Total Carbon Accounting:

A Framework to Deliver Locational Carbon Intensity Data

White Paper

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About the Co-Authors

Kevala is a data and analytics company that provides services to utilities, Independent System Operators (ISOs), regulators, Independent Power Producers (IPPs), and third party aggregators, as well as the mobility and financial sectors.

National Grid operates as a bulk power system grid operator in the United Kingdom (UK) and a distribution utility and retail utility in the Northeastern United States (US), including New York, Massachusetts, and Rhode Island.

Exelon is an independent power producer, retail supplier, and a distribution utility holding company in the US, operating in five states and the District of Columbia.

ComEd is a distribution utility, and a subsidiary of Exelon, serving more than 4 million customers across Northern Illinois.

Executive Summary

Climate change is the greatest existential threat of our time. The purpose of this white paper is to provide a framework to measure locational carbon intensity which will be important in determining where to best prioritize our climate change mitigation efforts. The co-authors are currently testing these framework methods and invite others to join in this collaboration to ensure that the best possible approaches are used to evaluate, prioritize and measure decarbonization activities.

Globally, the decarbonization of the electricity sector is a fundamental requirement to combating climate change. Much progress has been made on the deployment of sustainable, renewable energy technologies in recent decades, to the extent that solar and wind are the fastest growing and most economical forms of new electricity generation in many countries. Also increasing are residential and behind-the-meter deployments, with and without battery storage. This trend has been accompanied by an increasing focus on the electrification of "everything," meaning moving buildings, heating, and transportation from fossil fuels to clean, decarbonized electricity. The race to net zero, or ensuring the balance between the amount of greenhouse gas (GHG) emissions produced and removed from the atmosphere, has gained speed, and such goals are now prominent in policy and legislation in most of the world's leading economies. There is an urgent need to pick up the pace on our efforts to decarbonize, moving toward the elimination of GHG emissions. If our goal is to remove carbon from the electricity system, we require a more informed assessment of the locational carbon intensity of the grid.

Total Carbon Accounting (TCA) identifies where the consumed power is generated for any location on the grid. For any given point in time, TCA provides a basis for quantifying the carbon intensity of all energy consumption. TCA **focuses on the physical flows of electricity and supports improved reporting** of **carbon emissions**, and in so doing, also **enables better planning and operations** of infrastructure, rates design, and programs. This goal is achieved by **quantifying the carbon associated with all generation sources**, including those embedded in the distribution system, customer premises, as well as the **delivery paths taken by the power from these generators to supply load**.

Current efforts to measure the carbon intensity of electricity to inform decision making use averages across long time horizons and/or large market areas. These existing approaches have enabled voluntary emissions reporting and investment decisions related to decarbonization. While these efforts have moved the industry forward, an approach that neglects to consider the actual power flows on the grid and how they change over time is not sufficient for decarbonizing the global economy. It is now essential that new, transparent, accurate, and well-understood metrics for the locational carbon intensity of the grid are defined as a matter of priority. These issues are being considered by governments, regulators, large corporations and industry. The need for improvement in this area is becoming increasingly urgent.

In this paper we posit that the solution lies in the ability to compute the carbon intensity of the electricity supplied by the grid with a high degree of geographic and temporal granularity. This solution is achieved by leveraging information about the topography of the grid and the magnitude and direction of flows in light of the variability of both supply and demand. Using an illustrative example, we lay out the framework for calculating these values in a transparent and scientifically defensible way and call this method “Total Carbon Accounting” (TCA).

TCA represents a new approach to solving an increasingly important problem. The co-authors, including leading energy companies operating in the US and UK, and a data and analytics company, are currently testing these methods in the field across multiple geographies and invite others to join in this collaboration to ensure that the best possible approaches are used to evaluate, prioritize, and measure decarbonization activities.

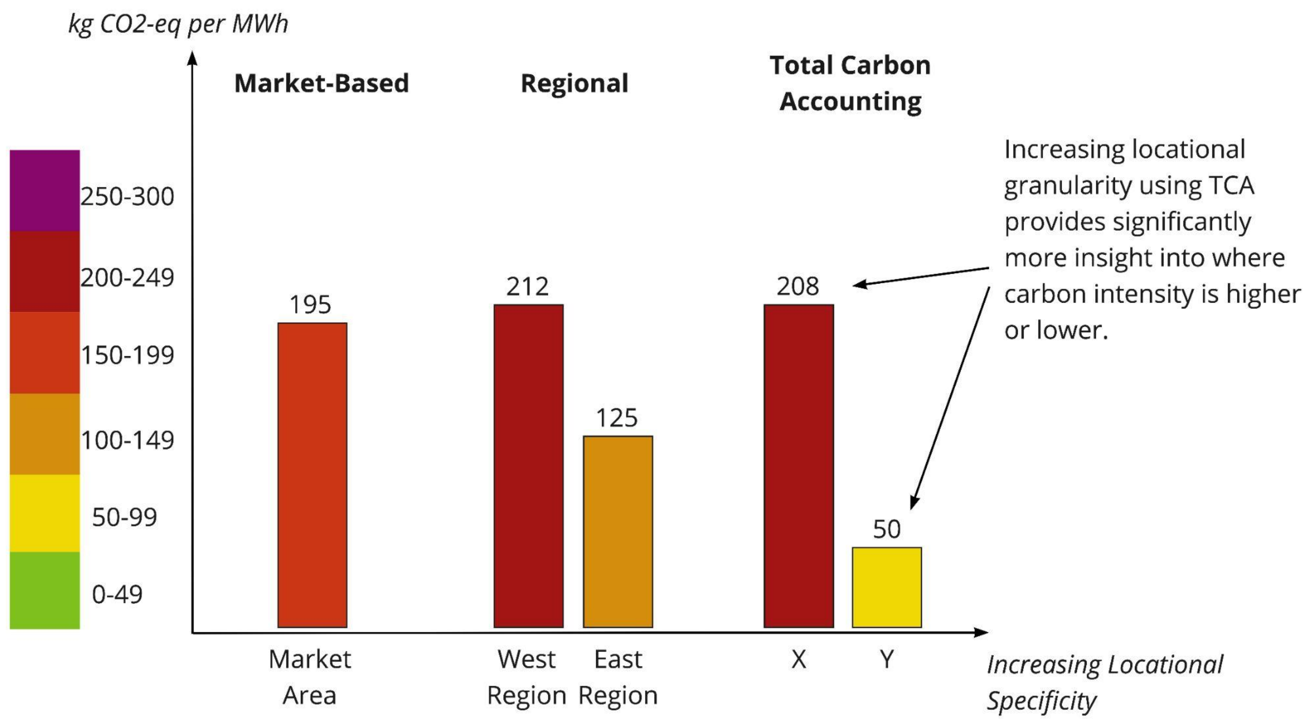
By focusing on discrete analysis of all components in the balance of supply and demand on the grid, **TCA serves as a long-term foundation** for evolving carbon awareness efforts. TCA **provides distinct advantages over current methods** that average carbon intensity over large geographic areas, or focus on the emissions of marginal units. These outdated practices can lead to unintended changes in the formulation of carbon intensity in energy markets. TCA **supports climate action policies, program and rate designs, and procurement strategies for policymakers, utilities, and energy consumers**, and can underpin carbon reporting efforts.

