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Emissions Response

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IN THIS ARTICLE, WE INTRODUCE EMISSIONS RESPONSE, the widespread use of real-time emissions factors in electricity grids as a signal for a dynamic response to facilitate decarbonization and system efficiency. Many articles and publications have suggested dynamic approaches to addressing systemwide emissions, reducing emissions through time-sensitive consumption, and aiding in the adoption of renewable and low-emissions technologies. With emissions response, we combine, broaden, and formalize these concepts as effective means of encouraging and regulating the energy transition with benefits to grid systems at large as well as individual stakeholders in generation, consumption, and storage. We provide an overview where real-time emissions factors serve as a metric toward grid efficiency, recognizing and promoting technologies that provide long-term stability along with technologies driving decarbonization.

Real-Time Emissions and Emissions Response

Emissions from electricity generation and associated consumption are defined based on emissions intensities, also

Efficient Decarbonization Using Real-Time Data

known as *factors*—a single value applied to a grid or system in units of mass of carbon dioxide equivalent per unit of power delivered ($\text{tCO}_2\text{e/MWh}$). Each unit of power (MWh) generated to or consumed from the grid is then assumed to have emitted the associated mass of carbon dioxide (equivalent) (tCO_2e) to the atmosphere. Emissions intensities in geographic areas and grids are typically updated infrequently and assumed as fixed values for annual periods if not longer. These fixed values are convenient in that they allow the simple allocation of emissions to associated consumers (scope II emissions) and provide a simple benchmark that emissions from individual generators can be compared to.

While convenient, this system fails to account for the complex interactions between new and low-carbon technologies and the technical requirements needed to support a stable and secure electricity grid. Fixed emissions encourage

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Storage assets can provide further stability to the grid and will see rewards based on charging at times of low emissions.

actions taken in isolation, where reductions are rewarded based on the static state of the system well before the action took place. Analysis based on fixed emissions factors also fails to identify the capacity for flexibility within the system that is useful for both reducing emissions and contributing to grid stability and efficiency.

A basic yet essential step in efficiently targeting improvements to the electricity system is adopting baseline metrics that capture the dynamic operations of the grid. This necessitates moving away from long-term, fixed emissions factors and applying real-time emissions factors for analysis, decision making, and regulatory action. Emissions response will invoke real-time, grid-level emissions factors as a dynamic baseline metric for financial regulatory frameworks as a signal for consumer-side scheduling and response and as a vital tool for long-term planning around the incorporation of low-emissions technologies. Emissions factors will serve as an active metric, similar to pricing, promoting economic and market forces to drive decarbonization efficiently.

Emissions response will incorporate real-time emissions metrics in three ways to impact generation, consumption, and long-term planning. First, emissions regulations

applied to generation sources, such as carbon taxes, carbon offsets, and cap and trade programs, will apply baselines built on the real-time emissions of the grid at the time a generator supplies power to that grid. Applying financial rewards and penalties based on dynamic emissions will allow economic forces to encourage system efficiency and emissions reduction, rewarding low-emissions generation most when their offsets are highest and discouraging high-emissions generation only when it is not required.

Second, consumers will be exposed to real-time emissions factors relevant to their own consumption from the grid, similar to a time-of-use system or pricing applied in the wholesale market. With accessible and transparent data, consumers will be encouraged to shift demand to times of low emissions while limiting demand during emissions peaks. The combination of forces on the generation and consumption side will also provide a value proposition for storage assets, which can increase the viability of arbitrage by charging from the grid in periods of low emissions and discharging to displace high grid emissions. Lastly, with granular data on emissions intensity, investors and planners will have a valuable tool to identify where grid inefficiencies exist to best guide decisions on long-term sustainable action.

Financial rewards and penalties would be separate from the wholesale pricing market and act similar to carbon pricing methods applied in many current regulatory structures. While carbon prices would remain fixed, in terms of $\$/\text{tCO}_2\text{e}$, or subject to a separate carbon offset market, the dynamics of the grid intensity would apply a realistic, accurate, and time-sensitive reflection of a generator's contribution to grid emissions and a consumer's scope II emissions.

