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Using marginal emission rates to optimize investment in carbon dioxide displacement technologies

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A B S T R A C T

Reduction in CO_2 emissions from fossil fuel-based electric power generation is a primary focus of both the public and private sector. Over 1,500 corporations, representing $11.4 trillion in revenue and 6.5 gigatonnes of carbon emissions, have formally announced their objective of meeting net-zero emissions by 2030. In this paper, we focus specifically on CO_2 emissions from electricity consumption, and how corporations can reach net-zero goals with respect to these emissions. We focus on three points: (1) the mathematically and economically correct methodology (Marginal Emission Rate, or MER) for calculation of CO_2 footprint in the power sector, (2) a detailed comparative analysis and critique of the generally-referenced alternative methodologies, (3) a detailed analysis of the economic benefits of using MER versus other methodologies to private sector corporations focused on net-zero emissions. This paper presents a mathematical framework for organizations to account for and plan their carbon footprint accurately and efficiently whether it is ex post carbon accounting using RTO published real time nodal MER data, or planning for renewable investment using forecasted MER under various future scenarios.

1. Background and introduction

In recent years, an increasing number of private organizations are taking action to reduce their carbon emissions. As of the end of 2020, more than 1,500 businesses had pledged to meet a net-zero emission target (Data Driven EnviroLab, 2020). In their pursuit of net-zero status, these organizations are leading a new wave of private sector investments to procure zero-emission renewable energy to offset carbon emissions attributable to their energy use. The goal of this paper is to present a methodology for accounting for power sector carbon emissions that is both accurate in terms of actual emissions and that can be the basis for a private market in emissions – the Marginal Emission Rate (MER). Although the marginal emission rate is generally accepted as a more accurate metric for electricity sector carbon emissions, the data were rarely available due to computational complexity (Google, 2021). Many data vendors have sought to derive MER data from a system's fuel mix, electricity prices and machine learning algorithms (Electricity Marginal Factor Estimator; WattTime), but these products lack the transparency and granularity that is crucial for arriving at an accurate and verifiable carbon footprint. However, with the advancement in computation technology and a renewed focus on climate change, marginal emission rates can now be calculated ex post and forecasted under a range of scenarios using detailed fundamental models for many North American markets. Additionally, nodal marginal emission rate data based on actual generation dispatch can now be obtained directly from PJM, the first RTO to provide such data. The paper provides a discussion of the physical accounting accuracy of MER compared to using average emission rate (AER), as well as a comparison of MER carbon accounting with the methodologies that are commonly used by today's large corporations. These alternative methodologies do not correctly account for the emissions attributable to electricity consumption or those displaced by investment in renewable technologies. The paper provides an initial mapping and logic for private investment in renewable energy focused directly on and denominated in reduction of power system carbon emissions.

At the end of 2020, wind and solar projects accounted for 88.9% of the generation capacity in the interconnection queues of U.S. ISOs/RTOs and major utilities, compared with 9.8% for natural gas (Rand et al., 2021). The fact that proposed renewable capacity is 9 times more than that of fossil fuel additions is a clear indication of growing commercial interest in renewable energy. Although a tremendous amount of capital is pouring into renewable energy development with a declared primary objective of reducing carbon emissions, most investors are not using an accurate and standardized metric to evaluate the performance of their renewable energy portfolio with respect to that objective. Many organizations focus on the amount (MWh) of renewable energy procured as a guiding metric for their renewable investment. They invest in renewable assets so that their total amount of procured renewable energy matches

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their total electricity load on an annual or hourly basis ("energy matching"). This type of investment strategy does not guarantee reaching net-zero carbon emissions, and it provides an inaccurate signal for the location of renewable investments, thus leading to less efficient economic decisions for carbon displacement.[1,2]

If an organization's goal is to reduce the carbon emissions associated with its electricity consumption, then its renewable investment should be evaluated by its impact on the reduction of carbon emissions in the electric power sector. In an interconnected power system dispatched on a least-cost basis (which describes most of the power systems in the United States and in the world), wind and solar generation, which have zero variable operating costs, will be dispatched before fossil fuel generators. Thus, adding solar or wind capacity to a node in a power system will generally lower systemwide carbon emissions by displacing marginal fossil fuel generation. The amount of carbon displaced is what would otherwise be emitted by marginal fossil fuel generators and can be measured in tonne-CO_2/MWh as the geographic consumption node's marginal emission rate (MER). Using MER can help organizations optimize their carbon displacement efficiency, which can be measured as the amount of carbon displaced for each dollar spent on renewable energy ($/tonne-$CO_2$ displaced).