TCA, delivered through specific locational and temporal carbon intensity calculations, provides a much more accurate basis for examining the carbon associated with electricity consumption at a location. The averaging methods currently used can introduce significant error, which we discuss in detail.

Additionally, TCA will support a more accurate matching of renewable energy to demand for large loads and corporations. Recent developments in locational marginal emissions (LMEs) will also be enhanced by the TCA framework, providing a basis for considering the actual electricity consumed at a location rather than the marginal generator meeting the market-wide marginal need.

In this white paper, we consider an illustrative example of a market area, with three generators and two load locations (X and Y) of interest from a carbon intensity perspective. As illustrated in Figure 1, relying on averages at the market area or regional level, result in significantly different carbon intensity estimates for a given location. Through a more granular approach, TCA leads to improved insight into where carbon intensity is higher or lower within a particular market or region.

Figure 1: Illustration of different carbon calculation approaches and benefit of TCA



Having a clear understanding of the carbon content of the electricity at any location and time is a key component of enabling and facilitating decarbonization. The TCA framework presented in this white paper is a step forward for industry in the pursuit of a common framework for greater clarity on the carbon emissions associated with delivered power.

Introduction

Determining how to appropriately analyze carbon to prioritize emissions reduction activities is a crucial part of the fight against climate change. To do this effectively, there needs to be a renewed focus on the locational and temporal aspects of the electricity provided to and supplied by the grid. There has been progress in improving the temporal granularity of regional carbon intensity (which is the change in the carbon intensity of the generation mix supplying power to the grid over the course of a day or some other time period) and marginal carbon intensity (which is the carbon intensity of an additional incremental unit of demand in a particular area, based on the market dispatch of a specific generator to provide the incremental unit of demand). These developments are welcome and useful to many industry participants. However, they do not provide for the full picture at the local level or meet the needs of the entire electricity sector.

There is a need for a third critical carbon intensity parameter to represent any period in time: locational carbon intensity. Locational carbon intensity can be thought of as the fuel mix for the power flow at each node on the power system, tracing flows from all generation sources to capture the carbon content of the electricity supply at any and all locations. The addition of locational carbon intensity to existing carbon analytics is the only means of capturing the full picture when it comes to determining the carbon intensity of the electricity system and to provide for effective decision making around supply and demand. We call this approach "Total Carbon Accounting" (TCA). TCA is a prerequisite for any government, organization, community, institution, business, or homeowner seeking to truly, accurately, and effectively decarbonize their electricity supply.

The electric grid is an enormous, integrated and interconnected machine. However, the grid does not represent a "pool" where everyone connects to everyone else in one homogenous, shared infrastructure. Electric grids have specific circuits and components through which power flows. The flows on these circuits are influenced by the dynamics of supply and demand close to them, and in the wider system, as well as by reliability considerations. Presently, carbon emissions associated with grid electricity are calculated based on averaging applied to large geographic areas, without accounting for the specific flows in any location. This means that if you live near a wind or solar farm, or have solar panels installed on your roof, the carbon intensity for your electricity (i.e., grams of carbon dioxide, or CO_2, per kilowatt hour, or kWh) is averaged across a large area and not representative of your proximity to those resources. This is as true for cities and regions as it is for data centers, large industrial and commercial customers, and for individual homeowners. In addition to this, averaging grid carbon intensity over long time periods does not accurately represent the carbon emissions associated with electrical consumption at specific locations and specific times during the day. For instance, consumption that primarily occurs in the evening cannot claim to have used solar power even though this was present in the "average" mix over the day (at least, not in the absence of energy storage).

Recognizing and using locational carbon intensity data does not replace the need for regional and marginal carbon intensity data, but its absence presents a significant impediment for a society seeking to decarbonize rapidly and at scale. Creating clarity around these issues can also better inform planning to ensure equity and climate justice for underserved communities who often suffer from higher levels of pollution and a lack of choice when it comes to purchasing energy. Accordingly, narrow solutions to decarbonization that leverage any single tool or methodology (including those presented in this paper) are inherently exposed to the risk of perpetuating harm through implicit bias and a lack of granular context for the impacts of decision-making. For example, when large loads consume power generated by coal or gas generators, but match their load to renewable power that was generated elsewhere in the same market area, the load can claim to have net zero emissions from one carbon accounting perspective (i.e., offsets), but not from a physical system flow perspective. TCA takes a step closer to a more complete picture and provides a basis for including the physical flows on the grid.

In this paper, we discuss the need for locational carbon intensity and provide a framework for quantifying the total carbon intensity of delivered electricity on a geographically and temporally granular basis, using a simplified power flow framework that recognizes the balance of load and generation and the relative flow of power between grid locations. Where stakeholders are supportive of this process and make data available, these calculations can be both precise and accurate. Where stakeholders are unwilling or unable to make information available, a clear and well-defined approach to estimating these values from publicly available or discoverable datasets will need to suffice until such datasets become available.

The framework presented in this paper is put forth by a consortium of interested stakeholders with the hope that, by sharing this framework, it can be improved through transparency and feedback. Together, the co-authors represent the capability to both demonstrate and assess the methodologies proposed in this paper and are currently engaged in an effort to do so. We seek to grow the community of those who support the goals of this framework, and to improve its effectiveness.

The paper begins by describing existing reporting requirements for companies today then moves on to describe recent developments in carbon intensity analytics, prior to presenting the concept and framework for TCA using locational carbon intensity data.

Identifying and Reporting Carbon Emissions

Follow the Carbon

The Intergovernmental Panel on Climate Change (IPCC) released its Sixth Assessment Report (AR6) in 2021. The IPCC's statements are definitive and unambiguous: the changes observed in the climate system are "unprecedented over many centuries to many thousands of years," and it is "unequivocal that human influence has warmed the atmosphere, ocean and land". The report describes a near-linear relationship between cumulative carbon dioxide in the atmosphere and the observed increase in global surface temperature since 1850. Because of this relationship, the IPCC states that achieving net zero carbon dioxide emissions is a requirement for stabilizing human-caused global temperature increase.

Carbon dioxide accounted for 74% of global greenhouse gas emissions (GHG) in 2016, most of which was caused by the burning of fossil fuels. In 2020, 73% of the world's 49.4 billion tons of GHG emissions were caused by the energy sector, and it's no wonder why: 63% of global electricity is still produced using fossil fuels, and coal, the most carbon-intensive fuel, remains king. However, the share of coal in the global generation mix has decreased steadily since 2010, corresponding with an increase in natural gas generation and notable increases in wind, solar, and other renewables. In 2020, over one-third of global electricity was produced using low-carbon sources.

Despite these strides, electricity demand is increasing globally and it is outpacing the growth in renewables. Although measurable decreases in GHG emissions from the electricity sector were observed in 2019 and 2020, these decreases are largely credited to decreased demand during the COVID-19 pandemic. The International Energy Agency (IEA) forecasts that carbon emissions will increase by 3.5% in 2021 and a further 2.5% in 2022, reaching all-time highs, as strained grids will rely more heavily on fossil fuels to meet demand.

The call to action has never been more clear. Without serious reductions in global GHG emissions and, more specifically, carbon dioxide (CO_2), surface temperatures will continue to rise and climate events will increase in both frequency and intensity. Human-induced GHG emissions have already caused irreversible changes in the ocean, ice sheets, and permafrost. The decarbonization of global energy systems is imperative to curb further changes in our atmosphere, ocean, and land.