The application of dynamic emission factors for generation and consumption is demonstrated in Figure 1, where a high-emitting generation source would be subject to penalties related to its emissions above the grid average, shown in red; a low-emitting generation source would receive rewards related to the grid emissions it is offsetting, shown in blue; and consumers would be encouraged to shift

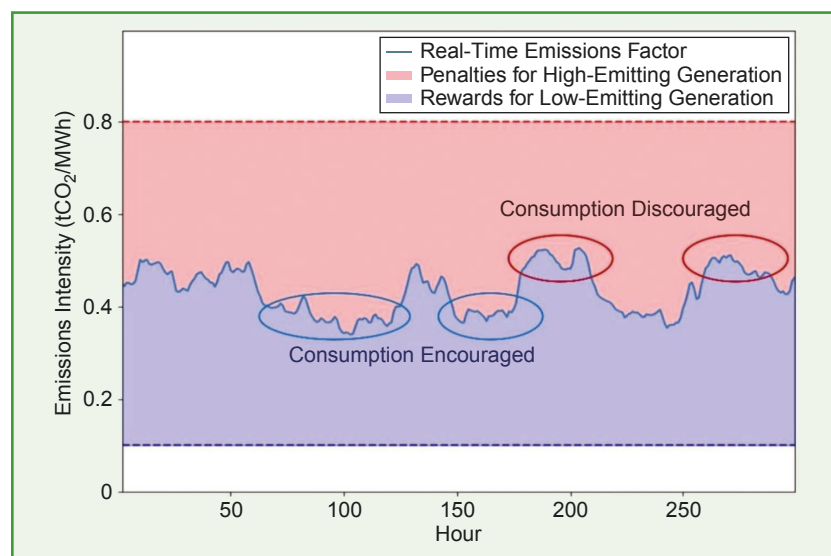


figure 1. Use of the real-time emissions factor to determine rewards and penalties for under- and overemitters, respectively, as well as using emissions as a signal for flexible consumption. With emissions forecasts, consumption signals can be sent in advance, and generators can plan for economic impacts of emissions regulations.

demand toward times of low gridwide emissions and avoid the highest gridwide emissions. While individual generation sources see little change in their emissions intensities, the rewards and penalties are dependent on the state of the grid at the time their generation is supplied, encouraging low-emitting generation most at times of high gridwide emissions, while high-emitting generators see lesser penalties if gridwide emissions are already high due to minimal renewable generation. The figure shows that, even for a generator emitting well above the average, dynamic penalties would vary by roughly 25% (in the example of the Alberta grid) during regular operations, which would require consideration in the generator bidding strategy.

Method for Adopting Emissions Response

The application of emissions response will depend on transparency and accuracy in three data types: 1) real-time generation from contributors to the grid; 2) emissions intensities associated with real-time generation data; and 3) emissions forecasting to guide the actions of generators, storage operators, and consumers. Generation data are available from independent system operators with varying levels of granularity in time and generation sources, with many being on the scale of fuel types (coal, gas, hydro, wind, solar, etc.). From various sources, emissions intensities for different generation types can be estimated with varying levels of specificity and accuracy.

Notably, while emissions intensities can generally be applied by fuel types, there is significant variance within fuel types across different geographies and grids. Under ideal circumstances, the emissions intensities of all relevant generators would be known, and a highly accurate average could be calculated based on the contributions from all relevant generation assets. In the absence of generator-level intensities, accuracy can be achieved

by considering the ages, capacity factors, cycle types, and other relevant data for the assets comprising each fuel type. A detailed outline on estimating emissions intensity for generators, fuel types, and grid level will be outlined in an upcoming work.

In emissions response, forecasted grid emissions intensities will become an essential tool for planning operations of flexible generation and consumption. The development and deployment of forecasting models also provides valuable insights for long-term planning. The analysis necessary to produce forecasts reveals features and patterns in time series data that can be used to identify system efficiencies and drivers of large variance. In a future work, we will outline the Forecasting Grid Emissions Intensity (FORGE-I) model as well as an analysis of model development.

