

Carbon-Sensitive Loads and Their Impact on Grid Emissions

Line A. Roald

LANL Grid Science Winter School

January 9, 2025





Julia Lindberg, Bernard C. Lesieutre, and Line Roald. "The Environmental Potential of Hyper-Scale Data Centers: Using Locational Marginal CO2 Emissions to Guide Geographical Load Shifting." *Hawaii International Conference on System Sciences (HICSS)* (2021).

Julia Lindberg, Yasmine Abdennadher, Jiaqi Chen, Bernard C. Lesieutre, Line Roald, "A Guide to Reducing Carbon Emissions through Data Center Geographical Load Shifting". Proceedings of the Twelfth ACM International Conference on Future Energy Systems (E2DC 2021), pp. 430-436.

Julia Lindberg, Bernard C. Lesieutre, and Line A. Roald. "Using Geographic Load Shifting to Reduce Carbon Emissions." Electric Power Systems Research, 2022



Joe Gorka and Line Roald. "Classification Models for Forecasting and Real-Time Identification of Solar Curtailment in the California Grid." In Proceedings of the 15th ACM International Conference on Future and Sustainable Energy Systems, pp. 158-169. 2024

Joe Gorka, Noah Rhodes and Line Roald. "ElectricityEmissions.jl: A Framework for the Comparison of Carbon Intensity Signals", under review. Preprint: <https://arxiv.org/abs/2411.06560>

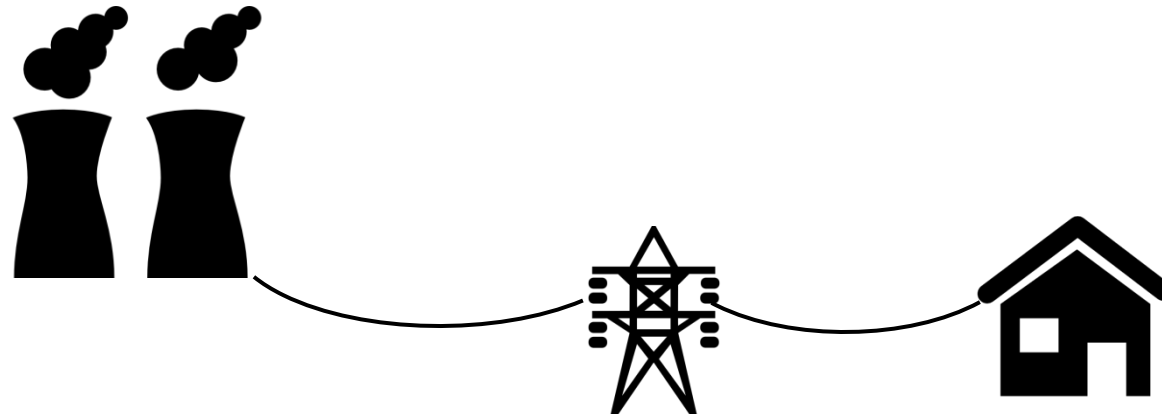
Wenqian Jiang and Line Roald, "Greening the Grid: Electricity Market Clearing with Consumer-Based Carbon Cost", submitted.



vmware®

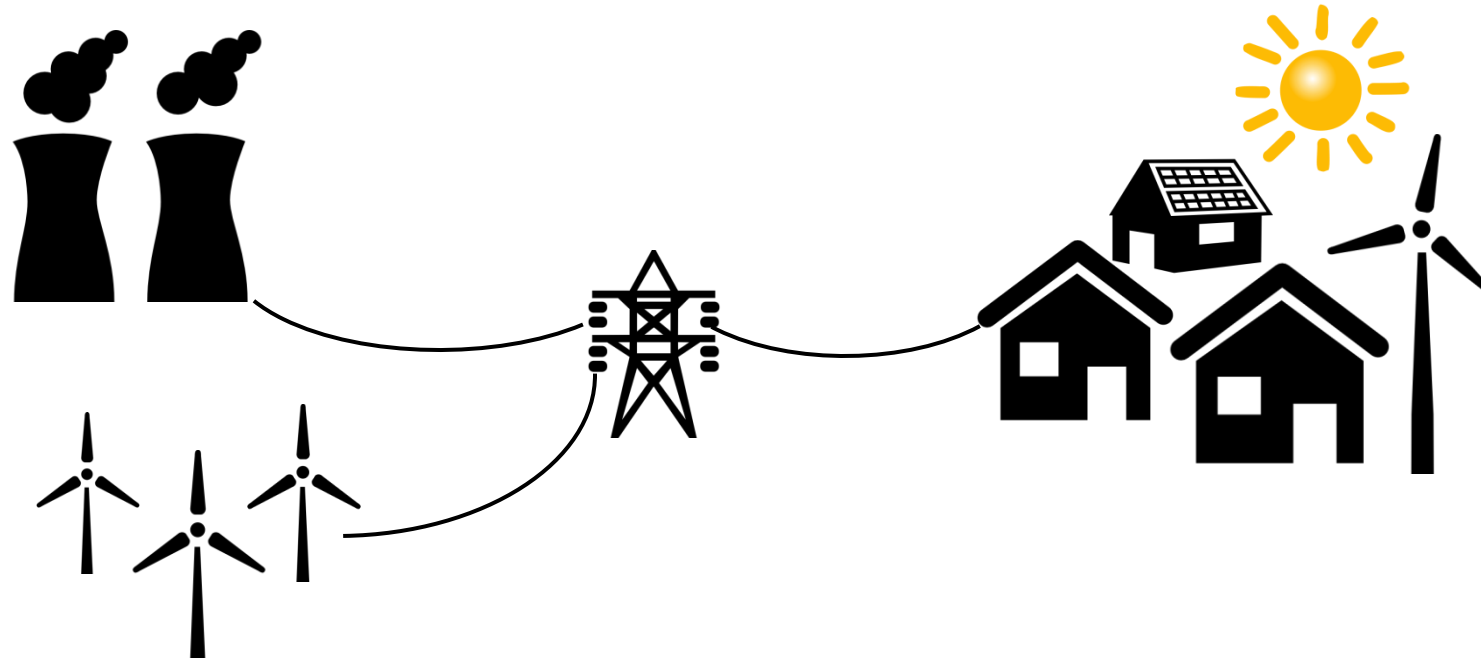


Carbon-sensitive electric loads



Electricity generation produces carbon emissions!

Carbon-sensitive electric loads



Electricity generation produces **time- and location varying** carbon emissions!

Carbon footprint of electricity consumption

- What should I (*i.e., the consumer*) do if I want to contribute to a greener real-time grid?



Power systems focused:

Let's help the grid!

Demand response

Market participation

Carbon footprint of electricity consumption

- What should I (*i.e., the consumer*) do if I want to contribute to a greener real-time grid?

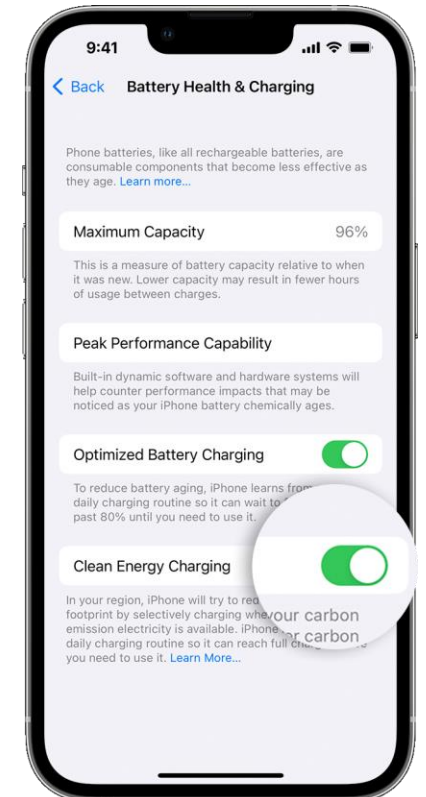


Power systems focused:

Let's help the grid!
Demand response
Market participation

Consumer focused:

By (more directly)
aiming to use
electricity when it is
“low carbon”



Carbon footprint of electricity consumption

- What should I (*i.e., the consumer*) do if I want to contribute to a greener real-time grid?

“Apple uses data that combines grid, emissions, and weather information into one, **easy-to-follow signal**.”

<https://shorturl.at/kvQRV>

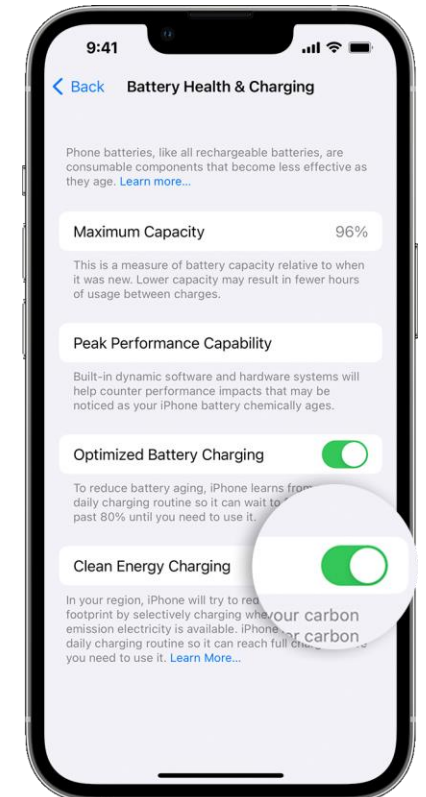
Samsung’s Smart Things “visualizes the sources of electricity and the associated carbon dioxide emissions, users can make more informed decisions about their energy usage and **reduce their carbon footprint**.”

<https://shorturl.at/ftGU7>

Google shifts data center loads:

<https://ieeexplore.ieee.org/document/9770383>

Consumer focused:
By (more directly)
aiming to use
electricity when it is
“low carbon”



Carbon footprint of electricity consumption

- What should I (*i.e., the consumer*) do if I want to contribute to a greener real-time grid?

“Apple uses data that combines grid, emissions, and weather information into one, **easy-to-follow signal**.”

<https://shorturl.at/kvQRV>

Samsung’s Smart Things “visualizes the sources of electricity and the associated carbon dioxide emissions, users can make more informed decisions about their energy usage and **reduce their carbon footprint**.”

<https://shorturl.at/ftGU7>

Google shifts data center loads:

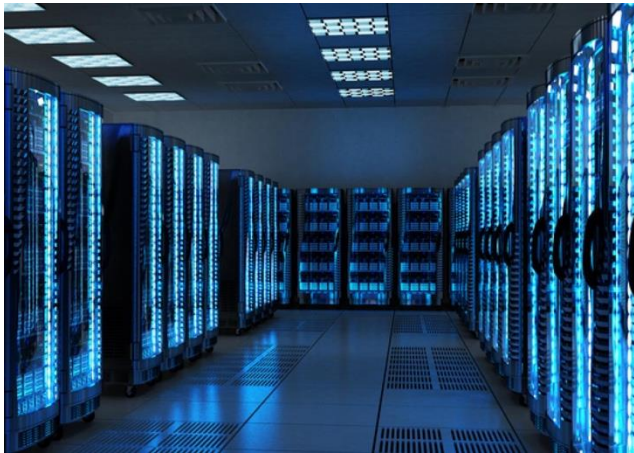
<https://ieeexplore.ieee.org/document/9770383>

National Grid “Green Light Signal” tells consumers when carbon intensity is low! <https://www.nationalgrid.com/greenlightsignal>



Carbon-sensitive electric loads

- Electricity consumers (individuals, companies, organizations) are interested in reducing the carbon footprint of their electricity consumption
 - **Voluntarily** (to help mitigate climate change)
 - **Carbon reporting** (to track carbon emissions)



Hyperscale computing companies want to publicly demonstrate their commitment to clean energy.



Individual consumers on flat electricity tariffs who want to contribute to a cleaner planet

Carbon-sensitive electric loads

- Electricity consumers (individuals, companies, organizations) are interested in reducing the carbon footprint of their electricity consumption
 - **Voluntarily** (to help mitigate climate change)
 - **Carbon reporting** (to track carbon emissions)
 - To receive **subsidies** (e.g. clean hydrogen production tax credits)

Carbon Intensity (kg CO _{2e} per kg H ₂)	Max Hydrogen Production Tax Credit (\$/kg H ₂)
4-2.5	\$0.60
2.5-1.5	\$0.75
1.5-0.45	\$1.00
<0.45	\$3.00

<https://www.energy.gov/eere/fuelcells/financial-incentives-hydrogen-and-fuel-cell-projects>



THE WHITE HOUSE



DECEMBER 22, 2023

Treasury Sets Out Proposed Rules for Transformative Clean Hydrogen Incentives



► CLEAN ENERGY ► CLEAN ENERGY UPDATES ► UPDATES

What is the carbon footprint of electricity?

What is the carbon footprint of electricity?