2. Marginal emission rate and carbon footprint

In an interconnected power market, an incremental injection (generation) or withdrawal (load) of electricity at a given node will result in a systemwide change in the economic dispatch and in carbon emissions. The marginal emission rate (MER) measures the change in systemwide emissions in response to a marginal increase or decrease in demand at a given location, as shown in the equation below (Ruiz and Rudkevich, 2010; Rudkevich and Ruiz, 2012). The magnitude of this change will depend on time and location. MER is expressed in units of CO_2 per unit of electrical energy. If 1 MWh of increased demand at one node results in systemwide emissions rising by 1 tonne, then the MER at that node is 1 tonne-CO_2/MWh.

$$\text{MER}_{\text{node A}} = \frac{\Delta\text{Systemwide Carbon Emissions}}{\Delta\text{Demand}_{\text{node A}}}$$

Marginal emission rate provides a mathematically sound and transparent way to quantify the carbon footprint of electricity consumption and production. Mathematically, the MER calculation is similar to the calculation of Locational Marginal Prices (LMP) and system lambda, which are used for economic dispatch of power systems across North America. It can be calculated by the same economic dispatch algorithms that system operators use to dispatch power systems. Like LMP and system lambda, MER can be calculated for each node in an interconnected power grid. For example, PJM has already begun publishing five-minute nodal marginal emission rate for all nodes and pricing hubs within the PJM footprint.

Marginal emission rate is a function of two variables:

- **Time.** The marginal emission rate depends on the time of energy consumption. Net demand (load minus renewable generation) changes from hour to hour, requiring system operators to dispatch different generators and often different types of generators to meet load. These generators can produce significantly different MER throughout the day. For example, in southern California, incremental load during mid-day is often met with PV generation, while incremental load in the evening is met with combustion turbine generation, as the system ramps up high-emitting peaker units to replace declining solar generation.
- **Location.** Between power markets, difference in generation mix causes large differences in MER. Within a single market, transmission constraints and losses can cause marginal emissions in one area to be higher than another. In New York, for example, transmission constraints often prevent New York City from accessing renewable energy from sources located upstate. These constraints force the grid to dispatch high-emitting fuel oil generators located in the city to meet marginal load, making this marginal load much more carbon intense in the city than upstate. Similarly, local transmission constraints could result in materially different MER values for two locations within the same area in close geographic proximity.

The carbon footprint of electricity consumption at a specific location (e.g., node or area) at a particular time is calculated as quantity of electricity consumed multiplied by the MER at that location:

$$\text{Carbon Footprint}_{\text{consumption}} = \text{MER}_{\text{Location}} \times \text{Consumption}$$

The carbon footprint of generation at a specific node at a particular time is calculated as the amount of generation multiplied by the difference between the generator's emission rate and the MER at that node:

$$\text{Carbon Footprint}_{\text{Generation}} = (\text{Emission Rate of Generator} - \text{MER}_{\text{Gen.Node}}) \times \text{Generation}$$

For renewable resources, the emission rate is 0, so the equation becomes:

$$\text{Carbon Footprint}_{\text{Generation}} = -\text{MER}_{\text{Gen.Node}} \times \text{Generation}$$

The important observation from the above is that an organization achieves net-zero status with respect to its power sector emissions when the carbon footprint of its consumption is offset by the negative carbon footprint – the displacement – of the renewable resources it procures. In contrast, matching megawatt-hours of consumption with megawatt-hours of procured generation, whether in total or instantaneously, provides no guarantee of carbon neutrality and, as we demonstrate below, is a highly inefficient and ineffective investment strategy for such an organization to adopt in its pursuit of net-zero carbon emissions.

3. Marginal emission rate vs. average emission rate

The amount of carbon displaced by renewable energy is directly related to the emission rate of the marginal generators, measured as the MER at the renewable's interconnection node. The average grid emission rate (AER), which is often calculated as total system emissions divided by total generation, does not accurately reflect what is happening at the margin.[3] By its mathematical definition, AER does not measure how incremental renewable energy affects the total carbon emissions of the system, making it difficult or impossible to accurately quantify the true carbon reduction impact of renewable generation.

Fig. 1 below shows load, MER, and AER of the Southern Company balancing area on a peak summer day. During the day, load slowly ramps up to its peak around early afternoon and decreases in the evening as the temperature falls. To meet this load, the system dispatches a fleet of Natural Gas Combined Cycle (NGCC), coal, and gas-fired peaking units based on their cost. The day starts with low load met by NGCC generators, the most economical of the fleet, on the margin. As load starts to increase around 7am, the system starts to ramp up coal generators, which cost slightly more than NGCC units and have high emission rates. Around noon, the system dispatches gas peaking generators to meet peak demand. Gas peakers are dispatched last because they have the highest operating cost, but they have a lower carbon emission

[1] In this paper, we define "net-zero carbon emissions" as when an organization's carbon emissions from electricity consumption are less than or equal to the carbon emissions displaced by their procured renewable energy.