While similar grid programs, such as demand response, require direct intervention from grid operators to signal response events, the accessibility of real-time and forecasted data will allow actors in generation and consumption to naturally seek the most beneficial strategy for themselves, which will ultimately contribute to efficient decarbonization of the grid. Emissions and efficiency will become a natural consideration in operational strategies, and benchmarks will automatically adjust with changes in the system.

The applications of emissions response will extend beyond the real-time accessibility of data by ensuring that long-term planning and investment is as informed as possible, based on an up-to-date picture of the grid, as well as exposing variability and grid inefficiencies. Figure 2 shows a comparison between the dynamic average emissions factor for the Alberta grid, calculated at 12-h intervals, and the annual values reported in the National Inventory Report submitted to United Nations Framework Convention on Climate Change (UNFCCC). While both reports demonstrate a consistent reduction in grid emissions for the period of 2019–2021, the real-time emissions factor shows

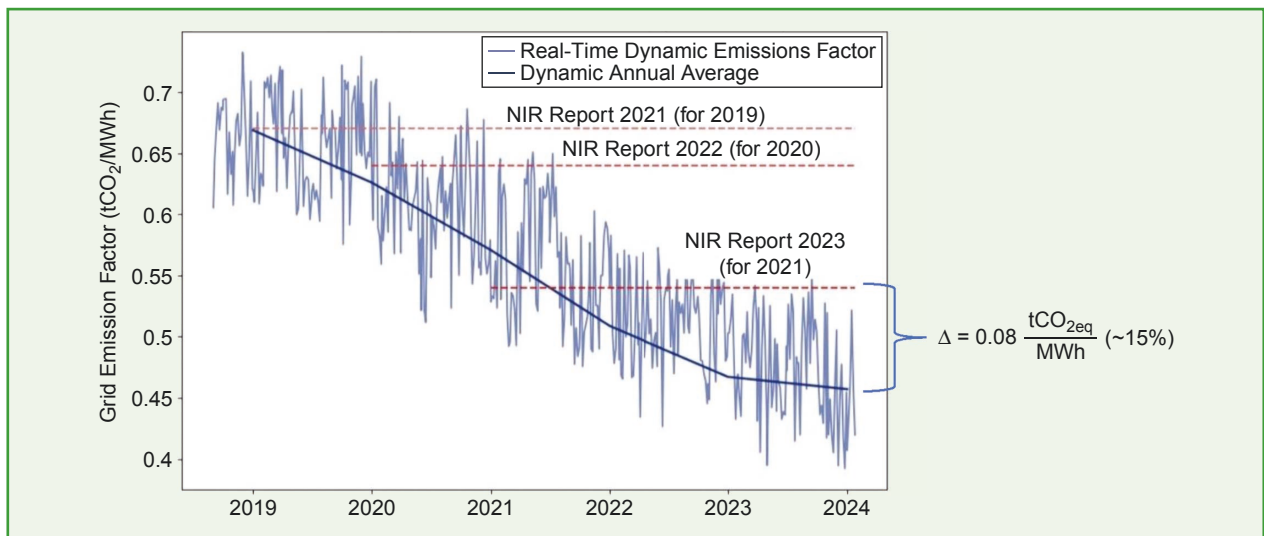


figure 2. Alberta real-time emissions factor (12-h periods) for 2019–2024 compared with the National Inventory Report (NIR) emissions factor. The real-time emissions factor allows reporting that is always up to date, and trends in the emissions factor, such as seasonal peaks and troughs, the amount of variability, and exponential decay, can assist in long-term decision making.

how these reductions have continued to the present, with a 15% reduction since the date of the last national report. Real-time factors also show regular and seasonal variation, as well as long-term trends, such as exponential decay, that can be used to guide investment into grid decarbonization measures.