- Emissions from generation **Well defined!** 

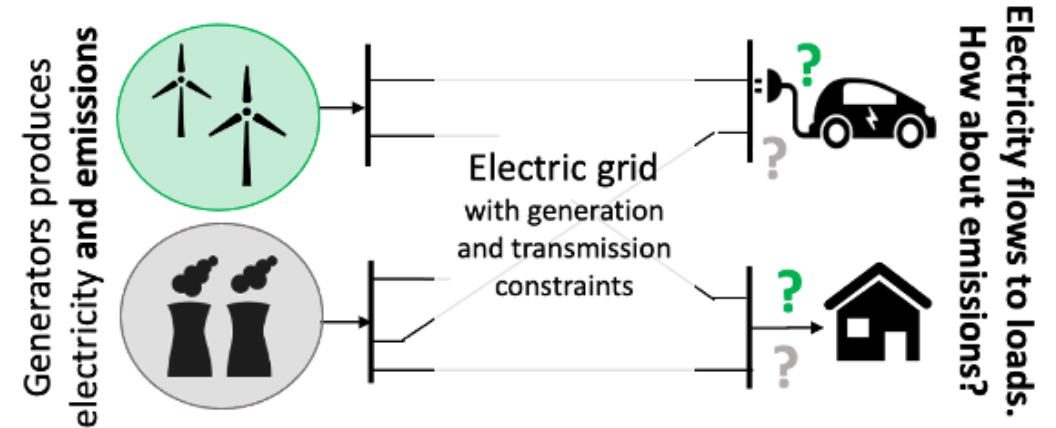
What is the carbon footprint of electricity?

- Emissions from generation **Well defined!** 
- Total grid emissions **Calculated from generation data** 

What is the carbon footprint of electricity?

- Emissions from generation **Well defined!** 
- Total grid emissions **Calculated from generation data** 

- Emissions of individual consumers **???**



Carbon footprint of electricity consumption

- **Market-based carbon accounting:** Renewable Energy Certificates (RECs)/ Energy Attribute Certificates (EACs), or Power Purchase Agreements (PPAs)
- **Location-based carbon accounting:** Carbon emissions from generation in the grid where the consumer is located
- Many challenges, e.g., double counting of renewables...
- Currently undergoing an update!



Scope 2 Emissions Accounting

Carbon footprint of electricity consumption

- **Market-based carbon accounting:** Renewable Energy Certificates (RECs)/ Energy Attribute Certificates (EACs), or Power Purchase Agreements (PPAs)
- **Location-based carbon accounting:** Carbon emissions from generation in the grid where the consumer is located
- Many challenges, e.g., double counting of renewables...
- Currently undergoing an update!

Section 45V Credit for Production of Clean Hydrogen; Section 48(a)(15) Election To Treat Clean Hydrogen Production Facilities as Energy Property

A Proposed Rule by the [Internal Revenue Service](#) on 12/26/2023



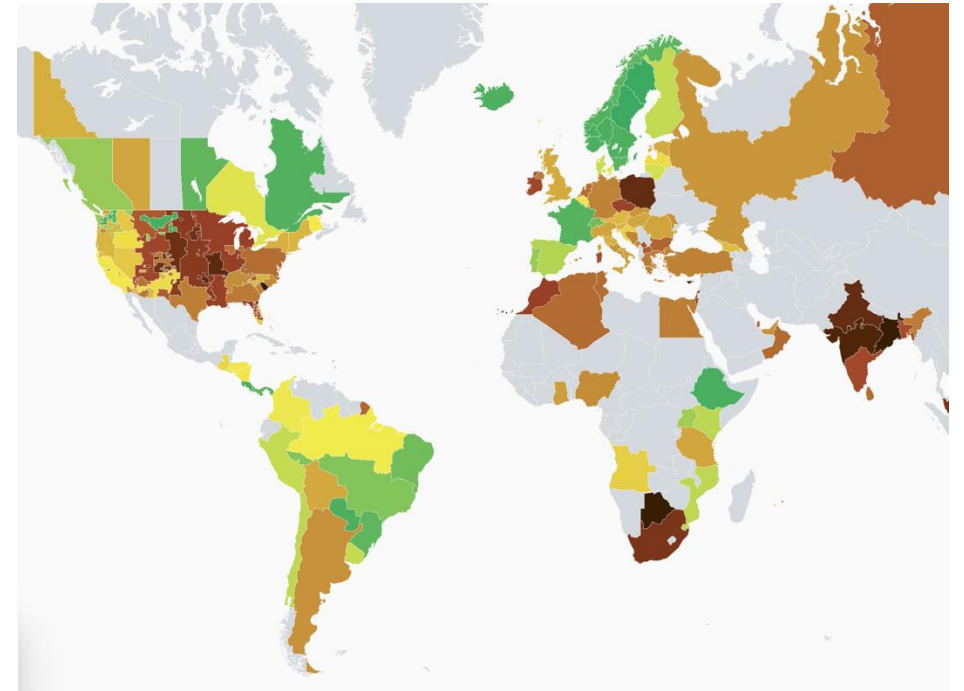
II. ZERO OR MINIMAL INDUCED GRID EMISSIONS THROUGH MODELING OR OTHER EVIDENCE

The Treasury Department and the IRS seek comments on whether to provide an opportunity to demonstrate zero or minimal induced grid emissions through modeling or other evidence under specific circumstances. A demonstrated or modeled minimal-emission approach could treat electricity produced by certain existing electricity generating facilities under certain circumstances as satisfying the incrementality requirement if it is demonstrated that such sources and circumstances would not give rise to significant induced grid emissions. Such a showing could be based on modeling or potentially be deemed to be made in certain circumstances based on regional grid characteristics, state policy, or facility history.



Location-based carbon accounting

- Average carbon emissions = $\frac{\text{total carbon emissions}}{\text{total electricity use}}$
- Benefits:
 - Easy to compute and widely available
 - Can be used for location-based accounting under the Greenhouse Gas Protocol



Average emissions over past 72 hours from Electricity Maps,
<https://app.electricitymaps.com/map/72h>
(accessed on Jan 8 at 2pm)

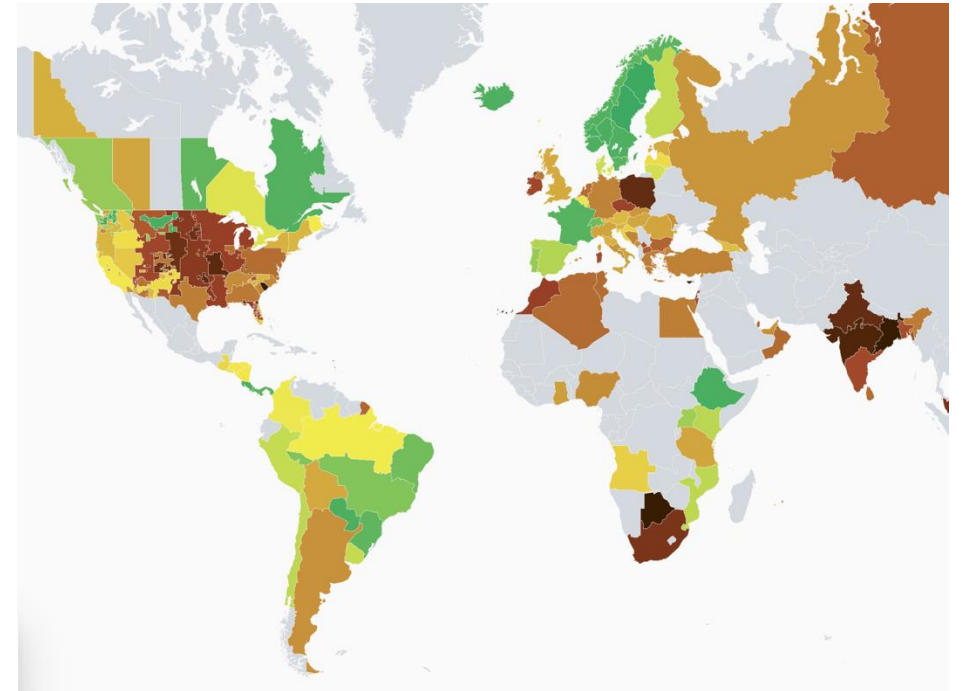
Location-based carbon accounting

- Average carbon emissions = $\frac{\text{total carbon emissions}}{\text{total electricity use}}$
- Benefits:
 - Easy to compute and widely available
 - Can be used for location-based accounting under the Greenhouse Gas Protocol

First step: Count emissions.

Second step: Take action to reduce emissions.
What happens then??

Is average carbon emissions an effective signal for helping loads become more “green”?



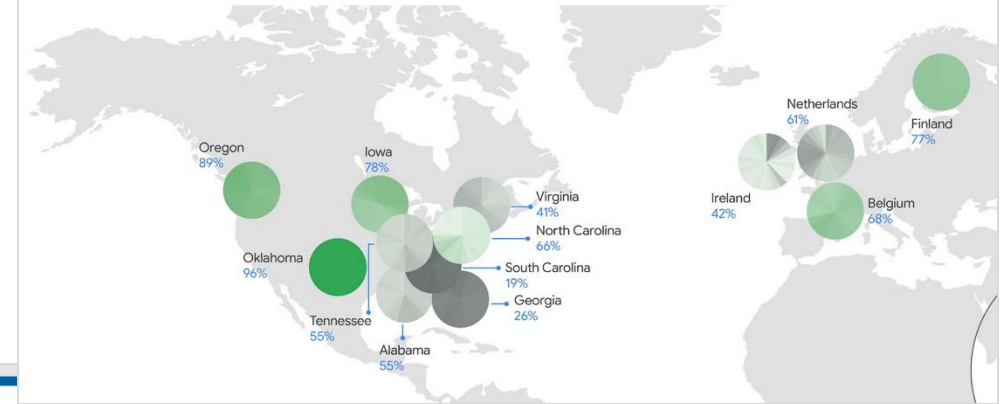
Average emissions over past 72 hours from Electricity Maps,
<https://app.electricitymaps.com/map/72h>
(accessed on Jan 8 at 2pm)

Operating on 24/7 Carbon-Free Energy by 2030.

Carbon-aware load shifting

Example: Hyperscale data centers

- Massive investments in new, power-hungry data centers
- Tech companies have made commitments to use green energy
- Interest in adapting power use to reduce emissions



POWER

Dominion: Virginia's Data Center Cluster Could Double in Size

Dominion Energy says it has customer contracts that could double the amount of data center capacity in Virginia by 2028 and is planning new power lines to support this growth.

Rich Miller

Oct. 11, 2023

Constellation to Launch Crane Clean Energy Center, Restoring Jobs and Carbon-Free Power to The Grid

Constellation signs its largest-ever power purchase agreement with Microsoft, a deal that will restore TMI Unit 1 to service and keep it online for decades; add approximately 835 megawatts of carbon-free energy to the grid; create 3,400 direct and indirect jobs and deliver more than \$3 billion in state and federal taxes

LONDON, PA (Sept 20, 2024) Constellation (Nasdaq: CEG) announced today the signing of a 20-year power purchase agreement with Microsoft that will pave the way for the launch of the [Crane Clean Energy Center](#) (CCEC) and restart of Three Mile Island Unit 1, which operated at industry-leading levels of safety and reliability for decades before being shut down for economic reasons exactly five years ago today. Under the agreement, Microsoft will purchase energy

Journals & Magazines > IEEE Transactions on Power Sy... > Volume: 38 Issue: 2 ?

