

# Consumer-based Carbon Costs: Integrating Consumer Carbon Preferences in Electricity Markets

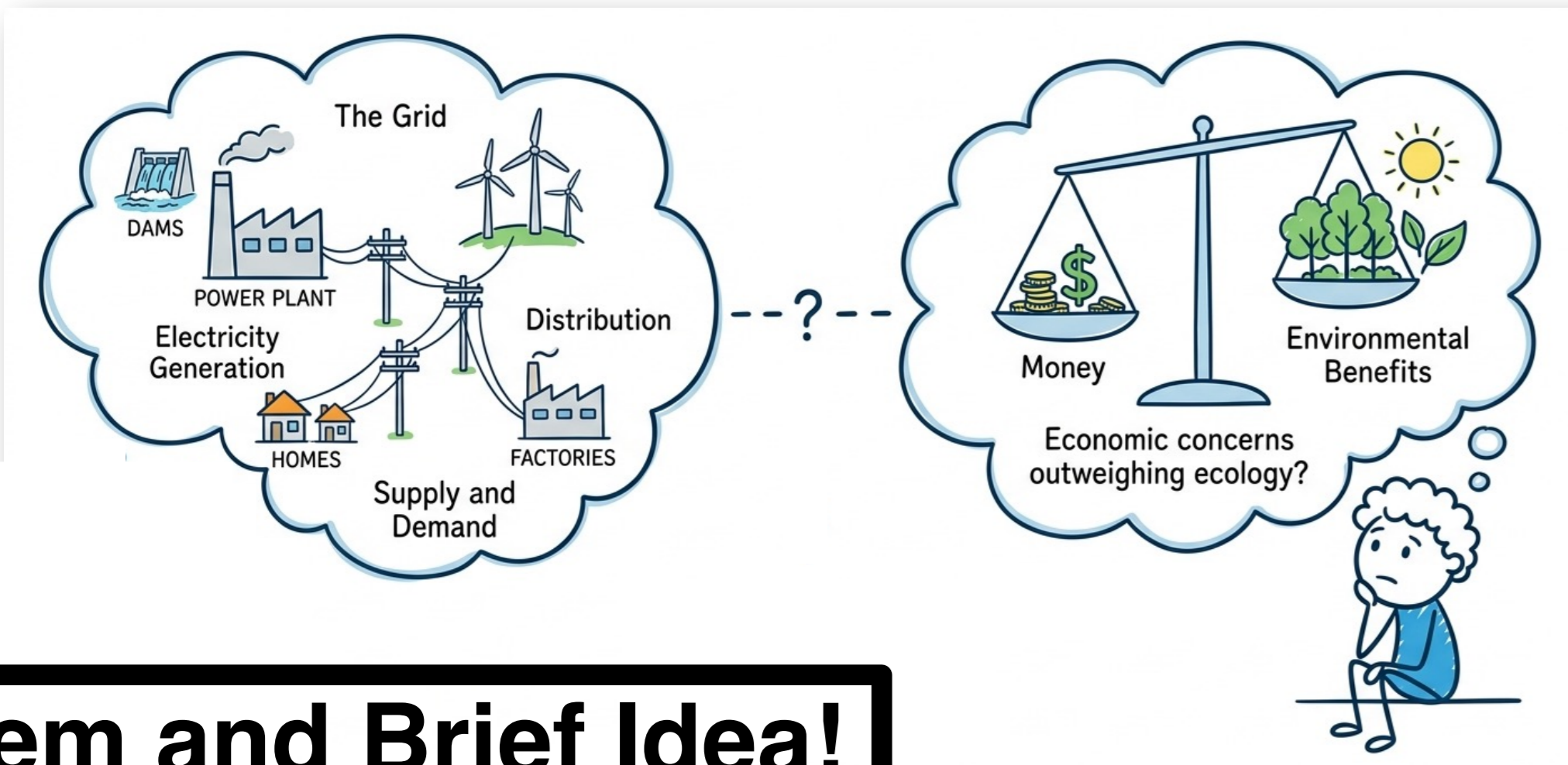
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## What is the Problem?

