How Better Accounting Can More Cheaply Reduce Carbon Emissions

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Abstract

Much of corporate renewable energy carbon accounting today relies on an analytical technique that the Greenhouse Gas Protocol notes is a significant simplifying assumption. We show with a simple example that this widespread accounting practice can mismeasure carbon savings by up to 45 percent. Recent advances in estimating the emissions foregone from renewable energy generation have made significantly more accurate accounting now entirely practical. There are environmental and financial reasons why the most accurate emissions accounting would be socially valuable--it would allow for locations which offset more carbon to be identified and thus receive more investment.

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1   Introduction

The United States lacks a coherent national energy policy, and as a result many states and firms are unilaterally enacting energy policies to achieve their own goals, including carbon reduction. Over half of states have now implemented Renewable Portfolio Standards or brought carbon legislation to voters. Many firms have been vigilant in unilaterally reducing their carbon footprints: approximately 60 percent of U.S. corporations now have a carbon target with some like Microsoft, the University of California, and Kaiser Permanente even pledging carbon neutrality (Goldenberg, 2012; University of California, 2013; Kaiser Permanente, 2016). While some of this carbon footprint reduction is aimed at lowering operating costs through energy reductions, many firms actively spend to reduce carbon footprints directly. NGOs like Greenpeace track firms' environmental footprint and rate firms with report cards.

Arguably the most important mechanism for firms aiming to reduce carbon footprints is to invest in renewable electricity sources like wind and solar. Investment in renewable energy in the U.S. continues to grow, having increased more than 310 percent since 2004, reaching $111 billion in 2015 (McCrone & Mills, 2015). Corporate renewable deals alone, in which a company directly subsidizes new renewable generation, totaled 4.41 GW from 2014 through 2015 (Rocky Mountain Institute, 2016). Although financial benefits are certainly one driver behind this surge in renewable energy purchasing since renewable generation earns money for selling electricity, voluntary "green" targets play a significant role as firms acknowledge the importance of corporate responsibility.

There are two main ways institutions reduce their carbon footprints with renewables: either directly constructing new utility-scale renewable generating units like wind or solar farms; or purchasing Renewable Energy Credits (RECs) from existing facilities. The 4.41 GW number above refers to new utility-scale renewables. By contrast, RECs are a widely recognized claim not on electricity itself, but on the zero emissions trait of the electricity produced by renewable generators. In both cases, the considerable resources currently being dedicated to renewables dictates that carbon-reducing effects of their purchases should be accurately accounted for: firms and states must know what they are buying.

Current carbon accounting rules for firms and states have been standardized in the past two years, resulting in a tremendous increase in transparency and interest in the market for renewable attributes.[1] These advances were useful and needed: previously there were several different accounting practices which were not easily comparable and thus gameable. Getting market participants to a unified standard has been a terrific success for all stakeholders because it has increased total market participants on both sides of the market, buyers and sellers. While standardization has invigorated the industry, we will show in this paper that imperfect but understandable simplifying assumptions embedded in these standardized accounting principles can lead to misleading carbon reduction measurements associated with renewable energy projects. These imperfections are analogous to imperfect accounting assumptions which must be made by public and private firms. This paper focuses on how recent advances in estimating foregone carbon emissions due to renewable generation enables significantly more accurate accounting than does the current standard industry practice.

There are both environmental and financial reasons why the most accurate emissions accounting possible would be socially valuable. From an environmental perspective, using more accurate measures of carbon reductions from new renewables would send more accurate price signals to the market: renewable locations with the highest offset emissions would increase in value relative to lower offset emission locations. Thus, better accounting incentivizes sustainability-driven investments to finance those projects which can in reality produce the greatest carbon reductions. From a financial perspective, if industry leaders adopt better carbon accounting principles, it can also highlight opportunities for firms and electricity rate payers to reduce carbon at a lower cost per ton. With lower costs of carbon reductions, better accounting could lead to both financial savings and more carbon reductions by states and firms.

2 Carbon Accounting Basics

At first glance, carbon accounting for renewable energy purchases might appear very straightforward. Since renewable energy facilities do not generate carbon, one simple accounting technique is to associate each megawatt-hour (MWh) of renewable energy production with zero pounds of carbon dioxide. Yet doing so ignores a crucial effect: every time more renewable energy is added to a power grid, it displaces whatever other energy sources might otherwise have met local demand. Put another way, the local composition of electricity generation matters for carbon offset by renewables.

To use an extreme example, imagine a company constructing a new 50 megawatt wind farm in a region where the power grid is already entirely renewable-powered. Despite the addition of 50 new megawatts of clean energy capacity to the grid, the project would not in fact reduce emissions. Had the project never occurred, all that electricity would have been supplied by renewable energy anyway. By contrast, constructing the exact same facility in a grid that would otherwise be entirely powered by coal creates a very significant emissions benefit, because in that case those 50 clean megawatts would be displacing a highly emitting power source. In other words, when measuring emissions, a renewable energy plant's effect on its neighbors matters.