Objectives and Benefits of Emissions Response

The highly sensitive nature of electricity grids, which must continuously operate within a narrow supply-and-demand balance, requires new actions to be considered not in isolation but in relation to the larger interconnected system. Taking a “gestalt” perspective, with grid emissions being seen as more than contributions from component sources, also presents the pos-

sibility of operational and systemic changes toward decarbonization with limited, targeted investment. Economic markets in the electricity sector are well designed to manage rapid temporal change within the system, with various markets meeting differing temporal needs and allowing generation sources to submit dynamic prices that reflect their capabilities in real time. As emissions regulations become more stringent in their requirements to reduce from a baseline, so too must they reflect the dynamic nature of the system and market that they oversee.

We propose emissions response as an effective strategy to improve pathways to decarbonization that focuses on targeted responses to dynamic emissions in the grid. Emissions response will center around the use of real-time emissions factors for electricity systems and provide 1) accurate, dynamic

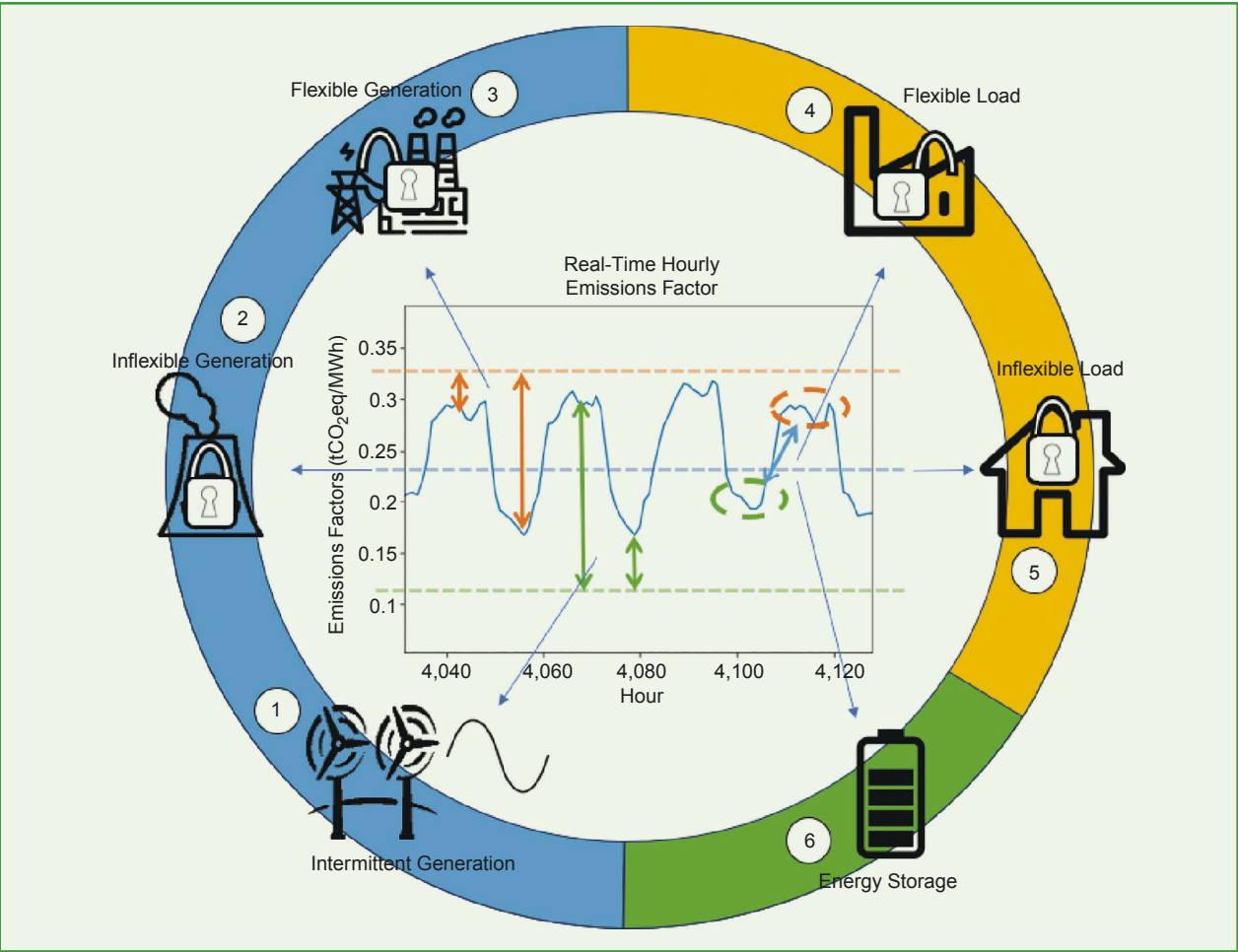


figure 3. Emissions response will incorporate real-time signals for actors in generation, consumption, and storage. ① Offsets for low-emitting generators are maximized when grid emissions are high and lower when baselines are low. This encourages adopting intermittent sources that generate at different times. ② Inflexible generators that largely contribute to the average emissions of the grid see a minimal net effect while still being encouraged to reduce to below the grid average. ③ Flexible generation sources are discouraged from generating when the grid average is far below the emissions intensity of the generator, when renewable generation is high, while emissions penalties are minimized when high-emissions generators are needed. ④ Rewards for consumers follow the grid emissions factor, encouraging demand response at the times of highest grid emissions, while ⑤ inflexible loads see benefits from gridwide emissions reductions, promoting consumer buy-in to decarbonization actions. ⑥ Storage arbitrage is rewarded for shifting consumption to low-emissions hours and offsetting high-emitting generation when discharging.

The use of real-time emissions factors will not only bring benefits to large-scale planning but also to three key stakeholder groups within the system: generators, consumers, and storage operators.

baselines for decarbonization actions; 2) the reasonable and equitable dispersion of financial rewards and responsibilities throughout the energy transition; 3) guidance on major and long-term investment that is up to date and reflective of the current operations of the grid; and 4) a response mechanism wherein demand and generation work together to maximize renewable utilization and systemwide efficiency.