Voluntary Reporting and GHG Protocol Scopes

The Greenhouse Gas Protocol (GHGP) defines the world's most widely used GHG accounting standards. Building on a 20-year partnership between the World Resources Institute and the World Business Council for Sustainable Development, the GHGP provides companies, financial institutions, cities, and countries with comprehensive frameworks for global GHG accounting.

Companies use the GHGP frameworks in voluntary disclosure systems such as the Carbon Disclosure Project to define and communicate their annual emissions. Under the Corporate Standard, which covers the accounting and reporting of seven GHGs covered by the Kyoto Protocol, companies report their GHG emissions under three scopes. More specifically, the GHGP standard called "Scope 2 Guidance", updated in 2015, prescribes how to calculate the carbon associated with electricity consumption from sources owned or controlled by another organization.

GHG emissions from purchased electricity can be calculated using two methods: "Market-Based" accounting and "Location-Based" accounting. The market-based method describes emissions from electricity purchased through chosen contracts, and the emission factors used are derived from these instruments. The location-based method describes emissions from electricity supplied via the grid, and the emission factor used represents the average emissions intensity of the grid over a given area and timeframe. An excerpt from the GHGP Scope 2 Guidance illustrating the reporting process is shown below, with the key locational and temporal components bolded.

Table 1: GHG Protocol Scope 2 Guidance - Comparing market-based and location-based methods

Scope 2 Reporting	Market-Based Method	Location-Based Method
Definition	A method to quantify the Scope 2 GHG emissions of a reporter based on GHG emissions emitted by the generators from which the reporter contractually purchases electricity bundled with contractual instruments, or contractual instruments on their own.	A method to quantify Scope 2 GHG emissions based on average energy generation emission factors for defined geographic locations including local, subnational, or national boundaries.
How the method allocates emissions	Emission factors derived from the GHG emission rate represented in the contractual instruments that meet Scope 2 Quality Criteria.	**Emission factors representing average emissions from energy generation occurring within a defined geographic area and a defined time period.**
Where the method applies	To any operations in markets providing consumer choice of differentiated electricity products or supplier-specific data, in the form of contractual instruments.	To all electricity grids.

Scope 2 Reporting	Market-Based Method	Location-Based Method
Most useful for showing	• Individual corporate procurement actions. • Opportunities to influence electricity suppliers and supply. • Risks/opportunities conveyed by contractual relationships, including sometimes legally enforceable claims rules.	• GHG intensity of grids where operations occur, regardless of market type. • The aggregate GHG performance of energy intensive sectors (for example, comparing electric train transportation with gasoline or diesel vehicle transit). • Risks/opportunities aligned with local grid resources and emissions.
What the method's results omit	Average emissions in the location where electricity use occurs.	Emissions from differentiated electricity purchases or supplier offerings, or other contracts.

The Scope 2 Guidance recommends that companies report their Scope 2 emissions using both methods but acknowledges that dual reporting does not eliminate all reporting inaccuracies. For instance, the market-based method is only accurate if the emission factors provided are unique to the company's consumption. The guidance outlines data quality criteria that must be met by contractual instruments used in the market-based method, but the responsibility of quality control is assigned to the reporting company. The market-based method is an important Scope 2 estimation method, and, paired with an accurate model of carbon flow throughout the grid that follows the Scope 2 Guidance, data quality could be greatly improved for both generators and customers.

The location-based method, as defined in Table 1, presents additional challenges. Companies must rely on public datasets that are typically compiled for uses other than corporate GHG accounting, such as the U.S. eGRID or the IEA's national electricity emission factors. These datasets use wide-scale averages over large geographic regions and can have significant delays between the year of generated energy and resulting emissions, and the year in which the data is published. These delays can be as long as 2-3 years.

Figure 2: Illustration of carbon intensity averaged across an entire market area

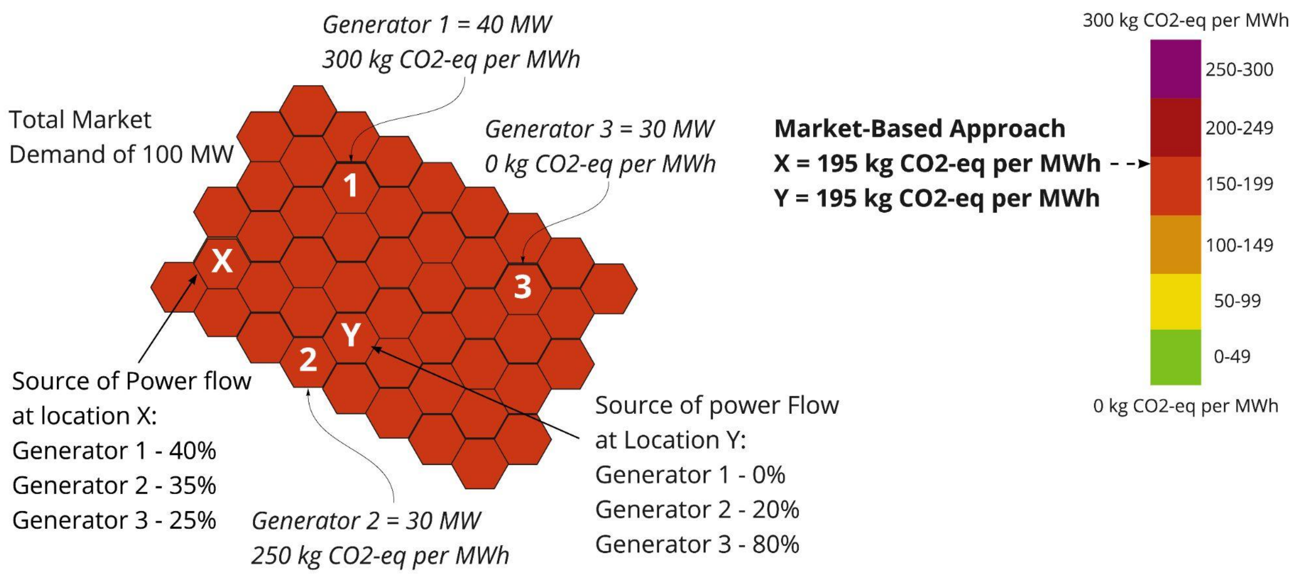


Figure 2 demonstrates some of the issues associated with the approach of using a single carbon intensity number for an entire market. On the left of Figure 2, it can be seen that the market occupies a geographic space with uniform carbon intensity. In other words, it is inherently assumed that the carbon Intensity is the same at all locations. For the purposes of this white paper, and to keep the example simple and illustrative, we will not consider losses within the calculations. In this example, if the exports of each generator (in MW) are assumed to be applied consistently to a one hour period (i.e., MWh) and multiplied by each generator's emissions factor (kg CO2-eq per MWh) and then summed together, this number can be divided by the total demand for that hour (MWh) to arrive at the average carbon intensity for the market area.

