Carbon-Sensitive Load Management: A Game-Theoretic Exploration

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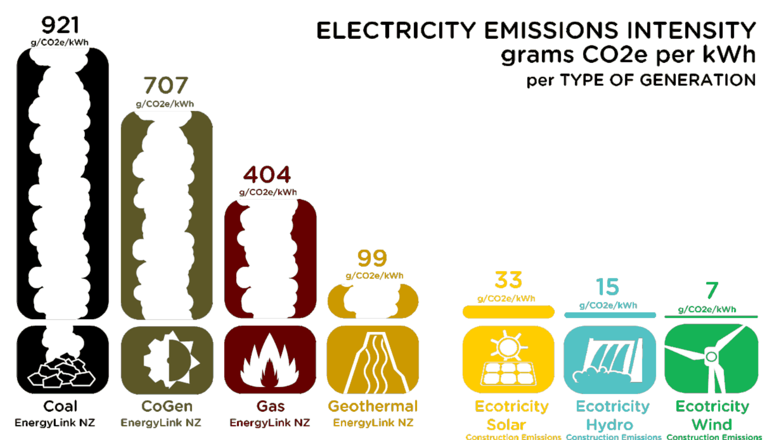
Introduction


A collage of typical climate and weather-related events: heatwaves, drought, hurricanes, wildfires and changes in sea ice coverage. (Image credit: NOAA)

- Worldwide carbon emission reduction targets and policy

World Bank Group: https://hdl.handle.net/10986/13334.



Source: https://ecotricity.co.nz/

- As one of the largest emitters, the electricity sector is required to cut the carbon emission
- Many carbon markets aim only for power generation

Conventional Wisdom and New Challenges

- **Core Strategy**

Increase the penetration of renewable generation and reduce carbon-intensive power generation (especially coal-based electricity).

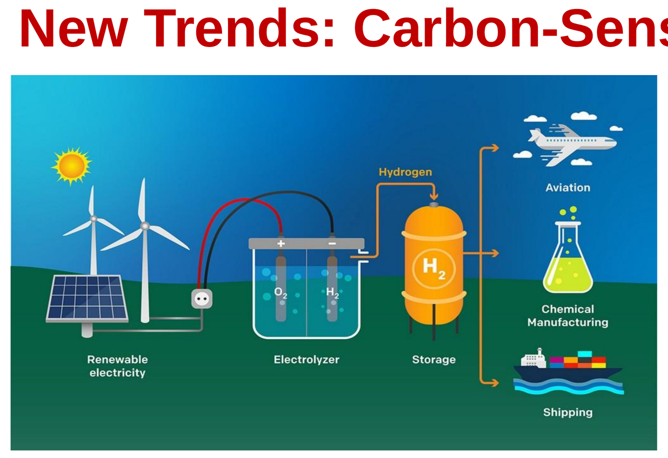
Carbon taxes on the generation side

Without Carbon Cost: $\min_{P_g} c^T P_g$

With Carbon Cost: $\min_{P_g} (c^T + c_{co_2} e_g^T) P_g$

✓ Change generator merit order and make cleaner generation competitive.
✓ Embed the impact of carbon into price signals (Increasing prices).
✓ Consumers act passively to price signals (no choice).

New Trends: Carbon-Sensitive Loads


Source: https://www.linkedin.com/pulse/largest-green-hydrogen-projects-world-futurefuels/


Source: https://verpex.com/blog/cloud-hosting/cloud-data-centers

- **Hydrogen Generation**: Separate carbon emissions from costs
- **Data Centers**: Actively involve carbon in their decisions

Generators:
$$\max_{P_{g,l}} (p - c_l) P_{g,l} \ s.t. \ P_{g,l}^{min} \le P_{g,l} \le P_{g,l}^{max}$$

Consumers:
$$\max_{P_{d,l}} (u_l - p) P_{d,l} \ s.t. \ P_{d,l}^{min} \le P_{d,l} \le P_{d,l}^{max}$$