Carbon-Aware Computing for Datacenters

Publisher: IEEE

[Cite This](#)

[PDF](#)

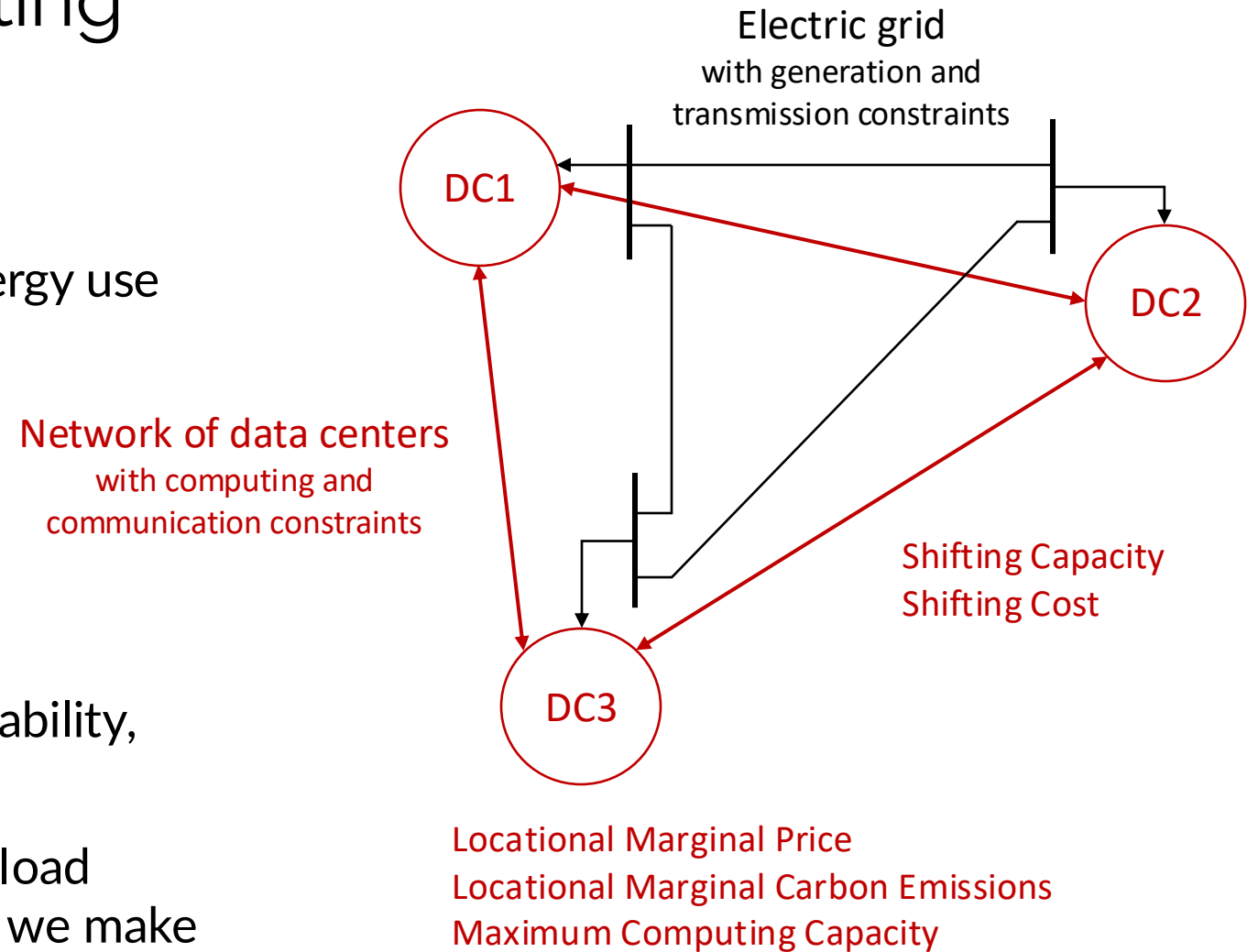
Ana Radovanović ; Ross Koningstein ; Ian Schneider ; Bokan Chen ; Alexandre Duarte ; Binz Roy [All Authors](#)

Carbon-aware load shifting

Example: Hyperscale data centers

- Network of data centers can shift energy use by shifting computing workloads!
- Temporal load shifting (start/stop/resume jobs)
- Geographical load shifting (load balancing across locations)
- Limitations such as latency, data availability, hardware requirements, etc

Algorithms for workload scheduling and load balancing already exist. What happens if we make them carbon-aware?



Carbon-aware load shifting

Day ahead

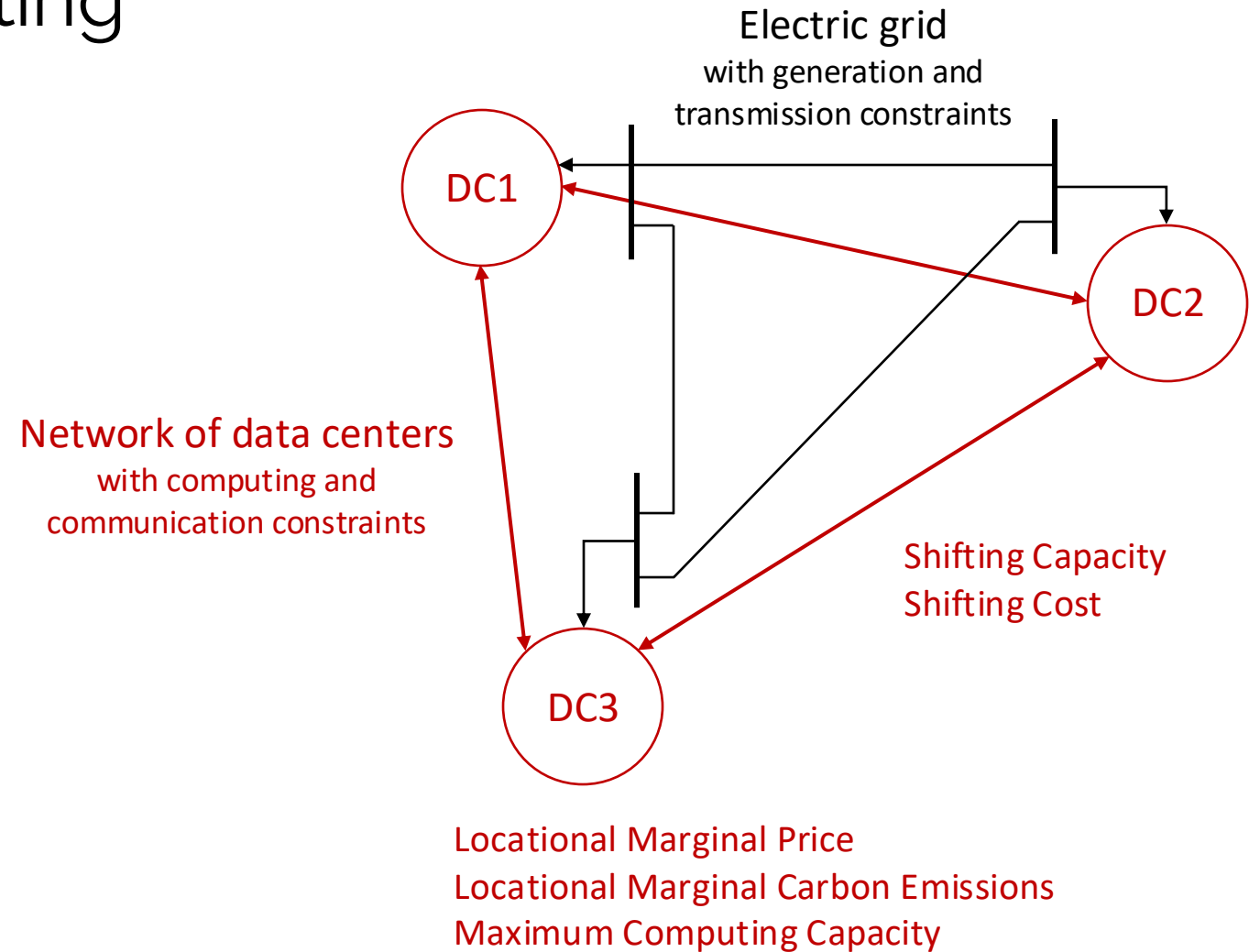
System operator clears 24h day-ahead electricity market



Compute carbon emission data



Data centers optimize load shifts to reduce emissions



Carbon-aware load shifting

Day ahead

System operator clears 24h day-ahead electricity market



Compute carbon emission data



Data centers optimize load shifts to reduce emissions

Solve DC OPF to minimize hourly cost

$$\begin{aligned} \min_{\theta, P_g} \quad & c^T P_g && \text{Minimize cost} \\ \text{s.t.} \quad & \sum_{\ell \in \mathcal{G}_i} P_{g,\ell} - \sum_{\ell \in \mathcal{D}_i} P_{d,\ell} = && \\ & \sum_{j:(i,j) \in \mathcal{L}} \beta_{ij}(\theta_i - \theta_j), && \forall i \in \mathcal{N} \\ & -P_{ij}^{lim} \leq -\beta_{ij}(\theta_i - \theta_j) \leq P_{ij}^{lim}, && \forall (i,j) \in \mathcal{L} \\ & P_{g,i}^{min} \leq P_{g,i} \leq P_{g,i}^{max}, && \forall i \in \mathcal{G} \\ & \theta_{ref} = 0. && \end{aligned}$$

Power flow and generation constraints

Carbon-aware load shifting

Day ahead

System operator clears 24h day-ahead electricity market



Compute carbon emission data



Data centers optimize load shifts to reduce emissions

Solve DC OPF to minimize hourly cost

Compute average carbon emissions

$$\begin{aligned}
 \min_{\theta, P_g} \quad & c^T P_g && \text{Minimize cost} \\
 \text{s.t.} \quad & \sum_{\ell \in \mathcal{G}_i} P_{g,\ell} - \sum_{\ell \in \mathcal{D}_i} P_{d,\ell} = \sum_{j: (i,j) \in \mathcal{L}} \beta_{ij} (\theta_i - \theta_j), && \forall i \in \mathcal{N} \\
 & -P_{ij}^{lim} \leq -\beta_{ij} (\theta_i - \theta_j) \leq P_{ij}^{lim}, && \forall (i,j) \in \mathcal{L} \\
 & P_{g,i}^{min} \leq P_{g,i} \leq P_{g,i}^{max}, && \forall i \in \mathcal{G} \\
 & \theta_{ref} = 0. && \text{Power flow and generation constraints}
 \end{aligned}$$

$$\text{Average carbon emissions} = \frac{\text{total carbon emissions}}{\text{total electricity use}}$$

Carbon-aware load shifting

Day ahead

System operator clears 24h day-ahead electricity market



Compute carbon emission data



Data centers optimize load shifts to reduce emissions

Solve DC OPF to minimize hourly cost

Compute average carbon emissions

Minimize data center emissions by shifting load in time and space

$$\begin{aligned}
 & \min_{\theta, P_g} c^T P_g && \text{Minimize cost} \\
 \text{s.t. } & \sum_{\ell \in \mathcal{G}_i} P_{g,\ell} - \sum_{\ell \in \mathcal{D}_i} P_{d,\ell} = \sum_{j: (i,j) \in \mathcal{L}} \beta_{ij} (\theta_i - \theta_j), && \forall i \in \mathcal{N} \\
 & -P_{ij}^{lim} \leq -\beta_{ij} (\theta_i - \theta_j) \leq P_{ij}^{lim}, && \forall (i,j) \in \mathcal{L} \\
 & P_{g,i}^{min} \leq P_{g,i} \leq P_{g,i}^{max}, && \forall i \in \mathcal{G} \\
 & \theta_{ref} = 0.
 \end{aligned}$$

Power flow and generation constraints

$$\text{Average carbon emissions} = \frac{\text{total carbon emissions}}{\text{total electricity use}}$$

$$\begin{aligned}
 & \min_{\Delta P_{d,s}} \sum_{i \in \mathcal{C}} \lambda_{CO_2,i} \Delta P_{d,i} && \text{Minimize emissions} \\
 \text{s.t. } & \Delta P_{d,i} = \sum_{j \in \mathcal{C}} s_{ji} - \sum_{k \in \mathcal{C}} s_{ik} && \forall i \in \mathcal{C} \\
 & \sum_{i \in \mathcal{C}} \Delta P_{d,i} = 0 && \\
 & -\epsilon_i \cdot \text{Cap}_i \leq \Delta P_{d,i} \leq \epsilon_i \cdot \text{Cap}_i && \forall i \in \mathcal{C} \\
 & 0 \leq \Delta P_{d,i} + P_{d,i} \leq \text{Cap}_i && \forall i \in \mathcal{C} \\
 & 0 \leq s_{ij} \leq M_{ij} && \forall ij \in \mathcal{C} \times \mathcal{C}.
 \end{aligned}$$