Carbon Intensity at Locations X and Y is the market average

$$\frac{((40\times300)+(30\times250)+(30\times0))}{100} = 195\ kg\ CO2\text{-}eq\ per\ MWh$$

The US Environmental Protection Agency's (EPA's) Emissions and Generation Resource Integrated Database (eGRID) provides an on-line calculator to estimate the carbon footprint of power plants in 26 eGRID subregions across the US. Each region was established to minimize energy imports into the region, in an attempt to reduce the potential distortion in the carbon content from unaccounted-for external generation. The average carbon intensity is calculated by adding up the total carbon emissions from each generation source in the region over the year and dividing by the total energy (megawatt hours, or MWh) consumed in the region. Most companies use the average intensity values for their respective regions of operations to calculate their carbon emissions by multiplying each location's total MWh consumed by the carbon value published in the EPA calculator. This approach, while still useful, cannot capture the locational or temporal aspects of any business operations, and fails to capture the realities of carbon for those connected close to and using physical power from fossil fuel sources (irrespective of the power they are buying in the market).

Recent Policy Initiatives

The US does not have a comprehensive long-term strategy to decarbonize the electricity sector at the federal level. Efforts to decarbonize have primarily been driven by state-governments through the enactment of Renewable Portfolio Standards (RPS). These standards are statutory or regulatory mandates that require a certain percentage of electricity sold within a state to be generated using renewable resources by a specified deadline. To date, thirty states and two territories have enacted a renewable portfolio standard. The requirements of different standards vary widely, and seven states and one territory have allowed their standards to expire without renewal. More recently, states have begun adopting decarbonization targets. For example, Hawaii has enacted a statewide target to sequester more atmospheric carbon and GHGs than it emits by no later than 2045. Illinois recently passed the Climate and Equitable Jobs Act (CEJA), which aims to achieve 40% renewable energy by 2030, 50% renewable energy by 2040, and to completely phase out coal and natural gas generation by 2045. CEJA requires utilities to file Multi-Year Integrated Grid Plans to support the state's clean energy goals and tasks state agencies with reporting on the current and projected status of carbon reductions and resource adequacy. The bill also preserves existing nuclear plants, establishes new electric vehicles incentives, and expands existing energy efficiency programs. New York State has adopted the Climate Leadership and Community Protection Act (CLCPA), which includes the goals of a 40% reduction in emissions below 1990 levels by 2030 and 85% below by 2050. Combined with other carbon offsetting activities, this will result in New York State achieving net zero emissions.

Some US cities have enacted their own climate policies which include requirements for building owners to track and report their energy consumption. New York City's Local Law 97, for instance, requires most buildings over 25,000 square feet to meet new energy efficiency and greenhouse gas emissions during the periods of 2024-2029 and 2030-2034. The New York Independent System Operator (NYISO) published emissions coefficients to be used by building owners when calculating annual GHG emissions during the 2024-2029 period. These include a single average of tons of CO2 equivalents per kWh consumed for utility-provided electricity.

The United Kingdom (UK) has national energy laws that guide the country's efforts, distinguishing it from the United States. The UK recently set into law a target of a 78% reduction in GHG emissions compared to 1990 levels by 2035 and was the first country to announce legally binding plans for net zero emissions by 2050. The country has also pledged to end all coal power generation by 2024. At the time of writing, the United Kingdom is joined by twelve countries and the European Union with net zero emission goals written into law.

As discussed, regional averages do not capture the true nature of carbon flow throughout the grid, especially when applied to long time periods . Now more than ever, energy regulators require a transparent, complete, and accurate tool that monitors the grid in real time. Existing tools are updated periodically and therefore rely on outdated information. These tools also employ gross averages that cannot identify high-carbon locations to any degree of granularity, optimize projects to best benefit communities, or support carbon regulation in a meaningful way.

Voluntary Corporate Targets

At the corporate level, carbon reporting is largely voluntary. Some carbon data is collected by voluntary disclosure systems such as the Carbon Disclosure Project, the Global Reporting Initiative, and the Sustainability Accounting Standards Board, but participation in these standards is voluntary, and the data that companies choose to report goes unverified. Many companies also produce their own sustainability reports with little consistency in the standards followed and the calculations used when reporting carbon emissions.

Numerous companies have pledged net zero goals, including the co-authors National Grid and Exelon. Other examples include Apple (2030), BBC (2030), Facebook (2030), Google (2030), Microsoft (2030), Coca Cola European Partners (2040), PepsiCo (2040), Visa (2040), BP (2050), Dell (2050), and Nestle (2050). In addition, both Google and Microsoft have operated as carbon-neutral since 2007 and 2012, respectively. It is important that as more companies set net zero goals, they have access to a tool that accurately models carbon flow throughout the grid and enables them to make project and purchasing choices that truly reduce their Scope 2 emissions.

The US Securities and Exchange Commission (SEC) has indicated that it will create a rule, likely within this year, requiring climate-related disclosures in public company filings, driven by the voluntary disclosure frameworks and global push toward mandatory disclosure of companies' climate impacts. The rule is intended to address issues including scope of reportable emissions, appropriate reporting standards, and other relevant benchmarking criteria, and may be informed by the Task Force on Climate-related Financial Disclosures (TCFD), Sustainability Accounting Standards Board (SASB), Global Reporting Initiative (GRI), and CDP (formerly the Carbon Disclosure Project). For this initiative to have meaningful effect, and to achieve decarbonization objectives in the most efficient manner possible, a Total Carbon Accounting assessment is needed. The GHG emissions resulting from the burning of carbon-based fossil fuels depend not only on the instant in time in which the resulting energy is used, but where on the grid the user is located. TCA will enable companies to comply with these new SEC requirements by providing a much more accurate report than is possible with the averaging techniques used today. This also has important implications for companies regarding where on the electrical grid their business operations should be located and when their most energy intensive operations should be scheduled to most efficiently manage their GHG emissions.

Recent Developments in Carbon Intensity Analytics

As more organizations seek to better understand the carbon footprint associated with their electricity use, three main trends in carbon intensity analytics have emerged:

- **Temporal Granularity** that permits alignment between time of generation and time of consumption.
- **Locational Specificity** that creates locational alignment between the point of generation and the point of consumption.
- **Locational Marginal Emissions** that recognizes the association between the marginal generation in the marketplace and the unit of power being consumed.

These three trends point toward an increasing need for more specific carbon accounting practices as they pertain to the production and consumption of electrical power.

Trend One: Temporal Granularity

Many large power consumers, in particular data center operators that consume huge amounts of energy such as Google and Microsoft, are interested in using "clean" energy, and the best way to do this today is to either locate these facilities in a "clean power" region, or create a power purchase agreement (PPA) with a large solar or wind farm. The GHGP permits the latter arrangement when calculating carbon created, as noted in the "Market-Based" allowance for (directly contracted) power through these PPAs.

However, these companies recognize that simply buying sufficient clean power to match total power consumed over time does not account for the temporal aspect (or instantaneous match) of generation to consumption. A solar farm may generate the total MWh required to meet the data center load, but only between the hours of 10am and 4pm, while the data center actually runs around the clock.

Recent attempts to improve the temporal problem caused by simple PPA purchases include the use of hourly certificates for clean energy, with leadership being provided by the EnergyTag initiative. Each certificate is for a MWh of renewable energy generated at a specific time which companies can purchase to "match" their consumption in that period. This is a welcome development that resolves some of the issues related to the temporal matching of supply and demand, but does not adequately consider the grid's topological relationship between the point of generation and point of consumption.

This approach has been embraced by Microsoft, who is working with Vattenfall AB in Sweden to match data center load to renewables available in the market. This is also a foundational aspect of Google's 24/7 renewable energy matching strategy and underpins the company's ambition to be carbon free by 2030. These approaches recognize the importance of locating renewable generation in the same region or area as the data centers, although they do not take account of the physical flows between the renewable generators and the data center.