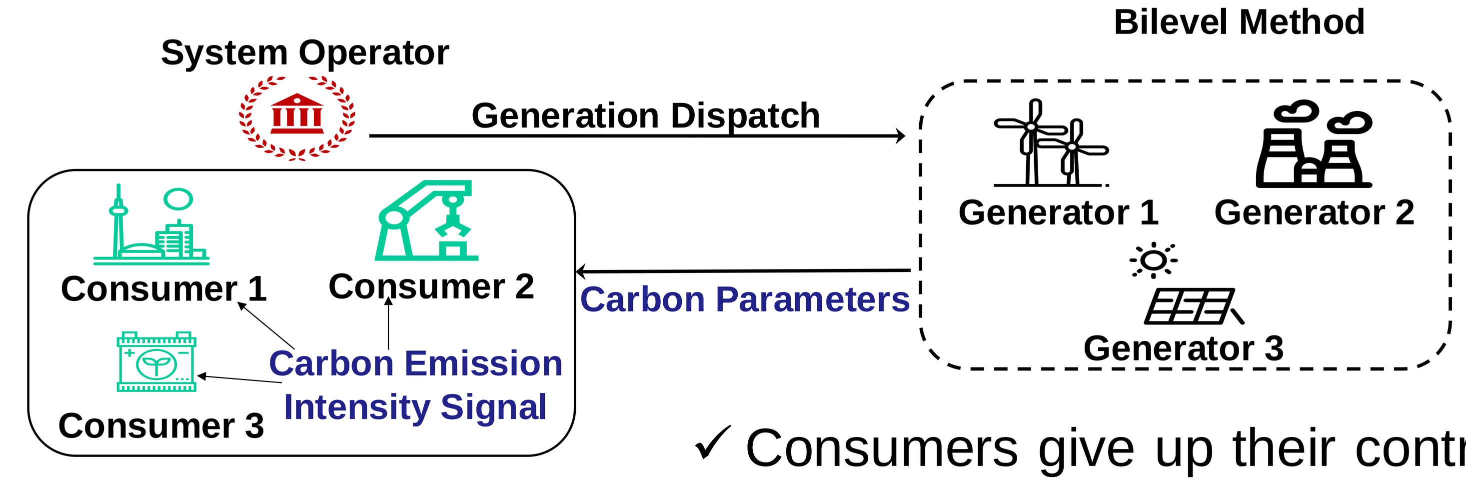
Price-setter Problem:
$$\sum_{l \in \mathcal{G}} P_{g,l} - \sum_{l \in \mathcal{D}} P_{d,l} \ge 0, \quad (p)$$

Equivalent

$$\max_{P_d, P_g} (u^T P_d - c^T P_g)$$
$$s.t. \ P_{g,l}^{min} \le P_{g,l} \le P_{g,l}^{max}$$
$$P_{g,l}^{min} \le P_{g,l} \le P_{g,l}^{max}$$
$$\sum_{l \in \mathcal{G}} P_{g,l} - \sum_{l \in \mathcal{D}} P_{d,l} \ge 0$$

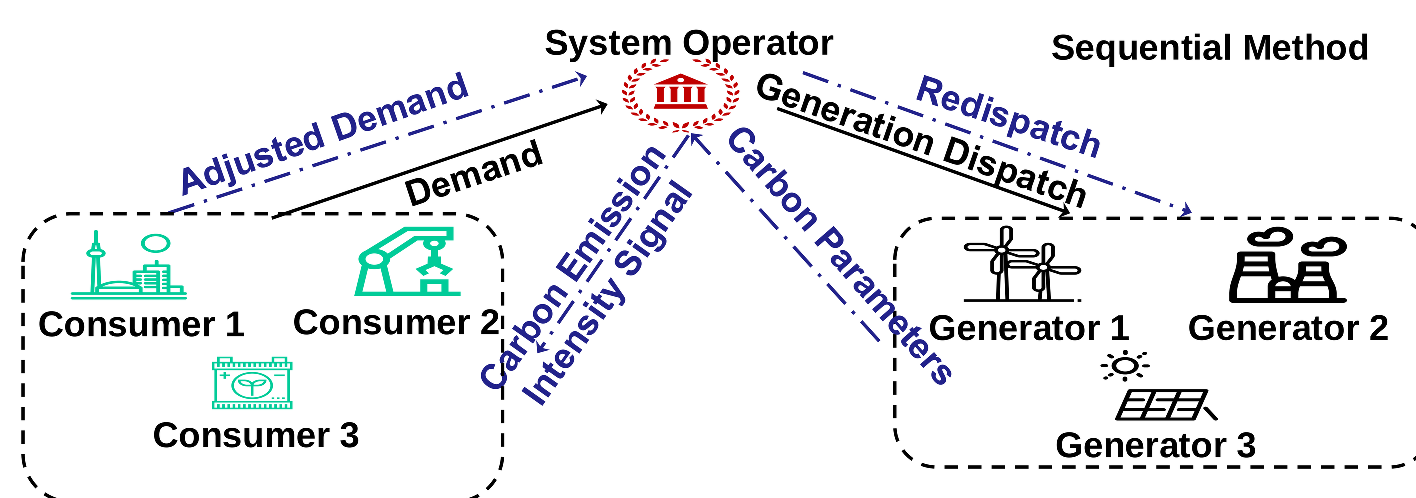
Related Works

Bilevel Formulation



✓ Consumers give up their control to market clearing.