[2] Because energy matching strategies often require renewable energy to match load in the same RTO/ISO

[3] One example of AER is the data in EPA's eGrid database.

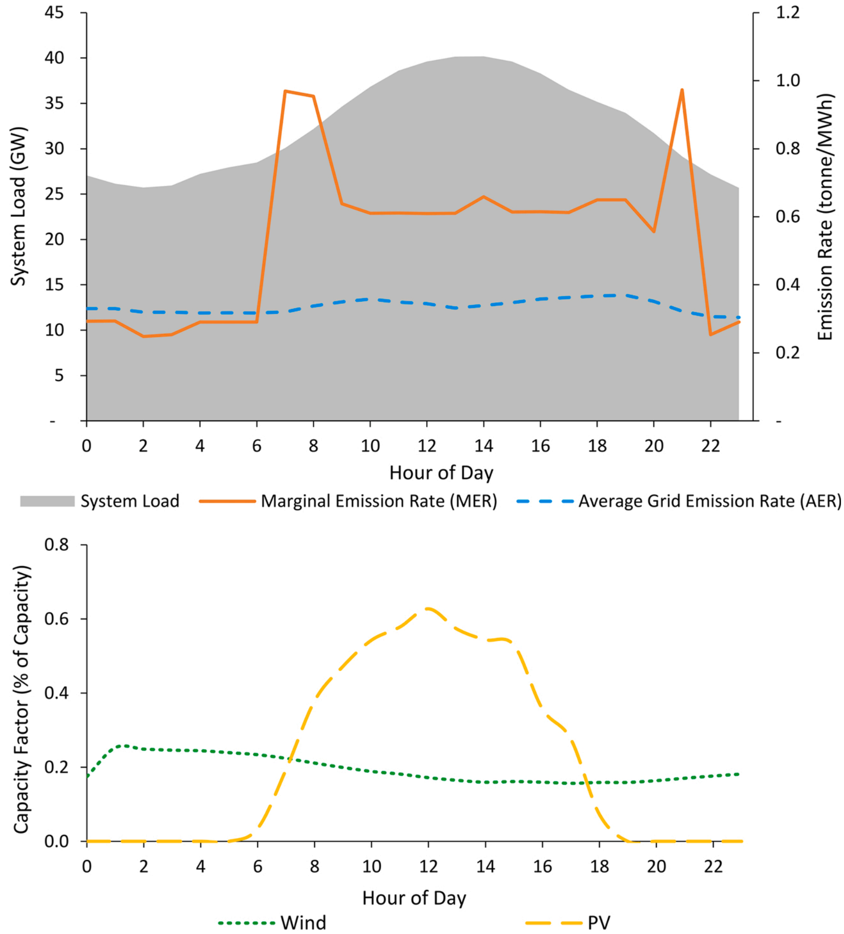

Fig. 1. (a) MER and AER, as well as load, in the Southern Company balancing area on a peak summer day; (b) Solar and wind capacity factors for the same day.

rate than coal.

The MER (orange) line in Fig. 1 follows this dispatch pattern. The system MER value starts at about 0.35 tonne/MWh. It then rises in the morning to 1.0 tonne/MWh, the level of a typical coal plant emission rate that becomes marginal with morning pickup. MER then transitions to 0.6 tonne/MWh (a simple cycle natural gas fired peaking unit) during the day, returning to coal on the margin as demand decreases in the evening.

The AER line, on the other hand, appears almost flat, with only a very slight increase during the middle of the day. The average emission rate is mostly influenced by the emission rate of baseload generation, but this generation is not affected by what is occurring on the margin, meaning that it is not relevant to the emissions impact of incremental load or renewable generation.

Using AER to evaluate renewable generation overlooks the true impact of renewable energy in displacing carbon emissions. Because the impact is at the margin, using the average rate leads to inefficient decision making. Table 1 below shows the estimated carbon displacement of 1 MW of wind and solar PV using AER vs. MER. It is calculated by multiplying a typical wind and solar PV generation shape, shown in Fig. 1b, by the emission data shown in Fig. 1a.

Table 1
Estimated carbon displacement per unit capacity using AER and MER for the peak summer day in Fig. 1.