Firms and many states with green mandates currently use a widely agreed upon framework called "market based" accounting to determine how green they are. In this system, which has been very useful in standardizing industry practice, total consumed electricity measured in MWhs is compared to the total MWhs of generation which the firm or state can claim came from a renewable generation source. Emissions calculations based on power grid makeup can be performed for electricity not "covered" by clean MWhs (e.g., the difference between

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[1]This has been facilitated by partnerships across industry, non-profits, and governments and is supported by frameworks such as the Greenhouse Gas Protocol Scope 2 Guidance (GHGP Scope 2 Guidance).

MWhs consumed and MWhs stemming from renewables). Because this system does not measure the emissions impacts of a renewable energy project on its neighboring power plants, it cannot distinguish between renewable energy projects of widely varying emissions benefits.

This is the problem that stakeholders addressed with the Greenhouse Gas Protocol's Guidelines for Quantifying GHG Reductions from Grid-Connected Electricity Projects (GHG Project Protocol). This portion of the GHG Protocol provides generally accepted best practices for "anyone seeking credible techniques to account for GHG reductions from projects that affect the production or consumption of grid electricity." It does this by directly measuring emissions in tonnes of carbon equivalent (tCO2e) rather than MWh of electricity generation. When implemented correctly, the GHG Project Protocol ensures a consistent and accepted accounting procedure for accurately capturing the emissions benefits of new renewable energy projects.

There are two key components which comprise the foregone emissions from a renewable project. The first and most important component in both theory and practice is the Operating Margin Emissions Factor. Construction of a new power plant will have immediate impacts on output levels from other nearby power plants since they no longer need to produce as much energy. This is represented as the Operating Margin Emissions Factor. Of course, the Operating Margin Emissions Factor varies across the U.S. and across the time of day within a given region. This Operating Margin is the main channel by which renewable investments reduce emissions.
The second, longer term and indirect margin to estimate foregone emissions is the Build Margin: constructing a new power plant on the construction of other new power plants on the grid. New power plants supply more electricity to the grid and reduce the wholesale price of electricity. The GHG Project Protocol notes that when a new renewable energy plant is built, "…another potential power plant either may not need to be built or can be reduced in size." (Broekhoff, 2005).

In the appendix, we offer a careful step-by-step treatment of how the Operating Margin and Build Margins jointly allow one to calculate the foregone emissions from renewables like solar and wind. Because the GHG Project Protocol offers only limited qualitative guidance on calculating the Build Margin and that margin is not often used in practice, we focus on the Operating Margin here. Modifying the standard around the Build Margin would be a matter of developing an industry consensus where none currently exists, and is outside the scope of this paper.

3   Problems with Current Carbon Accounting

The GHG Project Protocol's conceptual framework for analyzing Operating Margin is clear and precise. But as the Protocol itself readily acknowledges, data availability issues have often limited its effective use in practice and in particular how it can apply to firms and states using market based accounting. Specifically, it states that:
The ideal method to estimate operating margin (OM) emissions would be to identify precisely which power plants on a grid are backed down in response to the project activity's operation. In practice, this is difficult if not impossible to do (Broekhoff, 2005). Thus, the GHG Project Protocol goes on to suggest four different possible methods to estimate the marginal emissions rate through various proxies. It then separately notes there is another method, which "should only be used where other methods are not practicable." This last resort simplification is to use the annual average emissions for the entire region as a proxy for the marginal emissions rate. But this is not a particularly good proxy: it directly cautions that this technique "is significantly less precise than other methods" (Broekhoff, 2005). Similarly the GHG Protocol's Scope 2 Guidance also places local average emissions factors at the very bottom of its "data hierarchy" measuring the quality of various types of market based emissions factors. (Sotos, 2015).

In practice, however, the technique of using average emission factors is the most widespread technique used in renewable and green accounting today, especially for firms and states determining the carbon content of MWh legally attributable to them. In particular, Greenpeace and other watchdogs often score different firms on how green they implicitly using average emission rates since each MWh of electricity produced is weighted equally.[2] Because using average emission rates is the status quo, many firms, NGOs, and states use accounting methods which falsely imply that the emissions benefits of all renewable projects are identical. Counting all MWh of renewable production equally over space and time is one such accounting method.[3]

Why would a technique that is explicitly called inaccurate by the GHG Project Protocol be in such widespread use today, and even encouraged by the GHG Protocol Scope 2 Guidance? Presumably because widespread data availability makes it by far the most readily accessible technique. While in theory an analyst with unlimited data at his or her fingertips could follow the Protocol to produce fully accurate GHG accounting, it has been far more cost-effective to standardize, enforce and measure "clean" emissions in MWh and use local emission factors from EPA's eGRID for the rest.[4] This approach means firms are implicitly are counting emissions as if renewable energy project equally displaced output from all types power plants, with no regard to which will or will not actually be displaced by placing a renewable energy power plant in a particular location. Further, local emissions rates have proven difficult to keep up-to-date: the latest version of EPA's eGRID, released in 2015, has no data more recent than 2012.