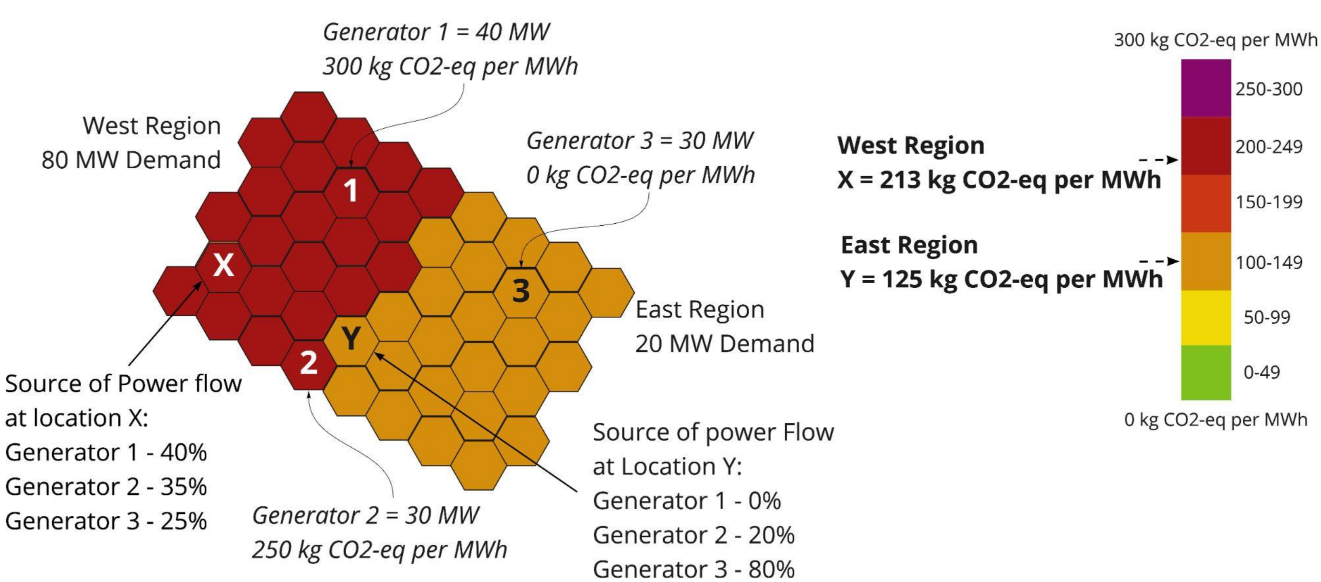
In North America, it is typical for ISOs to provide summary emissions data for their market area. For example, the California ISO (CAISO) provides five minute resolution CO2 emissions data. The NYISO provides five minute fuel mix data for the entire NYISO market, permitting a similar consideration of carbon intensity with temporal granularity.

Trend Two: Locational Specificity

The development of regional statistics for carbon intensity of electricity supply was previously driven by one of two main factors; the boundary of a market or market zone, or the natural watershed between two locations where there was little physical power flow exchanged between the two areas. The accuracy of these factors could be greatly improved by integrating systems flows to apportion carbon intensity.

Figure 3 provides an illustration of the regional carbon intensity approach. Both regions are part of the same market; however, the generation in each region and the flow of energy between them is used to define their respective carbon intensity values.

Figure 3: Illustration of regional average carbon intensity within a single market



The East Region's demand is met by 10 MW from generator 2 and 10 MW from generator 3, and has a carbon intensity of 125 kg CO2-eq per MWh, which is applied to any load in the East Region, including location Y. The West Region's demand is met by 40 MW from generator 1, 20 MW from generator 2, and 20 MW from generator 3. Subsequently, a carbon intensity of 213 kg CO2-eq per MWh is applied to location X and all other locations in the West Region. As was the case for the illustration in Figure 2, if we assume these generator export and demand values to be applied to a one hour period, then the following simple calculations can be performed for each region.

Carbon Intensity for the West Region and Location X

$$\frac{((40\times300)+(20\times250)+(20\times0))}{80} = 213\ kg\ CO2\text{-}eq\ per\ MWh$$

Carbon Intensity for the East Region and Location Y

$$\frac{((0\times300)+(10\times250)+(10\times0))}{20} = 125\ kg\ CO2\text{-}eq\ per\ MWh$$

The regional approach is a significant improvement on the market based approach in Figure 3 and can also be analyzed at frequent intervals to increase temporal granularity. To date, this method is the best approach for addressing the locationally specific nature of carbon intensity. However, it remains that individual locations could be provided with power from a range of sources that would place them less than or greater than the average carbon intensity of either region.

Numerous entities are producing tools to visualize carbon intensity at the regional level. This paper has already identified the US EPA's eGRID tool as one such authority. In the UK, National Grid is the first major utility to advance a more focused and sophisticated regional carbon intensity tool and Application Programming Interface (API). National Grid's tool and API are the current state of the art for breaking down regional areas, addressing both their local fuel mix and grid topology to determine the carbon intensity of grid-supplied electricity. It is to be expected that other utilities and markets will follow National Grid's lead, which utilizes a framework and methodology for transmission networks that is aligned with that presented in this white paper for distribution systems and Total Carbon Accounting.

Western Power Distribution (WPD) is a distribution utility in southwestern England, WPD is possibly the first distribution utility to explore variations in carbon intensity at the sub-transmission level using "carbon tracing". WPD first started working on carbon tracing in 2012, and has since expanded the initiative to bring in broader industry participation. As a result, it is possible to use the Carbon Tracer website and app to explore carbon intensity data at the distribution substation level. This is also a unique example of addressing carbon intensity for distribution networks, further cementing the UK as a leader in this area.

A more global perspective on carbon intensity is provided by Tomorrow in their electricityMap application, which, although focused on market-level data, is a very useful overview of the national and market dynamics associated with carbon intensity and the need for coordinated planning between countries and regions. The electricityMap application also provides an API with a range of options for users.

These developments demonstrate the progress being made in better understanding the carbon intensity of electricity supplied in countries and regions, with locational specificity increasing over the last decade. This trend is set to continue to provide much more granular data on total carbon intensity at specific locations based on physical flows, not just the broader market or zone where the location belongs.

Trend Three: Locational Marginal Emissions

The role of marginal economics in power markets is well established and is a fundamental aspect of how energy is bought and sold. Locational Marginal Prices (LMPs) are used extensively in North America and other markets around the world and represent the market price for the addition of another unit of electricity that would need to be delivered. In recent years, several companies have started looking at marginal emissions, thereby tying the decision to consume power at a particular time and location to the marginal emissions rate in the market, (i.e., the emissions associated with the provision of the additional unit of electricity, based on the generators that will provide the power to meet that additional unit). This works well for demand response market participants, but this is not a concept that easily captures the total carbon in the system and market, nor is it one that can be easily understood and considered by a broad range of participants in the sector.

Watt-time is a non-profit organization that provides temporal granularity of the marginal carbon intensity in each market. One of the objectives is to allow load that has some discretion as to when it can run, such as refrigeration, to delay consumption if the grid is being mainly supplied by carbon-intensive generation until times when the grid supply is "greener". Watt-time provides a range of data plans for ISO data. Users can enter zip codes to get access to market data, though the data is not specific to each zip code, but to the regional market containing the specified zip code. Resurety is also working on providing Locational Marginal Emissions (LME) data and is collaborating with multiple large corporations, including Microsoft. Resurety is focusing on LMEs with the idea that their customers will be able to determine the avoided CO2 emissions based on the clean energy that they buy.