Sequential Formulation



✓ Time mismatch.

A Game-Theoretic Perspective

Model

Generators:
$$\max_{P_{g,l}} (p - c_l) P_{g,l} \ s.t. \ P_{g,l}^{min} \le P_{g,l} \le P_{g,l}^{max}$$

Consumers:
$$\max_{P_{d,l}} (u_l - p - \lambda_e \cdot c_{co_2}) P_{d,l} \ s.t. \ P_{d,l}^{min} \le P_{d,l} \le P_{d,l}^{max}$$

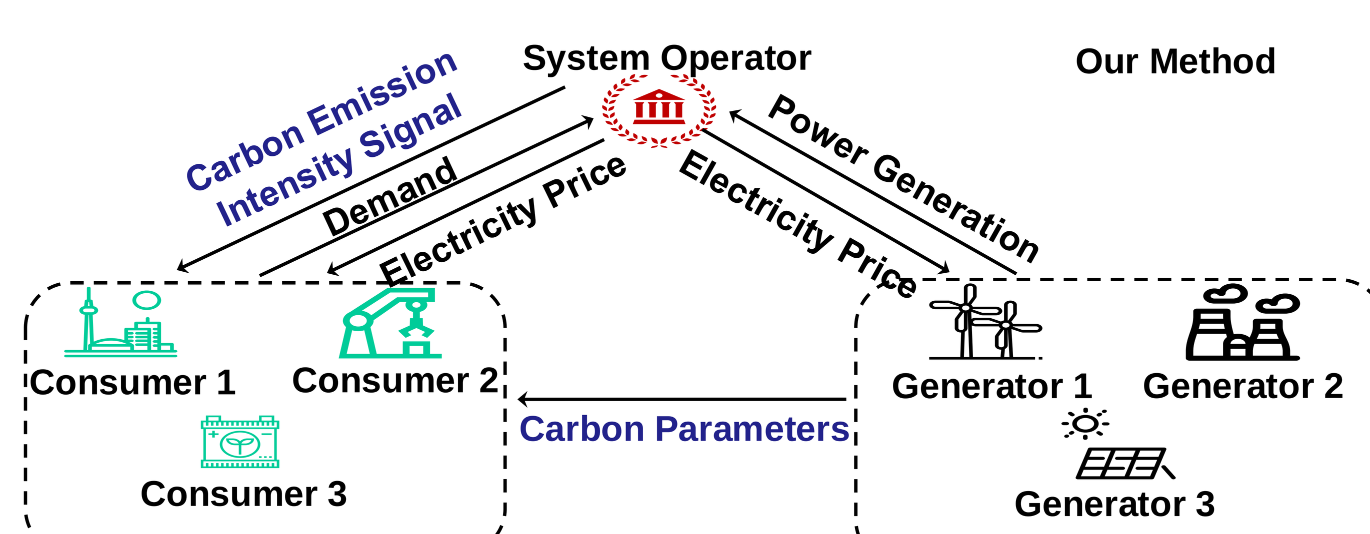
Price-setter Problem:
$$\sum_{l \in \mathcal{G}} P_{g,l} - \sum_{l \in \mathcal{D}} P_{d,l} \ge 0, \quad (p)$$

Average carbon emission:
$$\lambda_e \sum_{l \in \mathcal{D}} P_{d,l} = \sum_{l \in \mathcal{G}} e_{g,l} P_{g,l}$$