	AER-Based Carbon Displacement (tonne/MW)	MER-Based Carbon Displacement (tonne/MW)
Solar PV	1.70	3.40
Wind	1.66	2.44

Despite having similar energy output, a solar PV generator displaces almost 50% more marginal carbon emissions per unit capacity than wind on this day. The PV generator achieves this because all of its energy is generated during the daylight hours, allowing it to displace more high-emitting coal and peaker generation at the margin than the wind. This marginal impact difference is lost in the AER calculation. Using AER, one would conclude that the wind and PV units displace similar amounts of carbon. This example highlights the importance of understanding what is happening at the margin of the power system. If identifying investments that have maximum carbon displacement is the objective, understanding and making decisions based on MER provides the best demonstrable results as discussed in the next section.

4. Carbon displacement accounting with MER

Marginal emission rate provides a more accurate and defensible way to evaluate carbon displacement from renewable investments. MER is mathematically similar to the calculation of the utility's system lambda and LMP calculations. As a result, MER can be calculated in real time by the same economic dispatch algorithms that ISO/RTOs and utility companies use to operate power systems and calculate the market prices (for example, PJM now publishes real time nodal MER data). With the appropriate tools and expertise, MER can also be forecasted years into the future with hourly and nodal granularity using a slight modification of the standard production cost modeling methodologies (He et al., 2020). Detailed MER forecasting can provide critical information that help guide carbon-aware organizations to maximize carbon reduction from their renewable portfolio and provide the most impact toward a

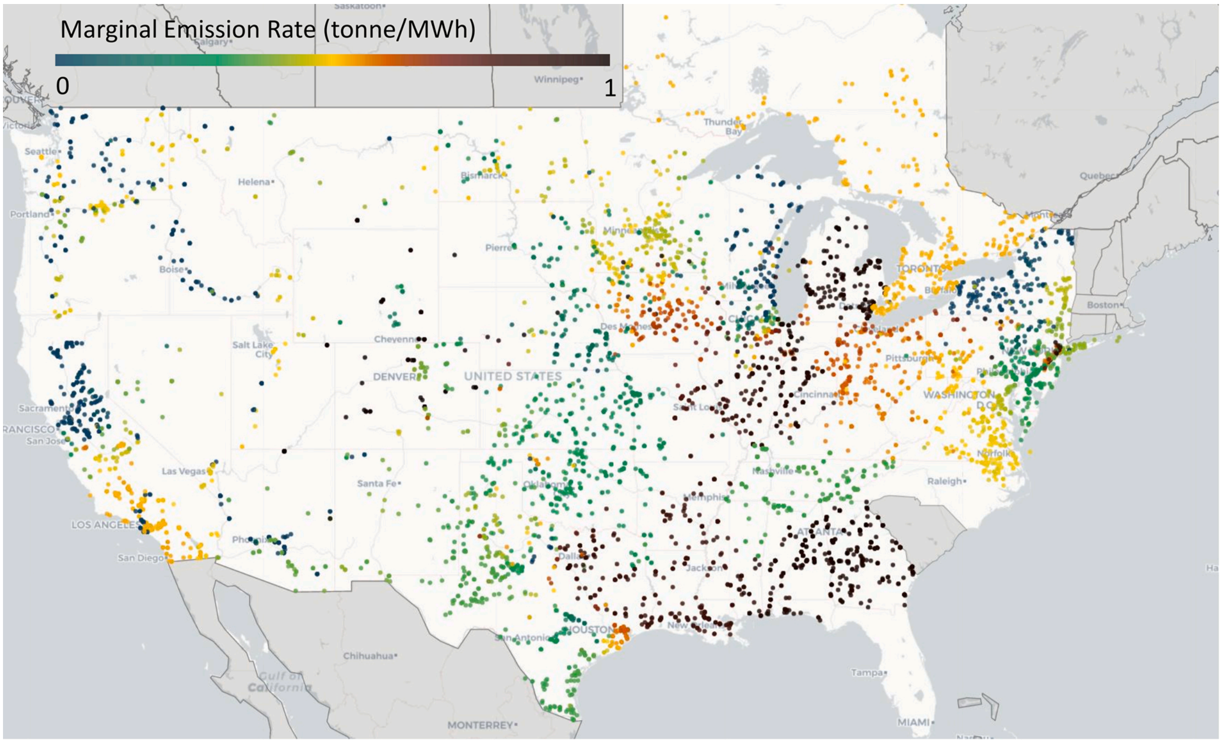

Fig. 2. Simulated nodal MER for a late afternoon hour in the winter of 2025.

decarbonized future.