Developments in LME make sense for particular industry participants, but do not address the physical connectivity of the grid and the need for Total Carbon Accounting.

LME is an attempt to identify if the next generator unit that would need to generate to meet increased demand is "dirty" (carbon emitting) or "clean" (solar, wind, or even nuclear), and if possible and financially practicable, delay that additional consumption until the grid turns "green" again. A data center could shift 1 MWh of demand to a time when the LME is zero (or low). There is nothing wrong with this idea, but the calculations used today suffer from similar issues as the gross averaging methods across market areas or regions. Furthermore, LMEs do not provide insight into the physical topology of the grid and the actual power flows between the location of the marginal generator unit and the location of the increased unit of demand. Indeed, the effects can sometimes be counterintuitive: it can be that a reduction in electricity use can cause an increase in the marginal emissions rates. For example, a change in demand at a location can cause a change in the dispatch patterns, such that if in the next five-minute interval a coal unit is on the margin, the expected benefits can be negated.

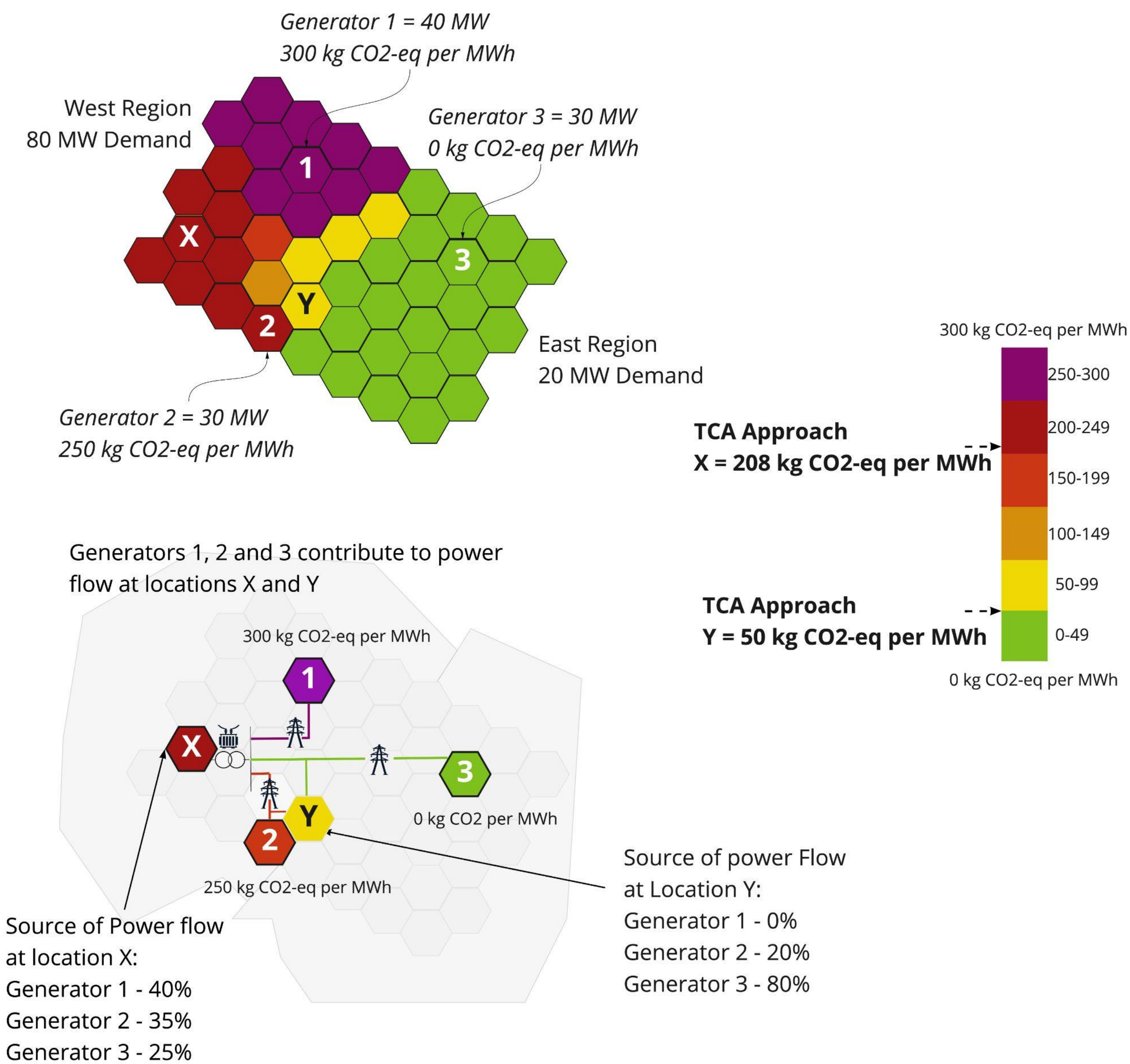
Total Carbon Accounting Through Locational Carbon Intensity

Recent developments and methods for marginal and regional carbon intensity are leading to improved approximations that work reasonably well for large, transmission-connected power consumers with significant capital. These entities employ sophisticated power management tools and staff, but they represent a relatively small (albeit increasing) percentage of all power consumed. This process is of little help to the vast majority of distribution-connected companies and other power consumers interested in understanding the total carbon footprint of their electricity supply. The rest of the power consuming world (and to a certain extent, even these giant consumers) still has a need to accurately know their carbon intensity both by location and over time at a highly granular level before they can take measures to reduce their footprint or meet their reporting requirements.

Total Carbon Accounting is concerned with capturing the representative carbon associated with all contributions to the power flowing at any individual node on the grid for a given point in time. This can only be achieved through the complex analysis of the physical flows on the grid and the carbon associated with all generation sources (including those embedded in the distribution system and customer premises) and the larger transmission-connected units that participate in the market.

In Figure 4, it can be seen that the actual distribution of power from the three generators in the market area has a much more localized impact on carbon intensity. In particular, the bottom part of the figure clarifies an illustration of the power grid topology supplying power to locations X and Y and the percentage associated with each generator.

Figure 4: Illustration of Locational Carbon Intensity to Support Total Carbon Accounting



Using the same assumptions as in the analysis of Figure 2 and Figure 3, while also recognizing the specific contribution of each generator to locations X and Y, permits the calculation of specific carbon intensity values that are unique to each location.

