et al. 1990.

Good tutorial: implicit-layers-tutorial.org

Carbon Tax vs Emissions-Aware Planning

Carbon Tax

- Indirect (inner) market penalty
- Consumer incurs *fixed* investment cost & *marginal* carbon tax cost

Emissions-Aware Problem

- Directly (outer) reduce emissions
- Consumer only incurs *fixed* investment cost

****NOT MUTUALLY EXCLUSIVE****

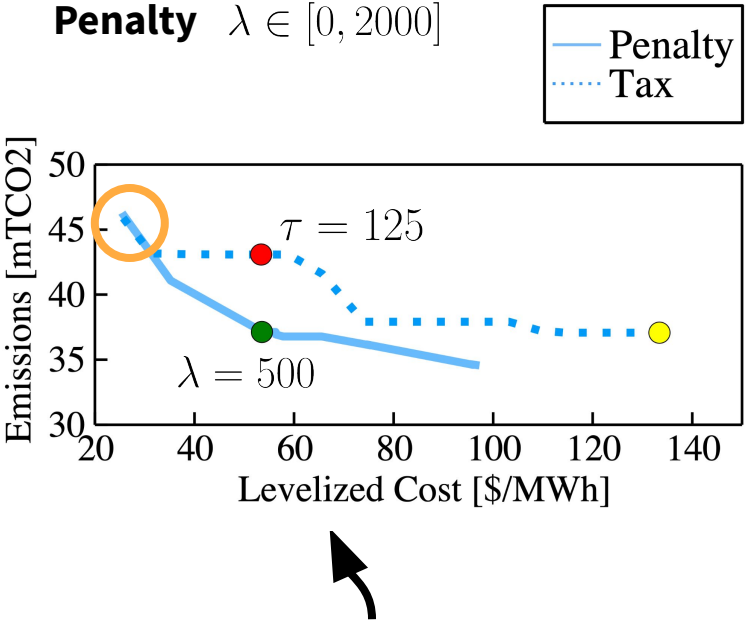
Experiment: IEEE 14-bus network

- Compare carbon tax and emissions-aware
- 50% renewable penetration
- **Planning Problem:** Expand transmission and storage

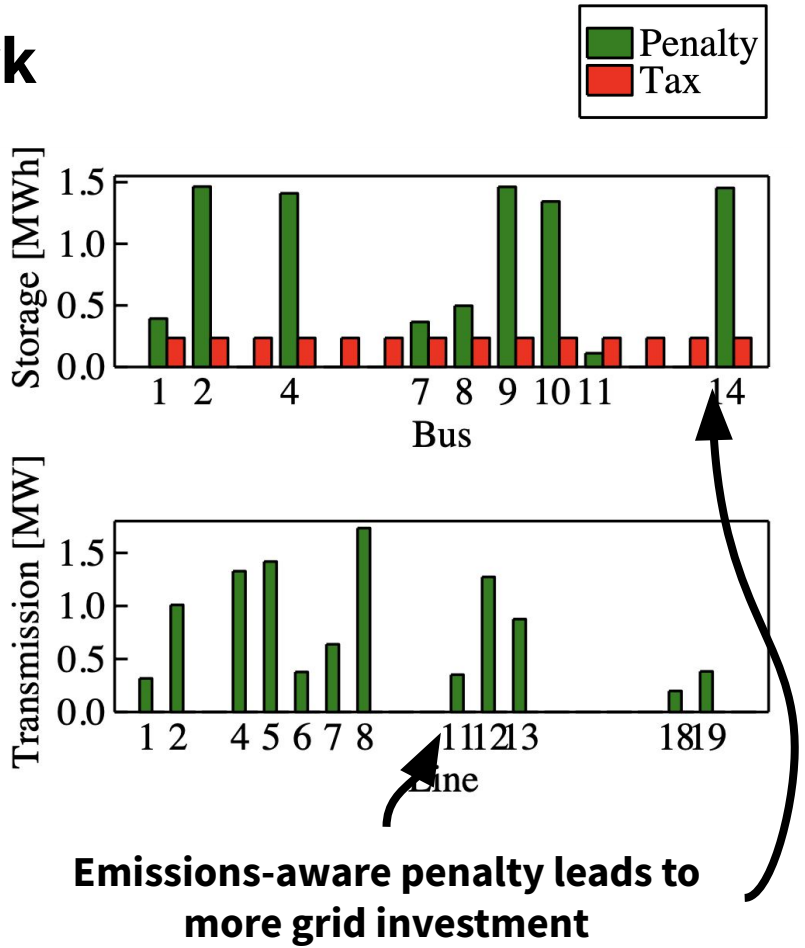
Experiment: IEEE 14-bus network

Tax $\tau \in [0, 500]$

Penalty $\lambda \in [0, 2000]$



Total Cost / Total Electricity Consumption



Emissions-aware penalty leads to more grid investment

Conclusion

- Emissions-aware planning finds **high impact investments for reducing emissions**
- Using just a **carbon tax may be overly expensive**
- Pathway to impact
    - Practical investment constraints
    - Real world case studies