### How to account for carbon emissions in the electricity market-clearing?



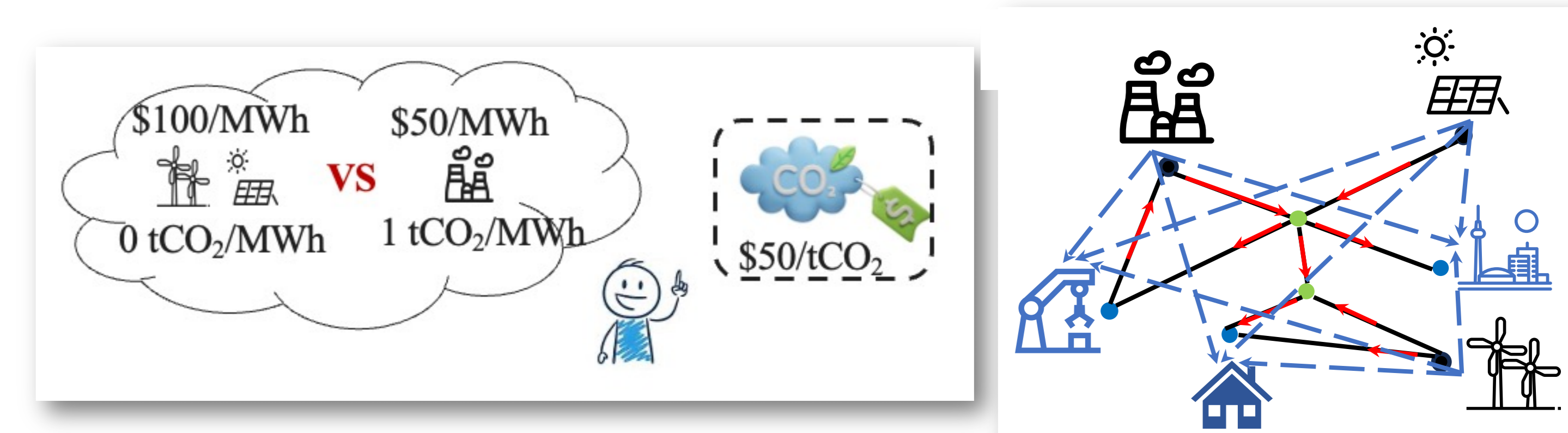
### Problem and Brief Idea!

## Why is it important?

- ▶ **Current Electricity markets** either maximize social welfare or minimize generation, which may lead to **economically efficient but environmentally suboptimal outcomes**.
- ▶ **Current carbon accounting methods for electricity usage** in GHG protocol scope 2 guidance decouple carbon emissions from electricity markets, which **limit consumers' influence on real-time generation dispatch decisions**.
- ▶ An increasing number of carbon-sensitive consumers care about their carbon emissions from electricity usage.

## Our Solution!

### Introduce **consumer-based carbon costs** and a **carbon allocation mechanism!**



## Electricity Market Clearing with Carbon Costs

- ▶ **Consumer-defined Carbon Costs**
  - Reflect how much revenue the consumer is willing to “forgo” to avoid carbon emissions.
- ▶ **Carbon Allocation Mechanism**
  - Allocate carbon emissions directly from generators to consumers without considering the physical power grid.

$$\begin{aligned} & \max_{P_G, P_D, \theta, \pi, E_D} u_D^T P_D - c_D^T E_D - c_G^T P_G && \text{(1a) Carbon-aware Objective} \\ \text{s.t. } & \sum_{d \in \mathcal{D}_i} P_{D,d} + \sum_{j: (i,j) \in \mathcal{L}} \beta_{ij} (\theta_i - \theta_j) = \sum_{g \in \mathcal{G}_i} P_{G,g}, && \forall i \in \mathcal{N}, \quad : \lambda_{P,i} \quad \text{(1b)} \\ & \beta_{ij} (\theta_i - \theta_j) \leq F_{ij}^{\text{lim}}, \quad \forall (i,j) \in \mathcal{L}, \quad : \bar{\eta}_{L,ij} \quad \text{(1c)} \\ & \beta_{ij} (\theta_i - \theta_j) \geq -F_{ij}^{\text{lim}}, \quad \forall (i,j) \in \mathcal{L}, \quad : \underline{\eta}_{L,ij} \quad \text{(1d)} \\ & P_{G,g}^{\text{min}} \leq P_{G,g} \leq P_{G,g}^{\text{max}}, \quad \forall g \in \mathcal{G}, \quad : \bar{\eta}_{G,g}, \underline{\eta}_{G,g} \quad \text{(1e)} \\ & P_{D,d}^{\text{min}} \leq P_{D,d} \leq P_{D,d}^{\text{max}}, \quad \forall d \in \mathcal{D}, \quad : \bar{\eta}_{D,d}, \underline{\eta}_{D,d} \quad \text{(1f)} \\ & \theta_{\text{ref}} = 0, && \text{(1g)} \\ & \sum_{d \in \mathcal{D}} \pi_{g,d} = P_{G,g}, \quad \forall g \in \mathcal{G}, \quad : \lambda_{G,g} \quad \text{(1h)} \\ & \sum_{g \in \mathcal{G}} \pi_{g,d} = P_{D,d}, \quad \forall d \in \mathcal{D}, \quad : \lambda_{D,d} \quad \text{(1i)} \\ & \sum_{g \in \mathcal{G}} e_{G,g} \pi_{g,d} = E_{D,d}, \quad \forall d \in \mathcal{D}, \quad : \lambda_{E,d} \quad \text{(1j)} \\ & \pi_{g,d} \geq 0, \quad \forall g \in \mathcal{G}, \quad \forall d \in \mathcal{D}. && \text{(1k)} \end{aligned}$$