The use of real-time emissions factors will not only bring benefits to large-scale planning but also to three key stakeholder groups within the system: generators, consumers, and storage operators (Figure 3). Regulations with economic incentives and penalties commonly make use of fixed baseline emissions factors where generation assets are rewarded for generation below the baseline and given financial penalties if above the baseline. For low-emissions generation, this encourages the development of assets that maximize energy production with no consideration as to the time in which energy is produced or system investments that must be made to account for intermittency. Low-emission investors will be encouraged to seek generation assets that produce when emissions are highest in the grid, which generally coincides with low generation from other renewable sources, mitigating the effects of intermittency.

High-emitting fossil fuel generators will be discouraged from operating at times of high renewable generation, when emissions are lowest, and they are least needed, while receiving lesser penalties when peaking units are required to be online. Baseload generators, with the largest influence over the grid average, will not be consistently penalized when generating at the grid average but will still be given incentive to decarbonize below the average, driving consistent reductions in the baseline. Storage assets can provide further stability to the grid and will see rewards based on charging at times of low emissions, typically with high renewable generation, and discharging at times of high emissions. This not only provides a financial incentive to storage but benefits the larger grid by spreading renewable production across time.

The use of emissions intensity as a response signal provides a proxy metric for response to efficiencies and inefficiencies in the grid. Times of high intermittent renewable generation coincide with low emissions intensity, prompting targeted utilization of renewable resources and limiting the effects of intermittency. Further to assisting in the efficient use of intermittent assets, signals of high emissions intensity will avoid consumption from higher emitting, low-efficiency generation sources. More than demand

response alone, which seeks to reduce consumption during times of peak demand, emissions response will more generally target inefficiencies in the grid and promote a smoother transition to low-emissions technologies.

While it has been theorized that demand response (peak avoidance) comes with environmental benefits, any benefit depends on a consistent correlation between demand and emissions. This correlation may be present when low-efficiency peaking plants are used during peak demand hours but may not exist in areas where low-emissions sources, such as hydro or storage resources, are used during peak times. The use of emissions intensity as a signal removes the assumption of emissions being correlated with demand or price. Data-driven emissions reduction policies using the most current and precise electricity emissions intensities will ensure stakeholder trust, guidance toward effective action, and accurate financial penalties and rewards for regulated entities.

For Further Reading

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