Carbon Intensity at Location X

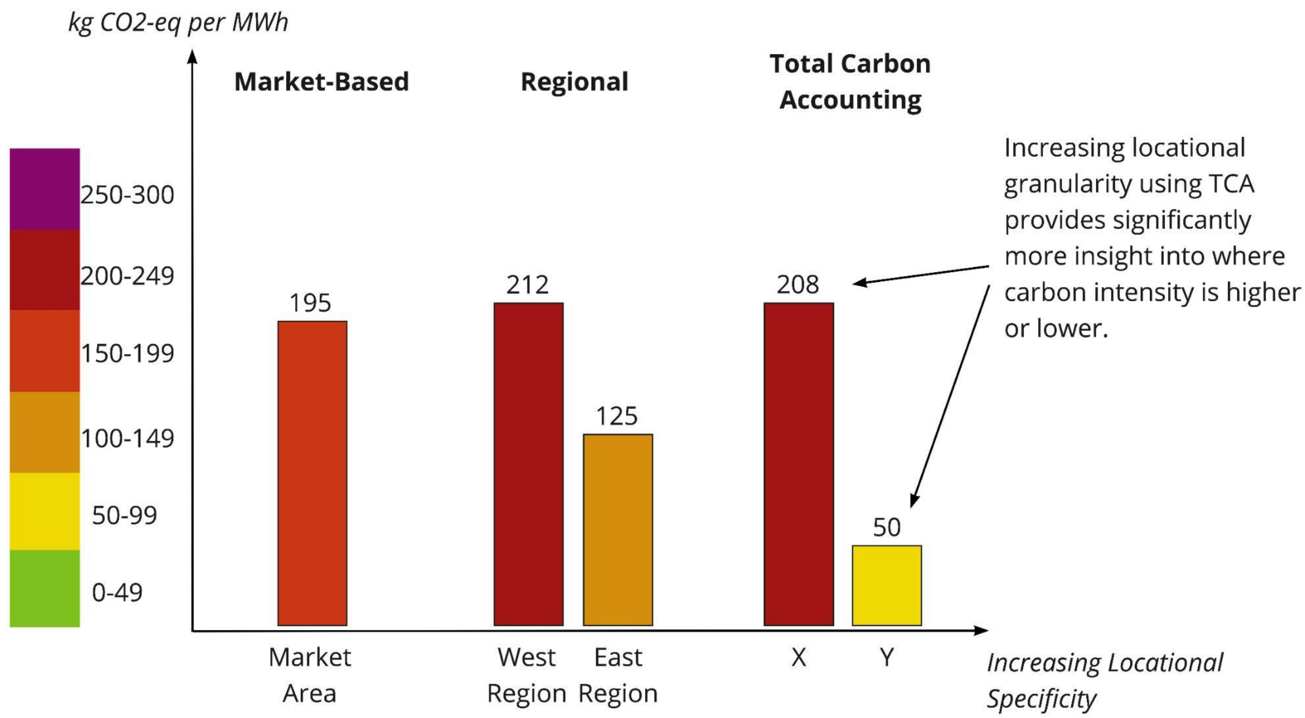
$$(0.40 \times 300) + (0.35 \times 250) + (0.25 \times 0) = 208 \ kg \ CO2\text{-}eq \ per \ MWh$$

Carbon Intensity at Location Y

$$(0 \times 300) + (0.20 \times 250) + (0.80 \times 0) = 50 \ kg \ CO2\text{-}eq \ per \ MWh$$

In Figure 5, it can be seen that simplifying the market area to a single market-based carbon intensity of 195 kg CO2-eq per MWh cannot possibly capture the clear difference between the West and East regions of the grid or the specific TCA values at locations X and Y.

Figure 5: Bar chart comparison of different carbon intensity calculations and the benefits of TCA



When compared to the market-based average of 195 kg CO2-eq per MWh, the West Region shows an increase in carbon intensity to 212 kg CO2-eq per MWh and the East Region shows a reduction to 125 kg CO2-eq per MWh. It can also be seen that by considering the actual contributions of the generators to the loads, the TCA approach identifies that location X has a carbon intensity of 208 kg CO2-eq per MWh, which is higher than the market-based average of 195 kg CO2-eq per MWh, and similar to the West Region value of 212 kg CO2-eq per MWh. The TCA result for location Y is even more interesting, as location Y has a carbon intensity of 50 kg CO2-eq per MWh, which is significantly lower than the market-based average of 195 kg CO2-eq per MWh and the average for the East Region of 125 kg CO2-eq per MWh. It is clear that other locations within both regions will also have different TCA values that vary significantly from the market or regional average. Identifying the TCA data and using it to prioritize and measure decarbonization activities will provide the best and most accurate means of addressing the true reduction of carbon in the system.

The Evolution Toward Total Carbon Accounting

There are a range of approaches that seek to capture data associated with the production and consumption of electricity as it relates to carbon. The three main trends discussed previously are incorporated as steps 1 through 3 on the evolution toward TCA below, while steps 4 through 8 require additional analytical capabilities to enable the appropriate calculation of locational carbon intensity. Provided that these analytical capabilities can be developed, additional use cases for localization can be evaluated. These steps and analyses are discussed in subsequent sections of this white paper.

1. Market or Regional Averaging (*e.g., CAISO)*
2. Sub-Regional Emissions Zones (*e.g., National Grid in UK*)
3. Locational Marginal Emissions (*e.g., Watt-Time, Resurety*)
4. Transmission Node Carbon Intensity
5. Sub-Transmission Node Carbon Intensity
6. Distribution Primary Feeder and Carbon Intensity
7. Distribution Secondary Feeder and Carbon Intensity
8. Customer Specific Locational Carbon Intensity

As discussed earlier, **Market or Regional Averaging** in step 1 is useful, but presents a range of deficiencies when accounting for the relative positioning of generation and load that is required to support TCA. Step 2 is concerned with greater visibility of **Sub-Regional Emissions Zones**, which provides greater clarity and improved accuracy for those interested in more specific carbon accounting, but still does not take into account the physical flows in the grid. Step 3 delivers **Locational Marginal Emissions**, which provides valid and useful information, but to a more limited set of industry participants.

Steps 4 through 8 directly improve the locational specificity by capturing and representing the influence of the physical flows on the grid. Step 4 is the specification of the **Transmission Node Carbon Intensity** as opposed to the use of an average value or locational marginal value. This requires an appropriate degree of system modeling to apportion the flows on the transmission system to specific generator sources, interfaces to neighboring transmission grids, and an understanding of the behavior of load and Distributed Energy Resources (DER) operating at the distribution grid level.

In Step 5, the **Sub-Transmission Node Carbon Intensity** calculations are based on tracing from the **Transmission Node Carbon Intensity** calculated in Step 4. This permits the upper voltage level of the distribution system (recognizing that sub-transmission voltage levels vary by region) to be analyzed for carbon intensity. In this case, a more detailed understanding of load and DER is required to facilitate this step.

Steps 6 and 7 are concerned with **Distribution Primary Feeder Carbon Intensity** and **Distribution Secondary Feeder Carbon Intensity**. These steps involve more detailed modeling of the feeders on the distribution system and the apportionment of load and DER data to specific locations and feeders.

To deliver Steps 4 through 8, a comprehensive understanding of the physical grid is required along with an ability to predict and analyze the behavior of load and DER as they impact the power flows throughout the distribution and transmission systems. The following section introduces a framework for TCA required to deliver this vision.

A Framework for Total Carbon Accounting

Total Carbon Accounting requires the ability to calculate locational carbon intensity. This is not simple and there are various challenges associated with the data and computational techniques required to perform the task. There are significant system modeling, machine learning, and time series components to the analysis, in addition to the complex calculations of flows from sources to sinks across vast electrical networks that can change quickly over relatively short periods of time. This goes far beyond the analytics required to calculate the data in Steps 1 through 3 of the evolution to TCA.