Data center shifting constraints

Carbon-aware load shifting

Day ahead

System operator clears 24h day-ahead electricity market



Compute carbon emission data



Data centers optimize load shifts to reduce emissions

New data center load profiles become input to the intraday market



Intra-day market

System operator clears 24h day-ahead electricity market



Compute carbon emission data

Carbon-aware load shifting

Day ahead

System operator clears 24h day-ahead electricity market



Compute carbon emission data



Data centers optimize load shifts to reduce emissions

New data center load profiles become input to the intraday market



Intra-day market

System operator clears 24h day-ahead electricity market



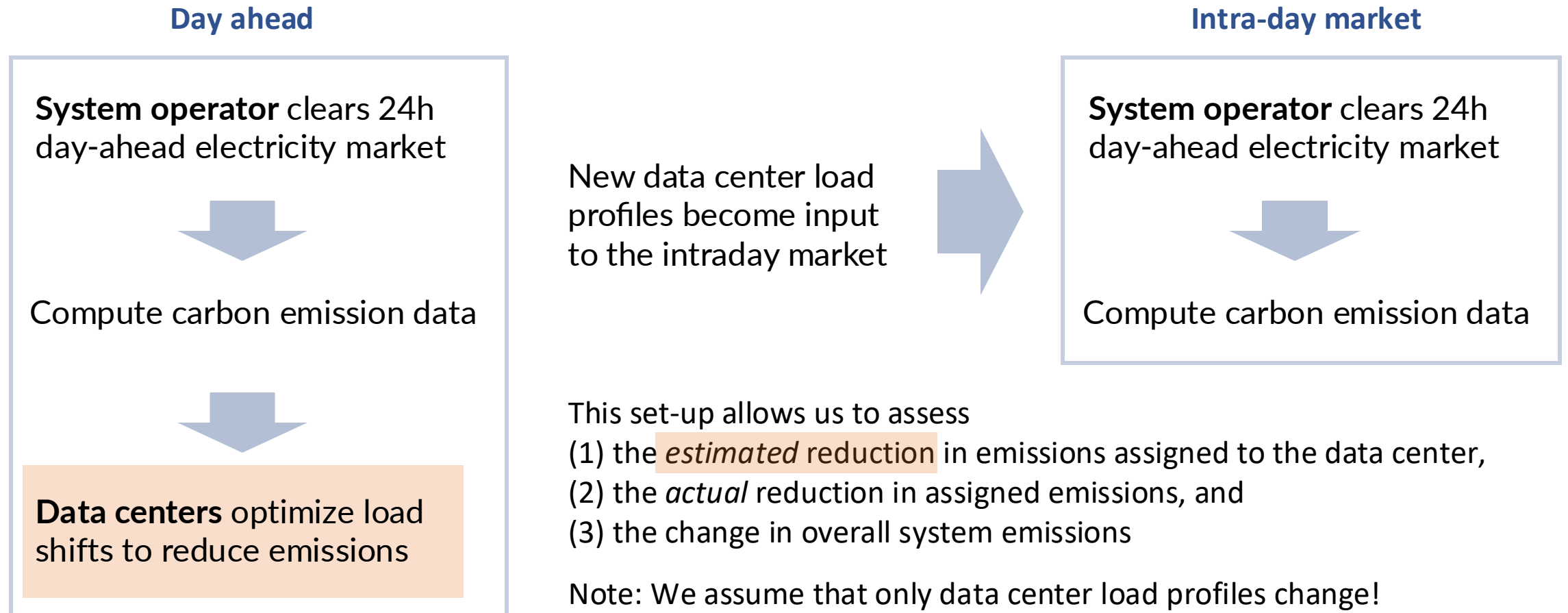
Compute carbon emission data

This set-up allows us to assess

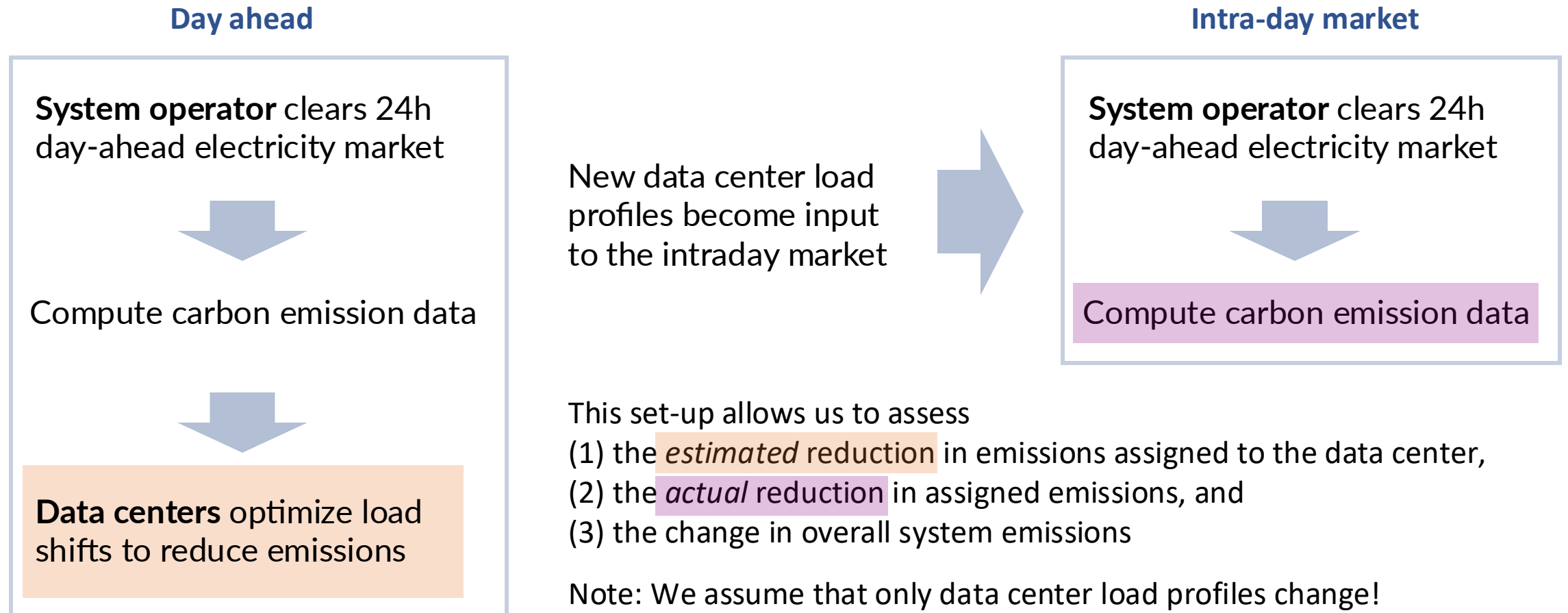
- (1) the *estimated* reduction in emissions assigned to the data center,
- (2) the *actual* reduction in assigned emissions, and
- (3) the change in overall system emissions

Note: We assume that only data center load profiles change!

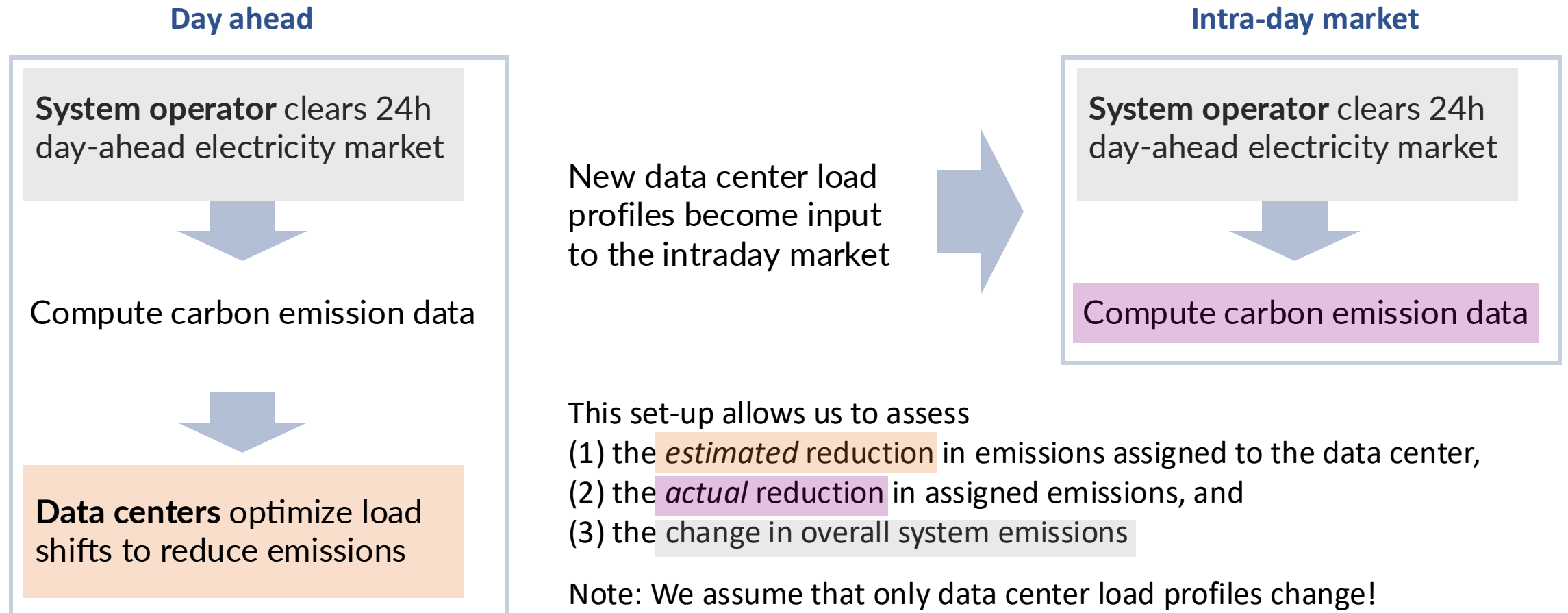
Carbon-aware load shifting



Carbon-aware load shifting

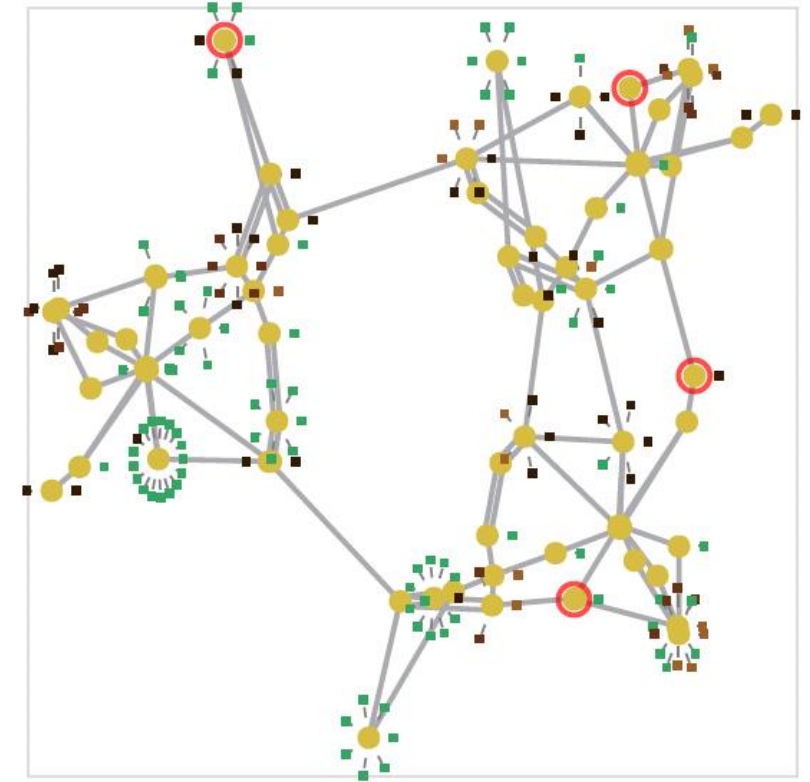


Carbon-aware load shifting



Data center load shifting

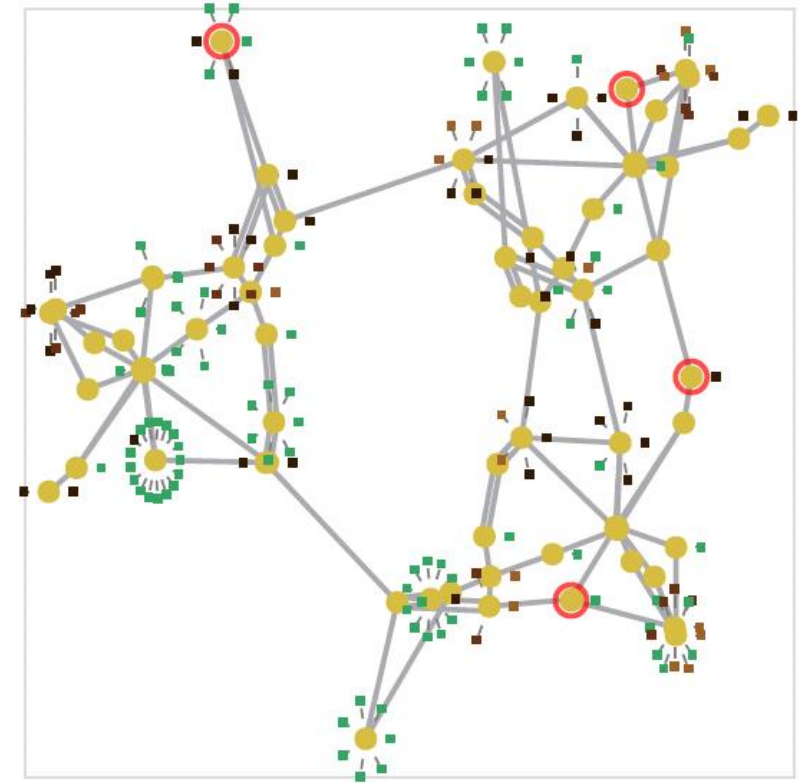
- Use RTS-GMLC test system, with one year of hourly load data



RTS-GMLC system. Buses marked in **yellow**, lines in **grey**, generators in **green/brown/black** depending on their level of emissions.

Data center load shifting

- Use RTS-GMLC test system, with one year of hourly load data
- Assume 4 data centers with 250 MW average consumption, equal to approximately 20% data center load



RTS-GMLC system. Buses marked in **yellow**, lines in **grey**, generators in **green/brown/black** depending on their level of emissions. Data center locations are circled in **red**.