MER data, when provided with hourly granularity over a multi-year forecasting period, can provide critical information that helps maximize carbon displacement by guiding organizations to:

1 Site renewable assets at locations with high MERs based on comprehensive analyses of hourly and nodal MER values.
2 Invest in new electricity-consuming assets in markets with the best long-term carbon displacement potential based on forecasts of the long-term trajectory of MER.
3 Choose technologies that generate clean energy during hours of high MER to maximize carbon displacement.

Renewable investments meeting these three targets can provide the maximum carbon displacement efficiency, measured in $/tonne- CO_2 displaced.

4.1. Conclusion 1: site renewable assets at locations with high MER

Some businesses pursue an energy matching strategy, attempting to offset the carbon emissions attributable to their electricity demand by procuring renewable energy equal to their consumption, often in the same balancing area where their load is sited. Because energy does not directly reflect carbon displacement, the hope with this strategy is that producing renewable energy and consuming electricity in the same market can help them get closer to net-zero carbon emissions. Economically speaking, entities pursuing carbon reduction need two products – energy and carbon displacement. They often buy these bundled in the form of locally-produced renewable energy, but they do not have to do that. Instead, they can continue buying energy locally and invest in renewable generation at locations where carbon displacement per dollar invested is the highest. Since climate change is a global phenomenon, the location of carbon displacement does not matter. By pursuing this strategy, the entity seeking to achieve net-zero carbon emissions would be able to do so at significantly lower costs. In contrast, energy matching does not guarantee net-zero status, because transmission constraints cause MER to vary even within a single balancing area. Energy matching is also inefficient, because it significantly limits the geography of investment into renewable projects. Hourly and nodal MER data can help organizations site investment in the most efficient location for carbon displacement.

As an illustration of the spatial distribution of MER, Fig. 2 below shows simulated MER for a single winter hour in 2025 for nine North American power markets, taken from a TCR study which simulated hourly nodal MER for all generator nodes in the nine markets for the period 2021–2035. As discussed previously, nodal MER differs significantly within markets and between markets, reflecting transmission constraints and the diverse economic and regulatory structure of each market. This figure shows that the highest-emitting nodes in this hour are located in New York City, western PJM, MISO south, and the Southern Company balancing area. Renewable generation injected into these locations in this hour would displace more than double the amount of carbon than in locations such as CAISO and upstate New York.

4.2. Conclusion 2: invest in markets with the best long-term carbon displacement potential

Renewable investments are typically structured as PPAs that last more than 10 years. Throughout the duration of a PPA, economic and regulatory structures can change and impact the carbon displacement performance of renewable investment. To maximize lifetime carbon displacement of a renewable asset, it is important to review a robust set of MER forecasts so that the asset can be sited in a location that can provide consistently high carbon displacement.

Fig. 3 shows forecasted MER at representative locations in PJM and SPP over the next 15 years. Currently both PJM and SPP have relatively high MER compared to other markets across North America because both markets have a large amount of coal and natural gas generation. However, in PJM MER is forecasted to decline steadily over the next 15 years due to state-level Renewable Portfolio Standard mandates, coal phase-out mandates, utility IRP commitments, and market mechanisms such as the Regional Greenhouse Gas Initiative (RGGI). On the other

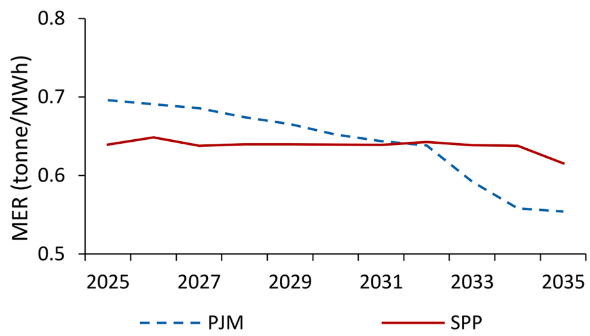

Fig. 3. Forecasted 2025 to 2035 PJM and SPP MER at select nodes.

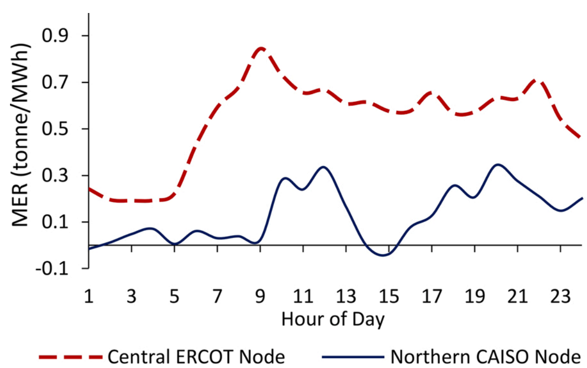

Fig. 4. 24-h Average MER profile for May 2025 at select nodes in central ERCOT and northern CAISO.

hand, in SPP MER is expected to stay relatively level because the utilities and states in SPP have much weaker policy incentives and mandates than those in PJM. These multi-year and multi-decade dynamics play an important role in a renewable asset's lifetime carbon displacement.