✓ Consumer-oriented choice
- Carbon signals
- Carbon costs

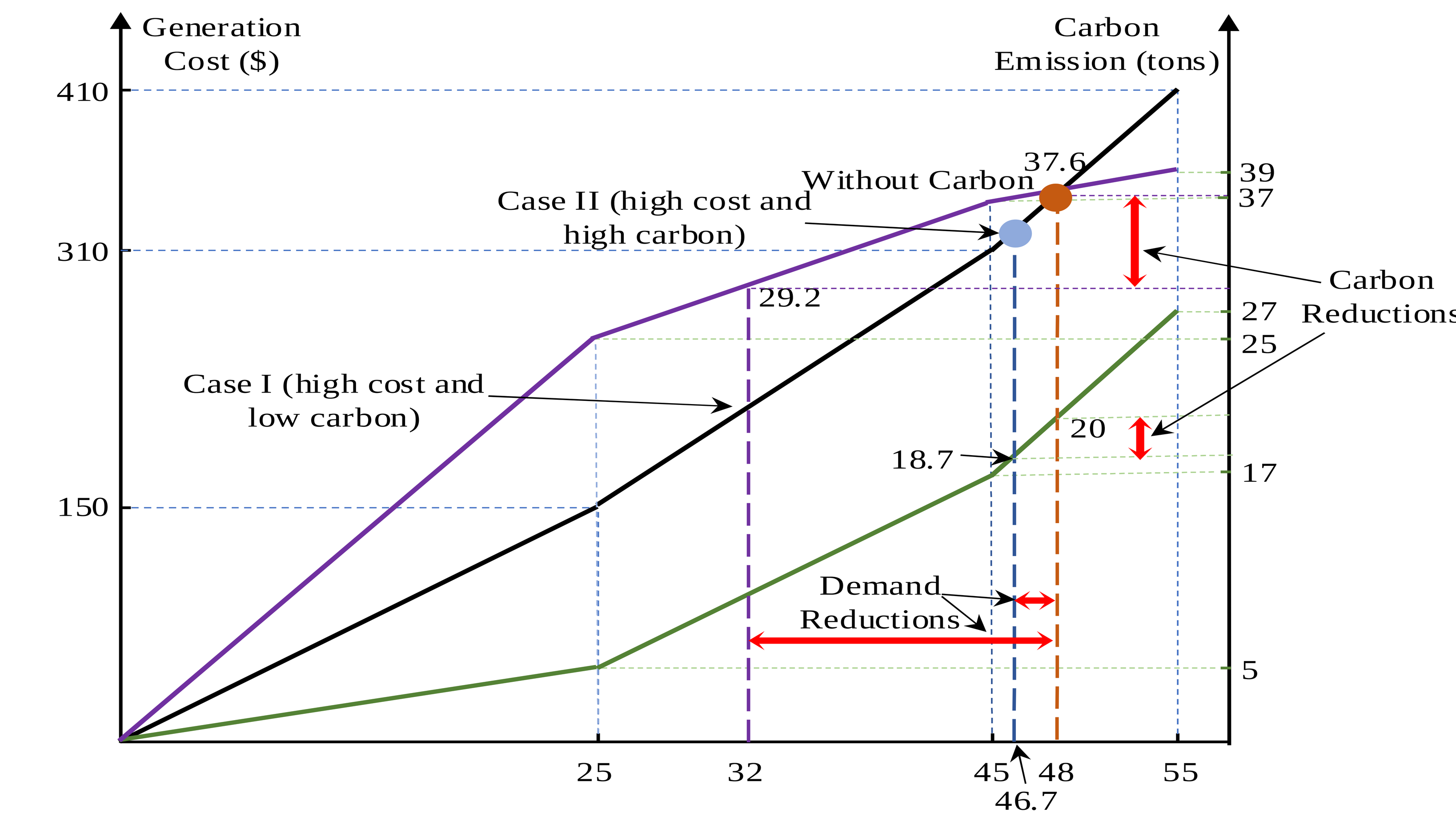
What would happen if carbon-sensitive loads had "perfect" knowledge of carbon emission intensity signals?

Equilibrium Formulation



Numerical Studies

Simplified Three-bus System



✓ Reduce consumers' electricity demand instead of impacting generation dispatch.
✓ Consumers act actively to carbon signals.
✓ Average carbon emission signals may not be so effective.

IEEE RTS-GMLC System

Models	Carbon Cost Range	Total Generation (MWh)	Total Generation Cost ($)	Total Carbon (tons)	Average Carbon (tons/MWh)	Total Carbon Cost ($)
WC	-	8550	63748	3001.8	0.351	0
GM	[10,40]	8550	**64691**	2870	0.336	26977.7
	[30,60]	8448.3	64400.25	2706.3	0.32	44113.4
	[50,80]	8431.8	64157.2	2696.4	0.32	61207.7
SM	[10,40]	8550	63748	3001.8	0.351	80271.3
	[30,60]	8515.8	63358	2969	0.349	138965.4
	[50,80]	**8349**	**61458.5**	**2808.8**	**0.336**	**188404.7**
OM	[10,40]	8550	63748	3001.8	0.351	80371.3
	[30,60]	8515.8	63358	2969	0.349	138965.4
	[50,80]	**8368.4**	**61677.3**	**2827.4**	**0.338**	**189575.5**

✓ SM is equivalent to OM for both low and high carbon cost ranges.
✓ GM reduces carbon more effectively at higher generation costs.

Conclusion

- Carbon-sensitive loads want to act actively to carbon signals, not reactively response to price signals.
- Average carbon emission intensity signal maybe not a good signal for load shifting. Marginal carbon emission intensity signal may be better one.
- Equilibrium model formulation contributes to measuring and evaluating the effectiveness of different carbon signals, especially consumer-oriented signals.