Data center load shifting

- Use RTS-GMLC test system, with one year of hourly load data
- Assume 4 data centers with 250 MW average consumption, equal to approximately 20% data center load
- Allow data centers to do spatial and temporal load shifting by choosing where and when to process computing workloads
- This allows for an increase/decrease of consumption up to 50MW at each location (about 4% of system load)



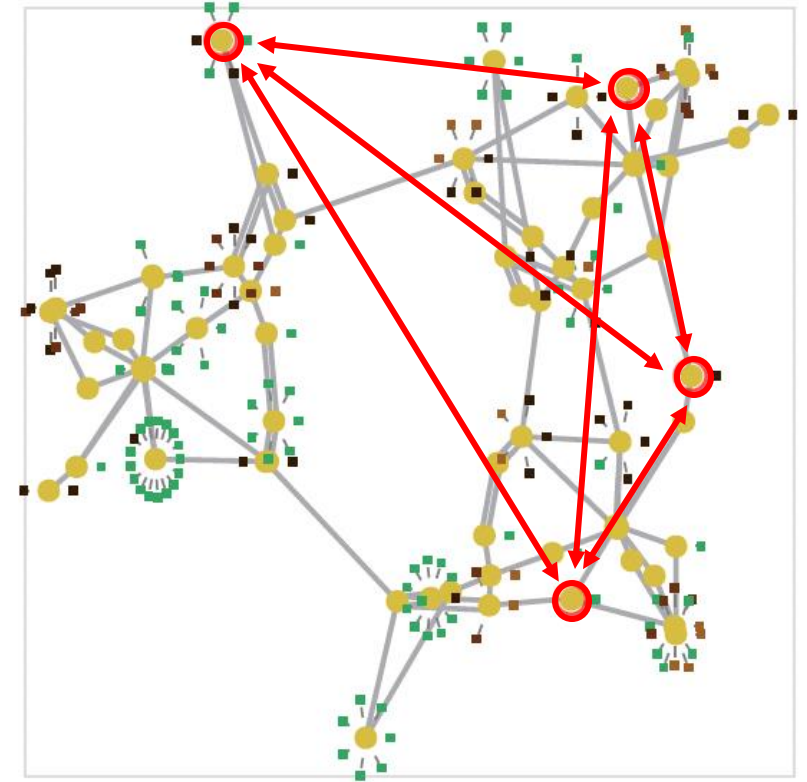
RTS-GMLC system. Buses marked in **yellow**, lines in **grey**, generators in **green/brown/black** depending on their level of emissions. Data center locations are circled in **red**.

Data center load shifting

- Use RTS-GMLC test system, with one year of hourly load data
- Assume 4 data centers with 250 MW average consumption, equal to approximately 20% data center load
- Allow data centers to do spatial and temporal load shifting by choosing where and when to process computing workloads
- This allows for an increase/decrease of consumption up to 50MW at each location (about 4% of system load)

First: Count emissions.

Second: Shift load to minimize emissions.



RTS-GMLC system. Buses marked in **yellow**, lines in **grey**, generators in **green/brown/black** depending on their level of emissions. Data center locations are circled in **red**.

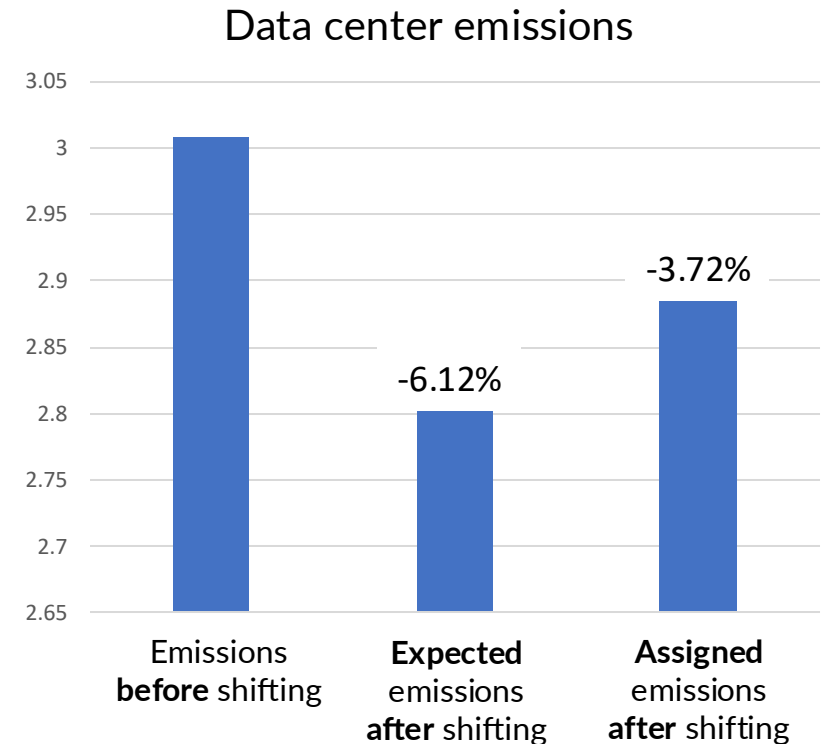
Data center load shifting

First: Count emissions.

- Data centers are assigned 3.008 million Tons of CO₂ emissions over the course of a year (~19% of system emissions)

Second: Shift load to minimize emissions.

- Data centers use *pre-shift* average carbon data to adapt load in real-time. Expected reduction in carbon emissions is 6.12%
- Shifting changes the generation mix and the average carbon emissions!
- With *post-shift* average carbon data, the data center emission reductions are 3.72%



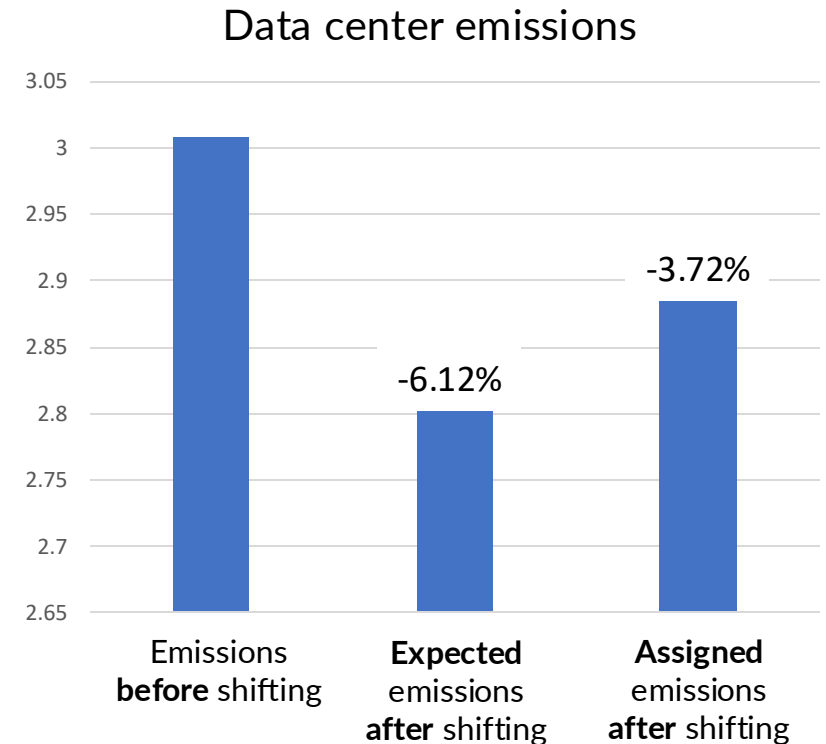
Data center load shifting

First: Count emissions.

- Data centers are assigned 3.008 million Tons of CO2 emissions over the course of a year (~19% of system emissions)

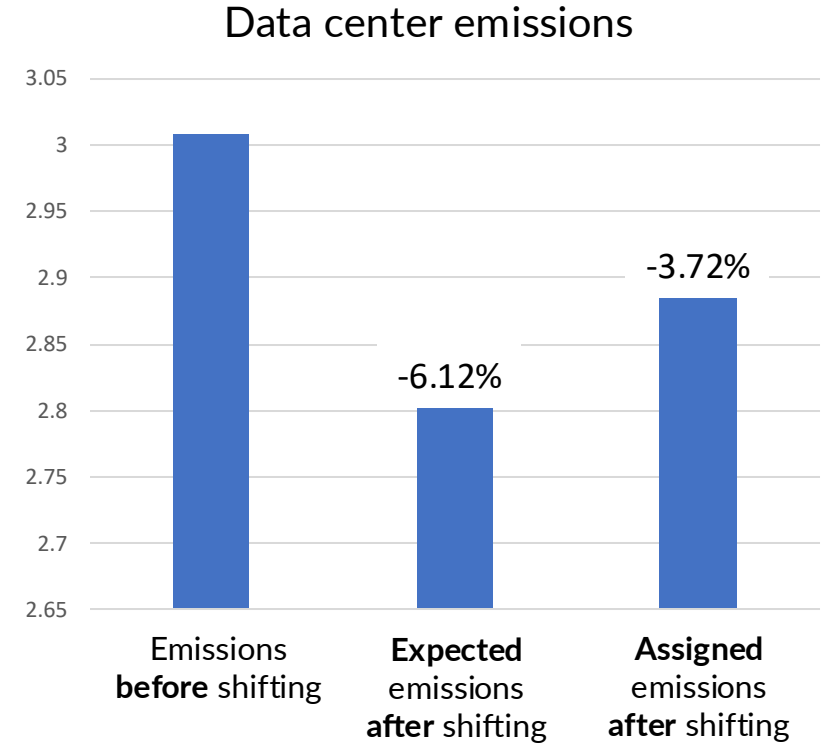
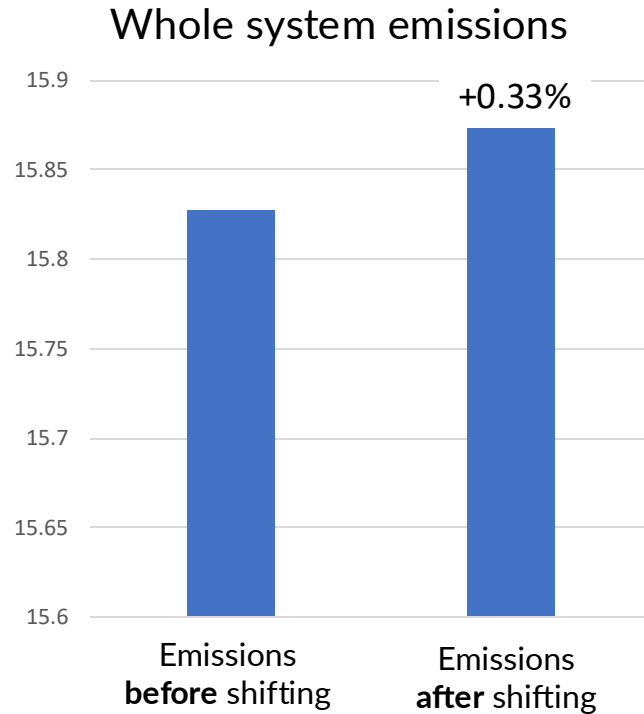
Second: Shift load to minimize emissions.

- Data centers use *pre-shift* average carbon data to adapt load in real-time. Expected reduction in carbon emissions is 6.12%
- Shifting changes the generation mix and the average carbon emissions!
- With *post-shift* average carbon data, the data center emission reductions are 3.72%



Looks pretty good!?

Data center load shifting



But...

Total system emissions increase by +0.33% !!

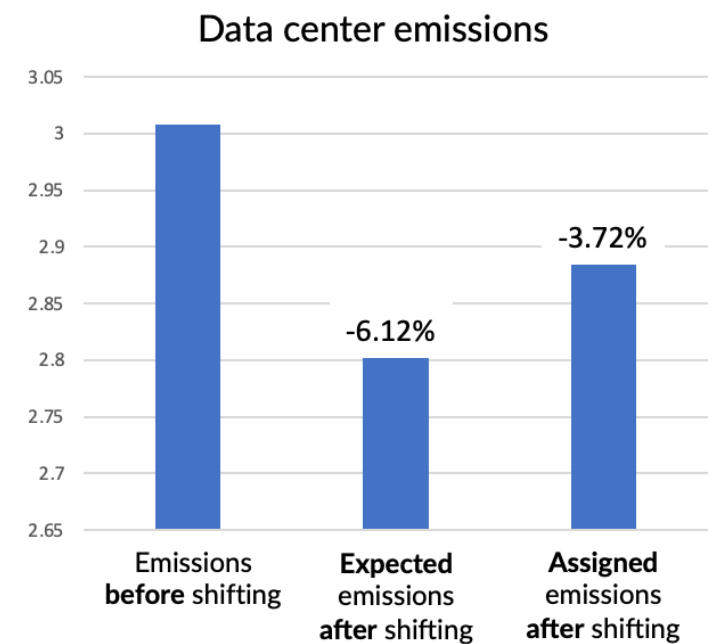
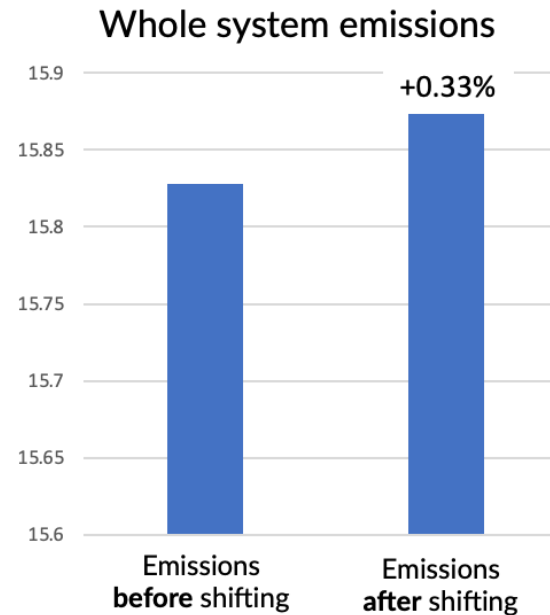
Data centers become cleaner, while all other loads become dirtier ☹️

Data center load shifting

Conclusion: Even if data centers *believe* they contribute to *lower emissions* (and are assigned fewer), their actions actually *increase emissions*.