4.3. Conclusion 3: choose technologies that generate clean energy during hours of high MER to maximize carbon displacement

MER at each node varies as the system operator re-dispatches generation to balance supply and demand. The hourly MER profile can differ significantly from location to location depending on the market structure and generation mix. To maximize carbon displacement of a renewable investment, choosing a generation technology that can maximize carbon displacement by generating clean energy during hours of high MER becomes a key criterion.

For example, Fig. 4 shows the forecasted 24-hour average MER profile in May 2025 for a representative node in northern CAISO and central ERCOT. Because the two markets have drastically different generation mixes, the profiles look very different. High penetration of PV in CAISO produces an MER "duck curve" similar to that of LMP. In ERCOT, on the other hand, midday MER is high because expensive and high-emitting fossil fuel generators are dispatched to meet high demand. Based on this data, PV would not be an ideal technology for displacing carbon in CAISO, but it would be an ideal investment in ERCOT.

As generation mix changes as a result of economic and regulatory development, the MER profile can also change. It is important that the generation technology chosen for an investment can be resilient enough to changes in MER to provide consistent carbon displacement throughout the PPA contract period.

5. Case study: the value of MER

To illustrate the impact of MER-guided investment, we used a case study to analyze three different strategies for renewable energy investment and carbon displacement: annual energy matching, hourly energy matching and annual carbon matching.

- ***Annual energy matching*** means generating renewable energy equal to or greater than electricity consumption in the same power market in each year.
- ***Hourly energy matching*** means generating renewable energy equal to or greater than consumption in the same power market in every hour of the year. This is similar to Google's commitment for 2030 (24/7 by 2030: Realizing a Carbon-Free Future, 2021).
- ***MER-based carbon matching*** means displacing an amount of carbon emissions equal to or greater than the emissions generated by electricity consumption, converting consumption and generation into carbon emissions and displacement using marginal emission rates.

This analysis used hourly nodal MER data from TCR's dataset of forecasted MER for major power markets in North America out to 2035 and PPA cost data from a 2021 Q1 renewable PPA price index (Level10 Energy, 2021). This analysis focuses on the year 2025 because it is a target year for many organizations' decarbonization goals.

For each strategy, we calculated the required capacity, generation, and cost to implement the strategy and the resulting net carbon footprint. We evaluated the effectiveness of these strategies in four power markets: NYISO, PJM, MISO, and CAISO.[4]

Fig. 5 summarizes the results of this analysis, illustrating the financial and carbon displacement performance of each strategy in each market. Fig. 5(a) shows the cost to achieve each strategy in each power market. Fig. 5(b) shows total carbon displaced as a percentage of load emission (100 % means net-zero). Fig. 5(c) shows unit cost to displace one tonne of carbon under each strategy.

As illustrated, the MER-based carbon matching strategy achieved 100% carbon displacement at a fraction of the cost of either energy matching strategy. This is because the MER-based carbon matching strategy directly targets carbon to ensure 100% displacement, and it allows investors to site renewable generators at locations with the highest carbon displacement potential. In contrast, annual energy matching fails to displace 100% of the load emission, and hourly energy matching is prohibitively expensive.

Annual energy matching consistently fails to displace 100% of load emission in each market. This is because this strategy does not address carbon directly, so its performance is highly dependent on the generation mix of individual markets. The annual energy matching strategy performance ranges from 100% carbon displacement in PJM to only 54% carbon displacement in NYISO.

Hourly energy matching is extremely expensive because it requires procuring enough renewable generation to match load hourly, even when weather conditions reduce renewable output systemwide. This requires significant over-buying of renewable capacity, as well as a battery storage system.[5] As a result, this strategy displaces much more carbon than necessary to reach net-zero, but at much higher total cost. Although the cost per tonne carbon displaced is just slightly higher than annual energy matching (Fig. 5b) because all excess energy procurement counts towards carbon displacement, total cost for hourly energy matching is astronomical (Fig. 5c). For each MWh of load that must be matched, hourly energy matching costs 5 times more than annual energy matching and 20 times more than MER-based carbon matching.

Notice that both annual and hourly energy matching perform poorly in terms of carbon displacement in CAISO and NYISO, both of which

[4] In each of these markets, electricity consumption was modeled as a commercial load located in a representative urban area in that market. The representative urban areas were, PJM: Sterling, VA; MISO: Des Moines, IA; CAISO: San Jose, CA; NYISO: New York, NY.