One of the fundamental barriers that has existed in the past is the inability to model the transmission system integrated with the distribution system in a holistic way and to respond to the rapid growth in DER. There are many significant challenges associated with analyzing the distribution system that must be overcome to perform the types of calculations described in this paper. These challenges include the model, the representation (graph or otherwise) of the topology of the power system, the ability to produce accurate and usable time series data, and the statistical approaches required to account for the behavior of DER that are known to be installed but are not monitored.

The approach described in this white paper recognizes that varying levels of visibility into the grid will require different, although related, approaches. Where partnerships exist (e.g., with grid operators or utilities) it will be possible to drive more accurate calculations into the model. However, it is also possible to use a range of techniques and data sources (public and private), before and after market closure, to facilitate TCA.

There are several sequential analytical processes required to calculate locational carbon intensity. These remain valid irrespective of the different approaches that could be adopted at each stage:

- Day-Ahead Market, Load and DER Forecasting
- Day-Ahead Pseudo Dispatch
- Allocate Generator Emissions Factors
- Solve Power Flow
- Establish and Trace Directed Graph
- Calculate Locational Carbon Intensity
- Ex-Post Settlement

Day-Ahead Market, Load and DER Forecasting

A fundamental first process required for TCA is forecasting the day-ahead position across the market (demand and price) and the location and behavior of DER connected to the system. The granularity of this forecast would be 30 minutes or less, depending on the market in question. This will require the use of historic data sets and integration with a range of platforms used by market operators, public data sources, and technology providers.

Day-Ahead Pseudo Dispatch

The framework requires a pseudo dispatch methodology to predict the market position for each time step in the day ahead period. This is dependent on the Day-Ahead Market, Load and DER Forecasting process and requires an understanding of generator characteristics, including seasonally adjusted Pmax, Pmin, heat rates by unit, annual production values, and region-specific estimates of fuel costs (when applicable). Considering market zones, or “bubbles” will make it possible to identify contingency scenarios that would require the selection and operation of specific generator units in the market dispatch. This is typically performed using unit commitment or security-constrained optimal power flow. This same approach can be extended to consider interface flows to surrounding “bubbles” and neighboring market areas. In order to perform “settlement” of these positions after the fact, It will be necessary to build, train, and test forecasting models on previous dispatch positions, and provide rolling forecasts based on a broad range of inputs. At the end of this step each generator and load should have an initial set-point applied to them for each timestep in the subsequent 24 hour period.

Allocate Generator Emissions Factors

Governments and market operators provide different data sets related to the emissions associated with types of generator and also with specific individual generator units. Wherever possible, statistics that are specific to the generator unit in question, (e.g., a coal plant at a specific location) will be used, as opposed to a generic set of statistics for coal plants in general. At the end of this process, every generator unit will have a specific emissions factor (kilograms of CO_2 per kWh or MWh) that can be applied to their production for that point in time.

Solve Power Flow

A model of the power system is required to support an analysis of the power flows on the interconnected transmission and distribution systems. This analysis can be performed on a full power system model or on a reduced version of the system model. The more detailed the model, the better. The objective of this analysis is to determine the direction of power flow rather than to accurately identify the full range of power system parameters normally associated with this form of analysis. It is important to know the direction and magnitude of the power flow, and to know that the analysis captures the losses in the system. At the end of this process, there should be clarity on the direction and magnitude of power flow between all relevant components of the power system. Additionally this analysis, and the ability to converge distribution and transmission power flow models, will help inform the appropriate and practical level of granularity for carbon intensity analysis.

Establish and Trace Directed Graph

The direction of power flow and model of the grid (reduced or otherwise) will be used to create a directed graph of the system to permit tracing from all sources to sinks. As discussed in the literature, the proportional sharing principle should be used to determine the contribution of multiple paths feeding a node and the allocation of flows to the multiple paths leaving a node. At the end of this process, each power flow on the grid being analyzed will be given a carbon intensity value (kilograms of CO_2 per kWh or MWh) at the location for a given point in time.

Calculate Locational Carbon Intensity

Once each of the previous processes has been performed (recognizing that there are options and levels of detail that can be considered to achieve the goal of each), a process must be performed to calculate locational carbon intensity for specific locations. This requires determining the contribution of any on-site DER to meeting local demand and calculating the carbon intensity for the site based on this and the proportion of the load provided by the grid. At the end of this process, the locations of interest will have locational carbon intensity data calculated for each timestep in the day-ahead forecast. At the most granular level, this could be for a single home or premise, or scaled up to an area (e.g., a community, ZIP code, census zone, or microgrid).

Ex-Post Settlement

After the final market position is determined and published, and if there is data available on load and DER performance during the period, it is possible to re-run the analysis and provide an updated “actual” locational carbon intensity data set that can be used for reporting purposes. The output of this process is a data set that can be used in GHG emissions reporting according to the requirements of the GHG Scopes and supports individuals, businesses, communities, cities, and governments in making informed decisions regarding decarbonization strategies.

Doing More with Data

Total Carbon Accounting is easy to grasp as a concept, as is locational carbon intensity. The framework presented in this white paper is intuitive and leverages developments in the sector to date. However, the implementation of the framework is complex and all about doing more with the available computational methods and data. It is important to acknowledge that, while the analysis presented is reliant on many proprietary datasets, locational carbon intensity is not entirely reliant on them.

In many places, it is possible to access a basic set of data on the power system. In the UK, Long-Term Development Statements (LTDS) published by each Distribution Network Operator (DNO) are readily available (e.g., Western Power Distribution's LTDS is available online). However, data is not always available to permit the type of analysis required by TCA. Where network models are not available, alternatives do exist. Locations of large power plants are generally available, as is the location of power lines. An estimation of hourly renewable generator output and an understanding of the built environment that is being supplied power are also available for many locations. The challenge is pulling these sources together in a transparent manner that creates improved insight and a basis for further improving accuracy of calculations over time.

The framework presented in this white paper can be applied using available market data combined with utility models, or alternatively combined with simpler representations of the grid as it forms the bridge between generation and demand. The flexibility of this approach means that locational carbon intensity can be calculated using the data that is available, even if this means a simple assessment of the temporal variations in load, generation, and constraints between subsections (i.e., zones) of the grid. Such analysis is entirely feasible and a significant improvement on the methods used today.

Conclusions

The premise of this white paper is that the historic, real-time, and forecast carbon intensity of the physical electricity supplied at any location should be available to anyone seeking to contribute to a carbon-free future. Current practices in carbon intensity analytics are insufficient to deliver locational carbon intensity. This white paper has demonstrated the need for locational carbon intensity as a critical component of decarbonizing the grid and has proposed a framework for calculating and delivering this important data through Total Carbon Accounting (TCA).

It is critically important that decarbonization efforts harness the best data available to improve coordinated decision making with respect to the development of the electrical grid, the adoption of renewable resources, and the electrification of heating and transportation. TCA is required for all governments and organizations seeking to deliver an effective, just, and equitable approach to decarbonization.

The concept presented in this white paper represents a cutting-edge approach to solving an increasingly important problem. The co-authors are currently testing these methods and invite others to join in this collaboration to ensure that the best possible approaches are used to evaluate, prioritize, and measure decarbonization activities.

What Next?

National Grid, Exelon, ComEd, and Kevala will continue to collaborate on the development and deployment of Total Carbon Accounting solutions across multiple locations in the UK and US with the intention of learning and demonstrating the concepts presented in this white paper and comparing results to alternative approaches. Please look out for further announcements from the consortium, and please contact us to learn more about what this could mean for you and your organization.

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