Why? Average carbon emissions does not tell us how a *change in load* will *change emissions*!

Problematic if this is the metric consumers are optimizing for!!



A Better Alternative?

$$\text{Locational marginal carbon emissions} = \frac{\text{Change in carbon emissions}}{\text{Change in electricity use at given location}}$$

Describes the emission impact from a change in load (i.e. how the marginal generator moves).

A Better Alternative?

$$\text{Locational marginal carbon emissions} = \frac{\text{Change in carbon emissions}}{\text{Change in electricity use at given location}}$$

Describes the emission impact from a change in load (i.e. how the marginal generator moves).

“Similar” to locational marginal prices (LMPs)!

Whereas LMPs are related to the cost minimization objective, locational marginal emissions are calculated by a more involved **sensitivity analysis of OPF solutions**

1. Identify binding constraints at a basic optimal solution, which allows us to derive linear system of equations that describes how a change in load parameter ΔP_d changes the optimal generation dispatch

$$\Delta P_g^* = B \Delta P_d$$

2. Use emission factors to calculate the change in emissions

$$\Delta E = e_{\text{CO}_2} \Delta P_g^*$$

Full explanation and derivation in
Lindberg, Lesieutre and Roald, HICSS
2021 <https://arxiv.org/pdf/2010.03379>

A Better Alternative?

$$\text{Locational marginal carbon emissions} = \frac{\text{Change in carbon emissions}}{\text{Change in electricity use at given location}}$$

Describes the emission impact from a change in load (i.e. how the marginal generator moves).

“Similar” to locational marginal prices (LMPs)!

Whereas LMPs are related to the cost minimization objective, locational marginal emissions are calculated by a more involved **sensitivity analysis of OPF solutions**

What happens if we use this metric for load shifting?

1. Identify binding constraints at a basic optimal solution, which allows us to derive linear system of equations that describes how a change in load parameter ΔP_d changes the optimal generation dispatch

$$\Delta P_g^* = B \Delta P_d$$

2. Use emission factors to calculate the change in emissions

$$\Delta E = e_{\text{CO}_2} \Delta P_g^*$$

Full explanation and derivation in
Lindberg, Lesieutre and Roald, HICSS
2021 <https://arxiv.org/pdf/2010.03379>

Carbon-aware load shifting

Day ahead

System operator clears 24h day-ahead electricity market



Compute carbon emission data



Data centers optimize load shifts to reduce emissions

Solve DC OPF to minimize hourly cost

Compute locational marginal emissions

Minimize data center emissions by shifting load in time and space

$$\begin{aligned} \min_{\theta, P_g} \quad & c^T P_g && \text{Minimize cost} \\ \text{s.t.} \quad & \sum_{\ell \in \mathcal{G}_i} P_{g,\ell} - \sum_{\ell \in \mathcal{D}_i} P_{d,\ell} = \sum_{j: (i,j) \in \mathcal{L}} \beta_{ij} (\theta_i - \theta_j), && \forall i \in \mathcal{N} \\ & -P_{ij}^{lim} \leq -\beta_{ij} (\theta_i - \theta_j) \leq P_{ij}^{lim}, && \forall (i,j) \in \mathcal{L} \\ & P_{g,i}^{min} \leq P_{g,i} \leq P_{g,i}^{max}, && \forall i \in \mathcal{G} \\ & \theta_{ref} = 0. && \text{Power flow and generation constraints} \end{aligned}$$

$$= \frac{\text{Change in carbon emissions}}{\text{Change in electricity use at given location}} \quad \text{Different value for each node!}$$

$$\begin{aligned} \min_{\Delta P_{d,s}} \quad & \sum_{i \in \mathcal{C}} \lambda_{CO_2,i} \Delta P_{d,i} && \text{Minimize emissions} \\ \text{s.t.} \quad & \Delta P_{d,i} = \sum_{j \in \mathcal{C}} s_{ji} - \sum_{k \in \mathcal{C}} s_{ik} && \forall i \in \mathcal{C} \\ & \sum_{i \in \mathcal{C}} \Delta P_{d,i} = 0 && \text{Data center shifting constraints} \\ & -\epsilon_i \cdot \text{Cap}_i \leq \Delta P_{d,i} \leq \epsilon_i \cdot \text{Cap}_i && \forall i \in \mathcal{C} \\ & 0 \leq \Delta P_{d,i} + P_{d,i} \leq \text{Cap}_i && \forall i \in \mathcal{C} \\ & 0 \leq s_{ij} \leq M_{ij} && \forall ij \in \mathcal{C} \times \mathcal{C}. \end{aligned}$$

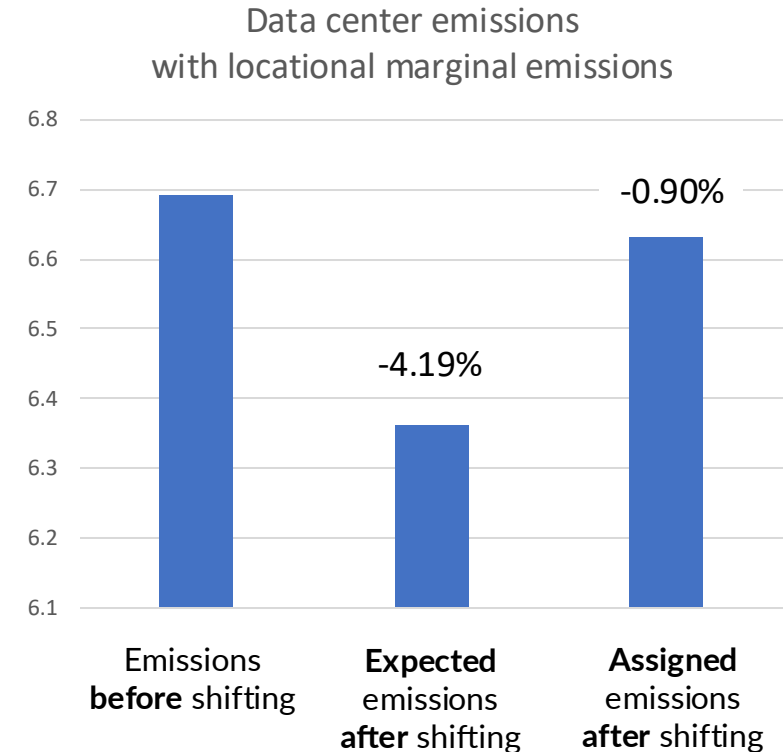
Data center load shifting

First: Count emissions.

- Data centers are assigned 6.692 million Tons of CO2 emissions over the course of a year (~20% of system emissions)

Second: Shift load to minimize emissions.

- Data centers use *pre-shift* locational marginal emissions data to adapt load in real-time. Expected reduction in carbon emissions is 4.19%
- Shifting changes the generation mix and the locational marginal emissions!
- With *post-shift* average carbon data, the data center emission reductions are -0.90%



Emission reductions are lower than before, and our prediction overly optimistic...

Data center load shifting

How about total system emissions?

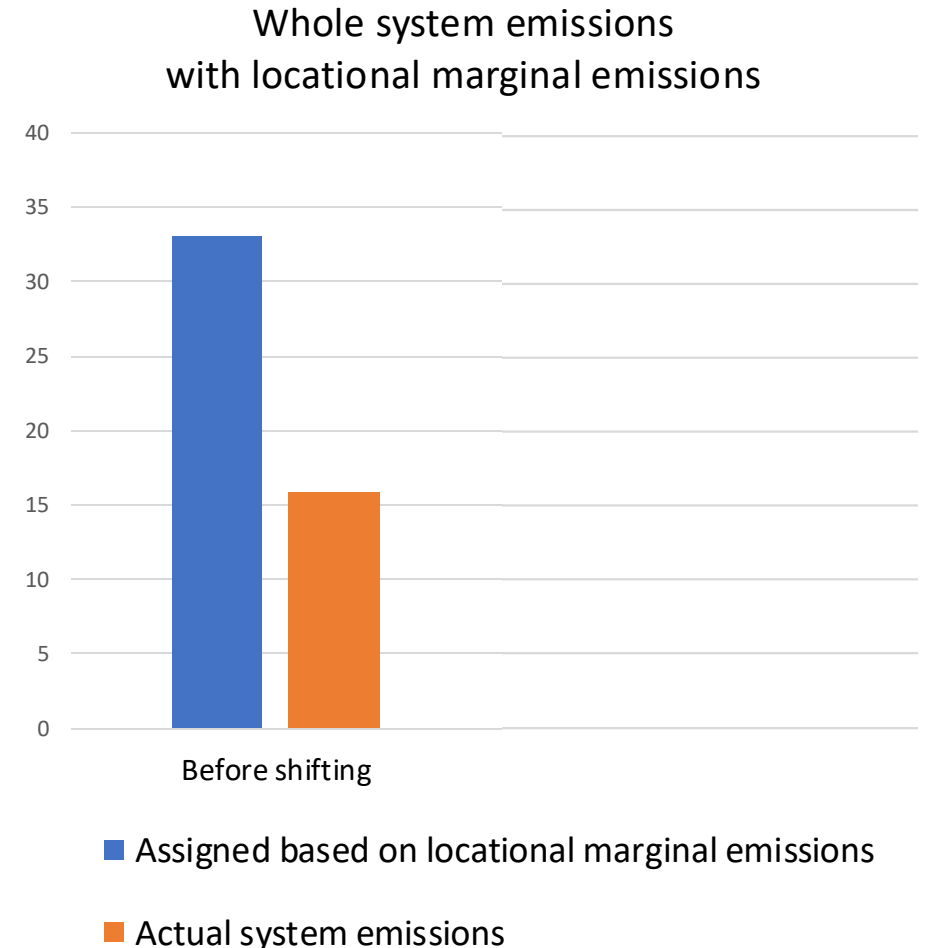
First observation:

If we use locational marginal emissions to assign emissions to load, the total emissions assigned $\neq$ total emissions from generation!

We can assign too many or too few, depending on how polluting the marginal generator is!

Why? Locational marginal emissions does not provide any information about emissions from non-marginal generators!

(In contrast, LMPs are always based on the most expensive generator to serve a node)



Data center load shifting

How about total system emissions?

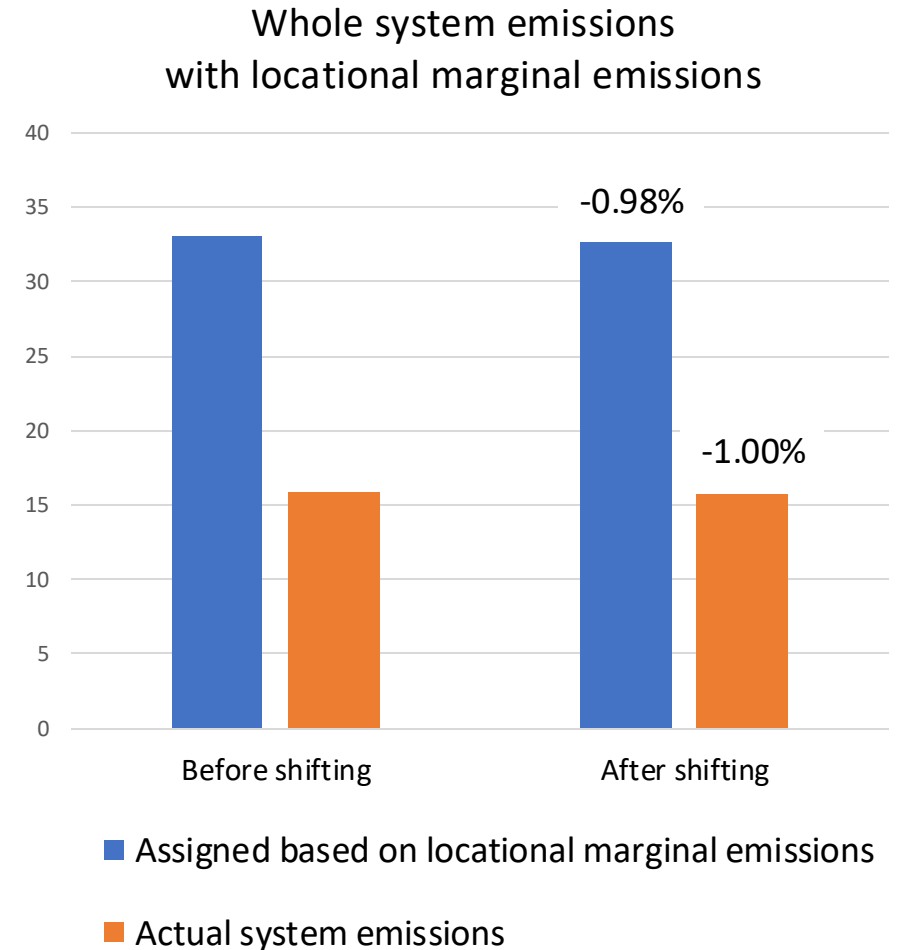
First observation:

If we use locational marginal emissions to assign emissions to load, the total emissions assigned $\neq$ total emissions from generation!