[5] The battery storage system was used to move excess renewable energy to hours where it was needed to match load.

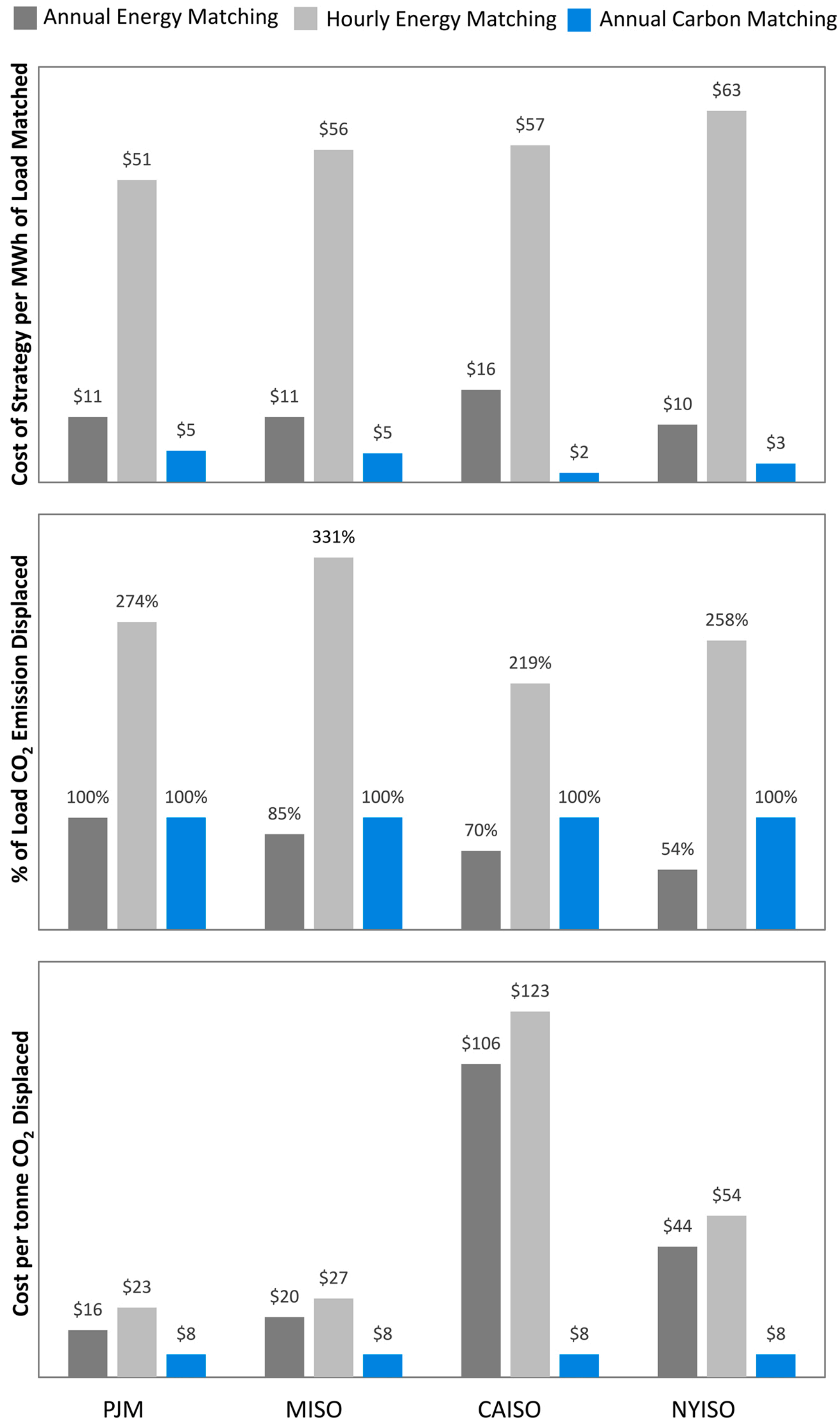

Fig. 5. Comparison of the three matching strategies across four power markets. (a) Top figure shows the cost of each strategy per MWh of load. (b) Middle figure shows % carbon displacement achieved, where 100% is full displacement. (c) Bottom figure shows the cost per tonne of CO_2 displaced.

have high renewable penetration and ambitious decarbonization targets. Because these markets already have substantial amounts of clean energy, additional renewable investment has lower carbon displacement than other markets. In CAISO, for example, there is enough solar penetration to significantly lower MER in the middle of the day. This means any additional solar energy in CAISO will displace little or no carbon at all. The same investment could contribute to much greater carbon reduction in markets with higher fossil fuel generation such as PJM or SPP.