## Equivalent Equilibrium Formulation

- ① **Generators:** Profit maximization problem
 
$$\begin{aligned} & \max_{P_{G,g}} (\lambda_{P,i: g \in \mathcal{G}_i} + \lambda_{G,g} - c_{G,g}) \cdot P_{G,g} \\ \text{s.t. } & P_{G,g}^{\text{min}} \leq P_{G,g} \leq P_{G,g}^{\text{max}}. \end{aligned}$$
- ② **Consumers:** Utility maximization problem
 
$$\begin{aligned} & \max_{P_{D,d}} (u_{D,d} - \lambda_{P,i: d \in \mathcal{D}_i} + \lambda_{D,d}) \cdot P_{D,d} \\ \text{s.t. } & P_{D,d}^{\text{min}} \leq P_{D,d} \leq P_{D,d}^{\text{max}}. \end{aligned}$$
- ③ **Transmission Owner:** Profit maximization problem
 
$$\begin{aligned} & \max_{\theta} \sum_i \lambda_{P,i} \cdot \left( \sum_{j: (i,j) \in \mathcal{L}} \beta_{ij} (\theta_j - \theta_i) \right) \\ \text{s.t. } & -F_{ij}^{\text{lim}} \leq \beta_{ij} (\theta_i - \theta_j) \leq F_{ij}^{\text{lim}}, \quad \forall (i,j) \in \mathcal{L}, \\ & \theta_{\text{ref}} = 0, \end{aligned}$$
- ④ **Price Setter:** Enforce the nodal power balance constraint
 
$$\sum_{d \in \mathcal{D}_i} P_{D,d} + \sum_{j: (i,j) \in \mathcal{L}} \beta_{ij} (\theta_i - \theta_j) = \sum_{g \in \mathcal{G}_i} P_{G,g}, \quad : \lambda_{P,i}$$
- ⑤ **Carbon Manager:** Total carbon cost minimization problem
 
$$\begin{aligned} & \max_{\pi, E_D} -c_D^T E_D \\ \text{s.t. } & \sum_{d \in \mathcal{D}} \pi_{g,d} = P_{G,g}, \quad \forall g \in \mathcal{G}, \quad : \lambda_{G,g} \\ & \sum_{g \in \mathcal{G}} \pi_{g,d} = P_{D,d}, \quad \forall d \in \mathcal{D}, \quad : \lambda_{D,d} \\ & \sum_{g \in \mathcal{G}} e_{G,g} \pi_{g,d} = E_{D,d}, \quad \forall d \in \mathcal{D}, \\ & \pi_{g,d} \geq 0, \quad \forall g \in \mathcal{G}, \quad \forall d \in \mathcal{D}. \end{aligned}$$

## Insights and Novel Things

**New Definition: Carbon-Adjusted Prices** are defined as

$$\begin{aligned} & \lambda_{P,i: g \in \mathcal{G}_i} + \lambda_{G,g} \quad \text{for generators } g \in \mathcal{G}, \\ & \lambda_{P,i: d \in \mathcal{D}_i} - \lambda_{D,d} \quad \text{for consumers } d \in \mathcal{D}. \end{aligned}$$

**Special Models:** Our model generalizes two standard market-clearing models as special cases.

- ▶ **All carbon costs are zero:** standard (carbon-agnostic) market-clearing model.
- ▶ **All carbon costs are identical:** unifying carbon tax mechanism on generation.

**Carbon Flow:** Lower-carbon power will be allocated to consumers submitting higher carbon costs.

**Money Flow:** Our carbon cost model will be cleared based on:

- ▶ Generators with different carbon emission factors are dynamically paid through carbon-adjusted prices.
- ▶ Consumers who submit higher carbon costs contribute more money for being allocated less carbon emissions.