Second observation:

When data center emissions decrease, the system emissions also decrease.

In this case, data center load shifting also reduces the carbon emissions of non-data center loads!



Daily load shifting results

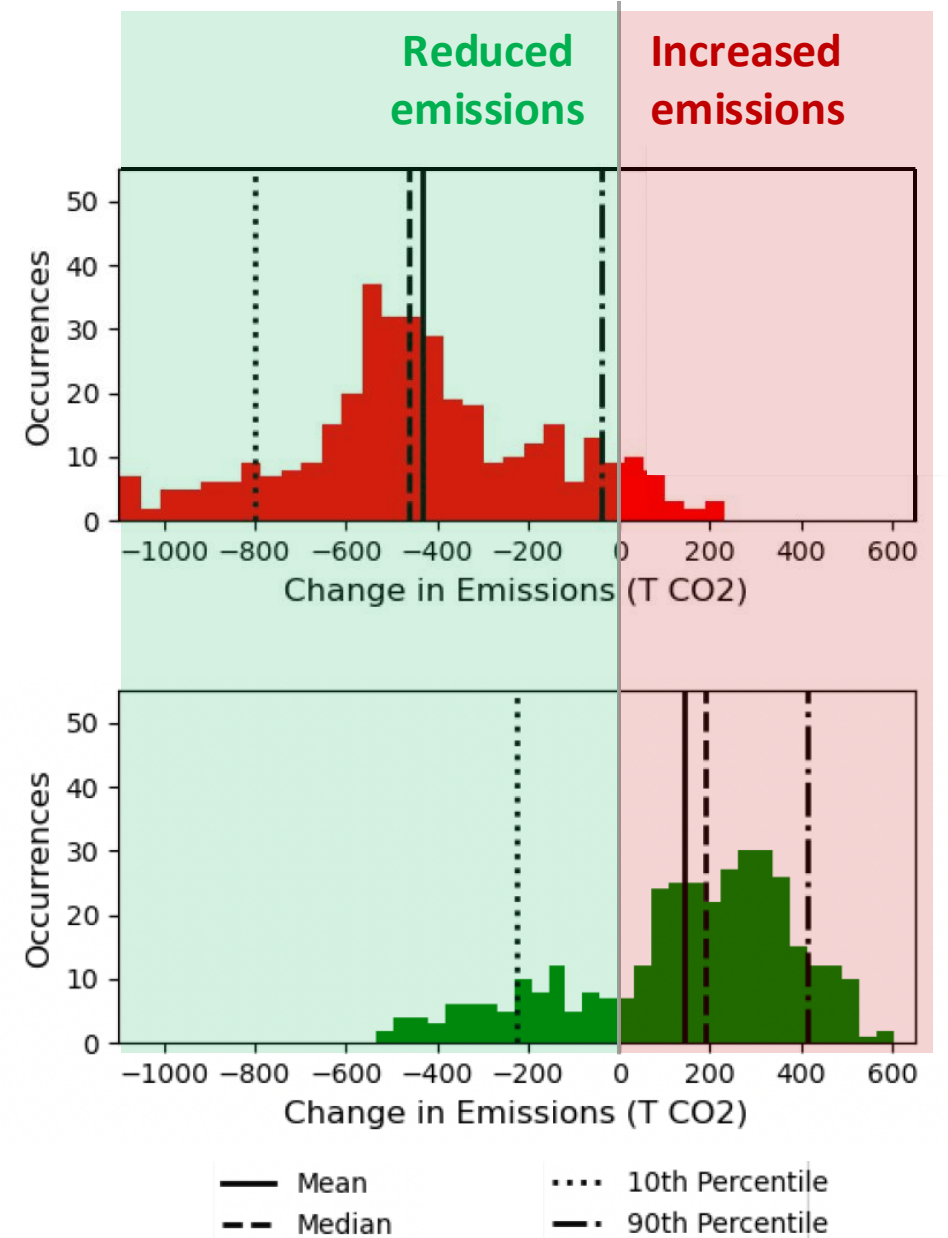
Previous results were aggregated across the full year.

For individual days, load shifting based on both average and marginal carbon emissions can lead to increases or reductions in emissions.

... but locational marginal emissions has fewer days with emission increases and more days with large emission reductions!

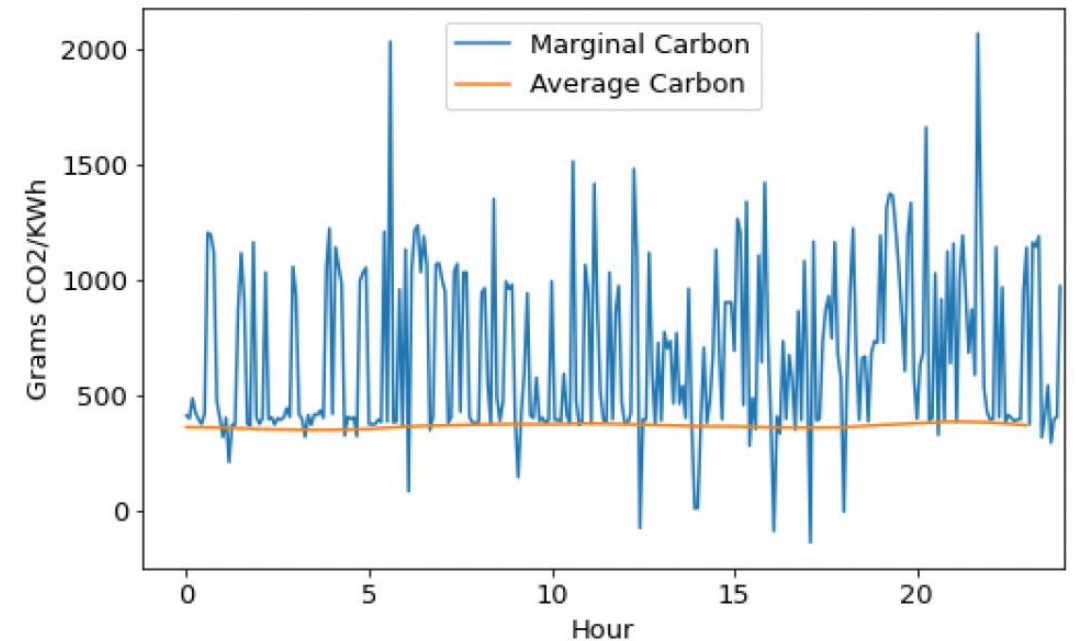
Shifting with
locational
marginal
emissions

Shifting with
average
carbon
emissions



Let's use locational marginal emissions?

- Verified data only available in very specific regions (to my knowledge only in PJM)
- Locational marginal emissions are highly unstable, which makes them hard to predict and act on
- It is hard to justify using locational marginal emissions for accounting, since total emissions assigned to load can be wildly different from the total emissions from generation.



Marginal and **average** carbon emissions for Chicago
(based on PJM and ElectricityMaps data)

We need new metrics!?

- **Locational Average Carbon Emissions**
 - Traces carbon from source to sink, using the proportional sharing principle at each node.
 - Ensures that the assignment of carbon emissions is consistent with physical power flow and that total emissions assigned to loads = total emissions from generation
- **Adjusted Locational Marginal Emissions**
 - Adjusts locational marginal emissions by a shifting factor (constant across all loads), such that the total emissions assigned to loads = total emissions from generation
 - Similar differences in carbon intensity as LMCE in a given timestep
 - Similar to ACE when there is no congestion

Chen, Yize, Deepjyoti Deka, and Yuanyuan Shi. "Contributions of Individual Generators to Nodal Carbon Emissions." *Proceedings of the 15th ACM International Conference on Future and Sustainable Energy Systems*. 2024.

Xin Chen, Hungpo Chao, Wenbo Shi, and Na Li. "Towards carbon-free electricity: A flow-based framework for power grid carbon accounting and decarbonization." *Energy Conversion and Economics* (2023).

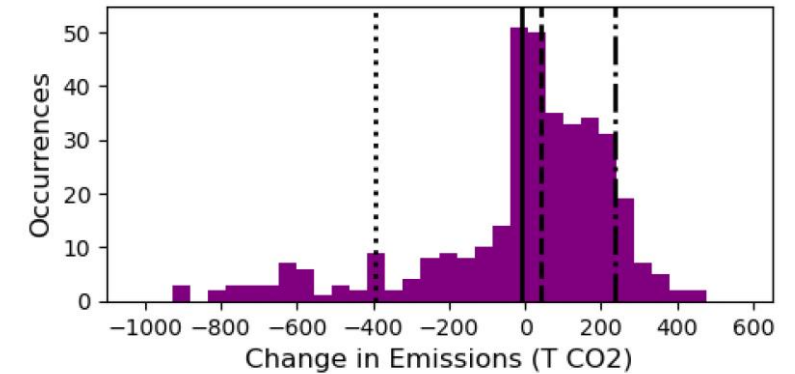
Xin Chen, Andy Sun, Wenbo Shi and Na Li, "Carbon-aware optimal power flow." *IEEE Transactions on Power Systems*. 2024.

Joe Gorka, Noah Rhodes and Line Roald. "ElectricityEmissions.jl: A Framework for the Comparison of Carbon Intensity Signals", under review. Preprint: <https://arxiv.org/abs/2411.06560>

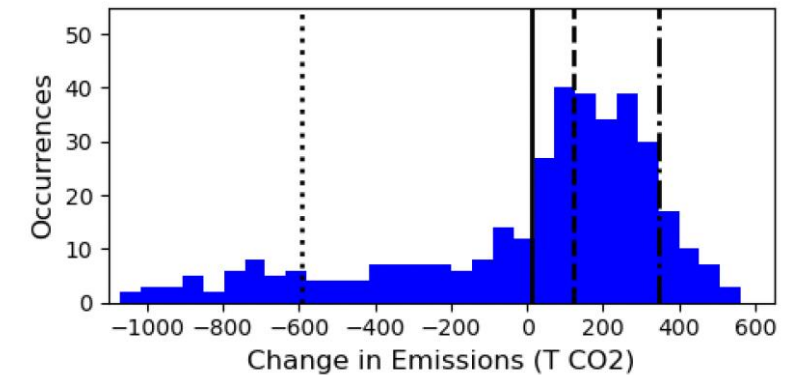
We need new metrics!?

- **Locational Average Carbon Emissions**
 - Traces carbon from source to sink, using the proportional sharing principle at each node.
 - Ensures that the assignment of carbon emissions is consistent with physical power flow and that total emissions assigned to loads = total emissions from generation
- **Adjusted Locational Marginal Emissions**
 - Adjusts locational marginal emissions by a shifting factor (constant across all loads), such that the total emissions assigned to loads = total emissions from generation
 - Similar differences in carbon intensity as LMCE in a given timestep
 - Similar to ACE when there is no congestion

Shifting with
locational
average
emissions



Shifting with
adjusted
marginal
emissions



On average, no change in emissions!

Similar results with other setups

Julia Lindberg, Bernard C. Lesieutre, and Line A. Roald. "Using Geographic Load Shifting to Reduce Carbon Emissions." Electric Power Systems Research, 2022

Real-time market, time t

System operator clears 24h day-ahead electricity market



Compute carbon emission data



Data centers optimize load shifts to reduce emissions



Real-time market, time $t+1$

System operator clears 24h day-ahead electricity market



Compute carbon emission data



Data centers optimize load shifts to reduce emissions

...

Similar results with other setups

Julia Lindberg, Bernard C. Lesieutre, and Line A. Roald. "Using Geographic Load Shifting to Reduce Carbon Emissions." Electric Power Systems Research, 2022

Real-time market, time t

System operator clears 24h day-ahead electricity market



Compute carbon emission data



Data centers optimize load shifts to reduce emissions



Real-time market, time $t+1$

System operator clears 24h day-ahead electricity market



Compute carbon emission data



Data centers optimize load shifts to reduce emissions

- Locational marginal emissions is the most effective signal for shifting
- Important to keep individual shifts small and build up over time to avoid “over-shifting”
- Use regularization / quadratic shifting costs

Fundamental limitations of load shifting

- Carbon-sensitive loads change when (or how much) they use electricity
- This means that they impact the dispatch of the **marginal** generator
- But they cannot change the order in which generators are dispatched, which is based on cost!