MER-based carbon matching, on the other hand, ensures 100% carbon displacement, and does so more cost-effectively than the energy matching strategies, providing cost savings of up to 60% in PJM and MISO, and savings of up to 90% in CAISO and NYISO in terms of cost per tonne CO_2 displaced (Fig. 5c). While the cost of the energy matching strategies varies across markets, the cost of the carbon matching strategy is the same in every market, because the carbon matching strategy sites renewable investments where they displace the most carbon, unconstrained by power market boundaries. MER-based carbon matching allows investors to make the most impact on carbon emissions with their renewable investments.

This case study illustrates two critical considerations for an efficient carbon reduction strategy:

- Energy is not directly related to carbon. Neither annual nor instantaneous matching of energy guarantees net-zero carbon. If an organization's goal is to reduce carbon, it should target carbon emissions directly through MER.
- Carbon is a global phenomenal. CO_2 emitted in California has the same impact on the climate as CO_2 emitted in Kentucky. However, the cost to displace a tonne of power sector CO_2 emissions is much higher in California because CAISO has much lower marginal emission rates. To maximize impact, renewable projects should be sited where they displace the most carbon.

6. Summary and conclusion

Accelerating emission reductions requires looking at the power system as a whole and asking how much CO_2 will be displaced by the addition of new clean energy. The displaced emissions will be those of the generating units whose output is reduced by the addition of new clean resources. What is important is the net change in overall system emissions. The net change in system-wide emissions depends on the marginal generating units and will be different depending on where clean electricity is added and the hours in which it is generated. What we have demonstrated in this paper is that the net reduction in carbon emissions can vary by several hundred percent from one location to another within a given electric power region and from one hour to another within the same day. Optimizing clean energy investments can often more than double their impact on reducing carbon emissions.

In a given hour the marginal generator in some regions might be a high emitting, coal-fired generator, or, in others, a gas-fired unit with an emission rate less than half that of coal, but still not zero. Alternatively, adding solar in a system that already has a surplus of solar power in certain hours may curtail the output of other renewable resources with no net impact of carbon emissions during hours of peak solar output.

PJM has demonstrated that system operators can calculate and publish real-time marginal emission rates for each node on the system to help stakeholders track their carbon footprint. And, with sufficient knowledge of the power system and appropriate models, time- and location-specific marginal emission rates can be reasonably forecast years into the future under different scenarios to help investors optimize the carbon impact of their investment.

By comparison, just keeping track of power purchased from renewable resources and assuming these purchases reduce emissions at the average system emissions rate or trying to match energy consumption and renewable generation on an hourly basis is economically inefficient and may not lead to fully offsetting the carbon emitted as a result of an organization's electricity consumption.

If the goal of energy purchasers or public policy is to reduce emissions, the most effective strategy is to purchase and use electricity in locations and at times when marginal emission rates are low and to invest in new renewable or clean generation that will deliver power into the power grid in locations where and at times when marginal emission rates are high.

For private corporations seeking to achieve net zero carbon, using marginal emission rates will bring benefits in terms of auditability, consistency and economics. Evaluating corporate responsibility based on the marginal emission impacts of energy use and clean energy purchases will help satisfy green shareholders and customers as well as competitors who might challenge the carbon emissions accounting. Consistency is provided by an approved methodology for calculating marginal emission rates that is theoretically correct, measurable, reproducible, and could grow to become an international standard. From a corporate perspective, the economics are critical. Identifying opportunities for investment in renewables would be driven by a probabilistically forecastable value for the carbon reducing investment. The result is that the corporate entity can find those investments that provide the greatest carbon displacement value per dollar of investment.

For government entities seeking to achieve emission reductions and eventual carbon neutrality, the marginal emission rate calculation provides auditable information on the value of current and alternative future investments in clean electric technologies expressed in a reduction in tons of electric system carbon emissions. The calculation of net emission reductions provides one step in understanding how investments can provide societal benefits.

The calculation and publication of marginal emission rates associated with the real-time operation and dispatch of power systems would be a first step toward the development of an effective Federal Energy Efficiency and Clean Electricity Standard. It would enable government authorities to track the actual emission impacts of efficiency and clean electricity investments made in compliance with the standard. If a federal agency awarding or purchasing clean energy credits decided to incentivize investments by basing credits on approved forecasts for expected reductions in emissions, the calculation of real-time marginal emission rates could enable the implementation of the standard to remain on track to meet long-term emission targets.

Declaration of Competing Interest

The authors report no declarations of interest.

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