Fundamental limitations of load shifting

- Carbon-sensitive loads change when (or how much) they use electricity
- This means that they impact the dispatch of the **marginal** generator
- But they cannot change the order in which generators are dispatched, which is based on cost!

“The right approach”: Add a tax or penalty on generator emissions

Makes low carbon generators more cost competitive.

Politically challenging:

- Requires agreement on a single carbon price.
- Makes electricity more expensive (and therefore also reduces demand)

A different approach? Two-dimensional consumer bids

- Allow consumers to submit *bids for electricity consumption and consumer-defined carbon cost*
- Change market design to maximize social welfare under consideration of the consumer-side carbon cost

Jiang, Wenqian, and Line Roald. "Greening the Grid: Electricity Market Clearing with Consumer-Based Carbon Cost." *arXiv preprint arXiv:2501.09853* (2025).



Key idea: Build carbon allocation into market design

$$\max_{P_g, P_d, \theta, \pi, E_d} u_d^\top P_d - c_{co_2}^\top E_d - c_g^\top P_g \quad (1)$$

$$s.t. \sum_{n \in \mathcal{D}_i} P_{d,n} + \sum_{j: (i,j) \in \mathcal{L}} \beta_{ij}(\theta_i - \theta_j) = \sum_{m \in \mathcal{G}_i} P_{g,m},$$

$$\forall i \in \mathcal{N}, \quad (1a)$$

$$-F_{ij}^{\text{lim}} \leq \beta_{ij}(\theta_i - \theta_j) \leq F_{ij}^{\text{lim}}, \quad \forall (i,j) \in \mathcal{L}, \quad (1b)$$

$$P_{g,m}^{\text{min}} \leq P_{g,m} \leq P_{g,m}^{\text{max}}, \quad \forall m \in \mathcal{G}, \quad (1c)$$

$$P_{d,n}^{\text{min}} \leq P_{d,n} \leq P_{d,n}^{\text{max}}, \quad \forall n \in \mathcal{D}, \quad (1d)$$

$$\theta_{\text{ref}} = 0, \quad (1e)$$

$$\sum_{n \in \mathcal{D}} \pi_{m,n} = P_{g,m}, \quad \forall m \in \mathcal{G}, \quad (1f)$$

$$\sum_{m \in \mathcal{G}} \pi_{m,n} = P_{d,n}, \quad \forall n \in \mathcal{D}, \quad (1g)$$

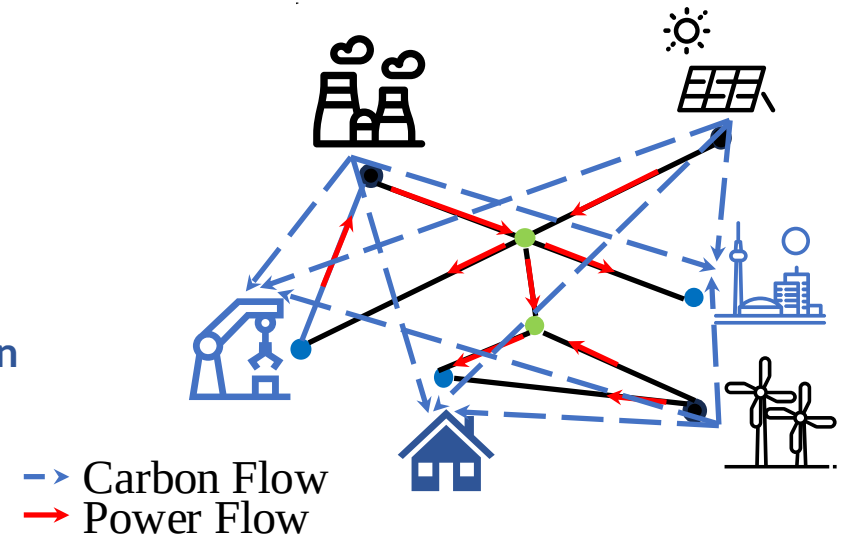
$$\sum_{m \in \mathcal{G}} e_{g,m} \pi_{m,n} = E_{d,n}, \quad \forall n \in \mathcal{D}, \quad (1h)$$

$$\pi_{m,n} \geq 0, \quad \forall m \in \mathcal{G}, \quad \forall n \in \mathcal{D}. \quad (1i)$$

Maximize social welfare, with
carbon-dependent consumer utility!

Power flow
constraints

Carbon
allocation



Key idea: Build carbon allocation and consumer carbon preferences into market design

$$\max_{P_g, P_d, \theta, \pi, E_d} u_d^\top P_d - c_{co_2}^\top E_d - c_g^\top P_g \quad (1)$$

$$s.t. \sum_{n \in \mathcal{D}_i} P_{d,n} + \sum_{j: (i,j) \in \mathcal{L}} \beta_{ij}(\theta_i - \theta_j) = \sum_{m \in \mathcal{G}_i} P_{g,m},$$

$$\forall i \in \mathcal{N}, \quad (1a)$$

$$-F_{ij}^{\text{lim}} \leq \beta_{ij}(\theta_i - \theta_j) \leq F_{ij}^{\text{lim}}, \quad \forall (i,j) \in \mathcal{L}, \quad (1b)$$

$$P_{g,m}^{\text{min}} \leq P_{g,m} \leq P_{g,m}^{\text{max}}, \quad \forall m \in \mathcal{G}, \quad (1c)$$

$$P_{d,n}^{\text{min}} \leq P_{d,n} \leq P_{d,n}^{\text{max}}, \quad \forall n \in \mathcal{D}, \quad (1d)$$

$$\theta_{\text{ref}} = 0, \quad (1e)$$

$$\sum_{n \in \mathcal{D}} \pi_{m,n} = P_{g,m}, \quad \forall m \in \mathcal{G}, \quad (1f)$$

$$\sum_{m \in \mathcal{G}} \pi_{m,n} = P_{d,n}, \quad \forall n \in \mathcal{D}, \quad (1g)$$

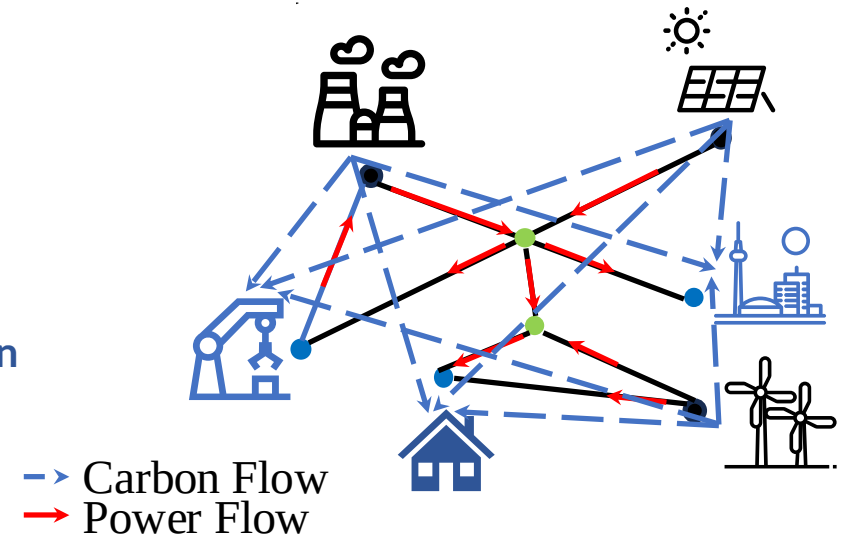
$$\sum_{m \in \mathcal{G}} e_{g,m} \pi_{m,n} = E_{d,n}, \quad \forall n \in \mathcal{D}, \quad (1h)$$

$$\pi_{m,n} \geq 0, \quad \forall m \in \mathcal{G}, \quad \forall n \in \mathcal{D}. \quad (1i)$$

Maximize social welfare, with **carbon-dependent** consumer utility!

Power flow constraints

Carbon allocation



Key idea: Build carbon allocation and consumer
carbon preferences into market design

Key idea: Build carbon allocation and consumer carbon preferences into market design

- Initial results indicate that this scheme is able to **reduce emissions** at a relatively **modest increase in generation cost**.

TABLE III

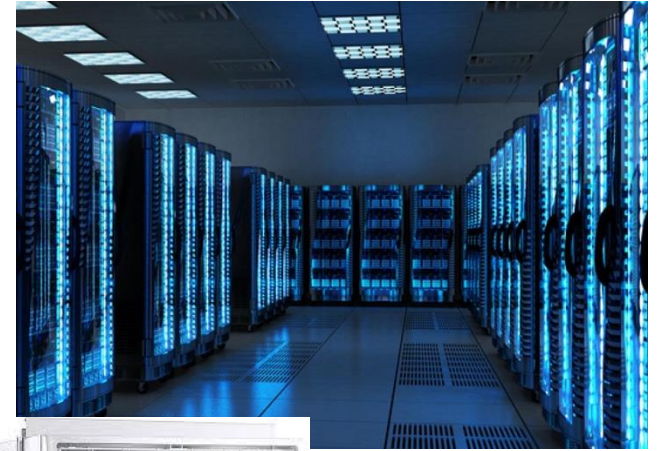
THE IMPACT OF DIFFERENT CARBON COSTS ON GENERATION DISPATCH, SYSTEM EMISSIONS, AND OBJECTIVE FUNCTION COMPONENTS.

Cases	Total Generation [MWh]	Total Generation Cost [\$]	Total Carbon [tons]	Average Carbon [tons/MWh]	$u_d^\top P_d$ [\$]	$c_{co_2}^\top E_d$ [\$]	Optimal Objective Values [\$]
P(2)	8550	63748	3001.8	0.351	457039	0	393291
P(3)	8550	63748	3001.8	0.351	457039	0	393291
[10, 20]	8550	64723.4	2866.9	0.335	457039	35591.4	356724.2
[10, 40]	8550	65468.5	2804	0.328	457039	50088.7	341481.8
[30, 60]	8263.3	61675.1	2594.6	0.314	448896.9	99168.8	288053
[50, 80]	8063.2	58907	2473.7	0.307	439138.2	143270.5	236960.7

- A lot more analysis is needed – ongoing 😊

Summary

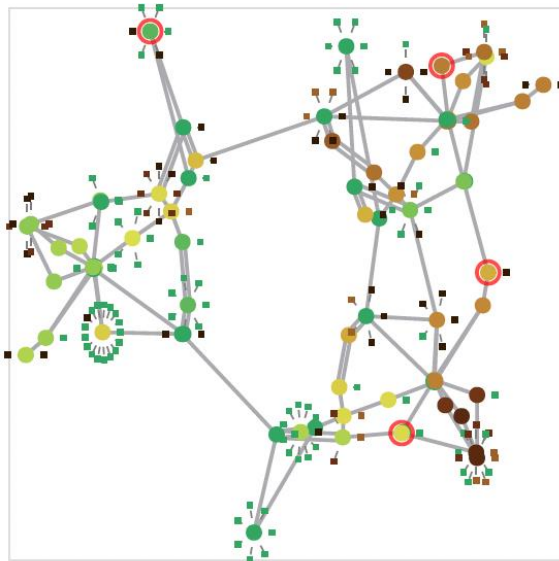
- Carbon-sensitive loads may become an increasingly important group of loads in the future
- We need a system for carbon accounting of electricity that is fair, transparent and aligned with the real-time physical operation of the electric grid. It must reward actions that truly reduce total carbon emissions (not only shifts them to other consumers!)
- Carbon-based load shifting has limitations, and it is important to explore how to more effectively account for consumer's carbon-sensitivity and carbon reduction preferences



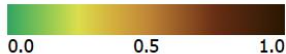
Want to do your own emissions accounting study?

Use our package!

<https://github.com/WISPO-POP/ElectricityEmissions.jl>



Emissions Intensity



0.0 0.5 1.0

README MIT license

ElectricityEmissions.jl

 [Build Status](#)

ElectricityEmissions.jl is a Julia package for the calculation of carbon emissions intensity metrics for power system test cases. It also includes visualization functionality via the [PowerPlots.jl](#) package.

Installation

The latest development version of `ElectricityEmissions.jl` can be added via: `Pkg> add https://github.com/WISPO-POP/ElectricityEmissions.jl.git`

Basic Use

To use `ElectricityEmissions.jl`, simply load a test case in MATPOWER format, assign emissions intensity values to all generators, and calculate nodal carbon intensity values. Optionally, it is then possible to visualize these nodal intensity values.

```
using ElectricityEmissions, PowerModels, HiGS

case = PowerModels.parse_file("/test_cases/case30nw1.m")
```

Thank you!

Line A. Roald
roald@wisc.edu