The inapplicability of total emissions-based accounting can be seen with the following stylized example. Suppose a given power grid consists of two power plants: 50 percent of power comes from a baseload nuclear power plant and the other 50 percent from a natural gas plant which increases and decreases production with electricity demand or system "load". Adding a new wind farm, solar farm, or other intermittent resource to this grid will decrease pressure on the existing power mix. But which plant will reduce its output accordingly? Certainly not the nuclear plant, which cannot reasonably ramp up and down in response to real- time variation in the supply of renewable energy. Thus, the actual emissions benefits of the new wind farm would in this example be exactly double those which an analyst would estimate by using local average emissions factors which average the nuclear and gas plants. Despite their best efforts, watchdogs, firms and states have been hampered by this lack of precision in evaluating the actual emissions reductions from renewable projects.

Thus, the emissions mitigated by renewable energy can sometimes have little to do with the mix of all power plants on the local grid. Instead what matters is, as the GHG Project Protocol says, "which power plants on a grid are backed down in response to the project activity's operation." In the TVA footprint in the southeast, for example, there is a mix of generation technologies including nuclear, coal and natural gas. It is exactly in regions with diverse fuel mixes like TVA where accurate carbon accounting can improve efficiency the most.

4   Advances in Carbon Accounting

The primary reason why average methods have been used in practice, is that at the time the latest versions of the GHG Protocol and market based accounting rules were written, marginal emissions-based accounting was "difficult if not impossible to do." Over the last four years, though, new research has substantially advanced the state of the art on historical marginal emissions estimation. Economists including Silver-Evans, Azevedo,

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[2]See http://www.greenpeace.org/usa/wp-content/uploads/legacy/Global/usa/planet3/PDFs/2015ClickingClean.pdf

[3] In a second-best attempt to avoid perverse incentives, many have adopted policies which simply mandate that renewable generation be co-located with where electricity is used, rather than actually quantifying the true emissions impacts of location generation in a particular place. This is costly: it is entirely possible that emissions can be more cheaply reduced by not collocating with consumption. A collocation policy can be costly in this way despite being well-intentioned.

[4]The Emissions & Generation Resource Integrated Database (eGRID) is a "comprehensive source of data on the environmental characteristics of almost all electric power generated in the United States" United States EPA & Associates (2015).

and Morgan (2012), Cullen (2013), Kaffine, McBee, and Lieskovsky (2013), Graff Zivin, Kotchen, and Mansur (2014), Wang et al. (2014), Holladay and LaRiviere (2015), Novan (2015), and Callaway, Fowlie, and McCormick (2015) have all developed models that can accurately estimate marginal emissions rates for various times and places in the United States and several other countries. These methods work by doing what the GHG Project Protocol says is "ideal" -- they identify which power plants on a grid would be backed down in response to a new renewable project's operation.

The different authors all have slightly different means of calculating the marginal emissions rates, with slight variation in technique and results. Key subjects of difference are whether to use theoretical least-cost dispatch models or empirical observation-based models, and how best to divide America's grid into regions. But ultimately, any one of these marginal emissions factor-based approaches represents a very substantial theoretical and empirical improvement in accuracy over the "last resort" of using total emissions-based factors to proxy for OM. The number of studies which find similar results across regions is reaching a consensus and accurately calculating marginal emissions is possible.

In order to examine the effect newer technologies can have on carbon accounting in practice, we compare the results of the newer and older estimation techniques for both solar and wind power plant types in three different regions. For ease of reference, we will call the older technique "conventional" emissions accounting, and the newer technique "marginal" emissions accounting.

For the conventional technique we use local average emission factors for a region. This is equivalent to, for example, the emissions reductions that a firm gains for each 1 MWh of RECs that it buys under the market-based method. These average emission rates for a given hour of the day cover an entire region. Disaggregating to the hourly level is important: solar farms generate during daytime hours and wind farms often generate at night. For the newer marginal technique, we use a variant of the technique first described in Siler-Evans et al. (2012). Specifically, we use the variant which an NGO called WattTime.org, whose cofounder is a coauthor on this paper, has implemented and made accessible to the public on their website.[5] The marginal approach forms a counterfactual of which plants would have produced more energy had a particular solar plant or wind plant never been constructed. This forecast accounts for which plants are already producing to isolate the characteristics of the marginal fossil fuel power plant or hydroelectric dam. This contrasts with the conventional technique of examining average emissions retrospectively.

We use the latest available full year of data. For the conventional emissions analysis, this is data from the Environmental Protection Agency's eGRID database for the year 2012. For the marginal emissions accounting analysis, this is data from the year 2015. For a clean comparison, we restrict our analysis to regions where eGRID subregions happen to match the grid balancing regions suggested by the Protocol.[6] Those regions are shown in Figure 1:

[5]These techniques have been operationalized by organizations like WattTime.org, an NGO co-founded by one of the authors. At WattTime.org, analysts can access a comprehensive database of the marginal emissions rate of electricity for any point in the continental United States, for any hour between 2006 and the present hour in real time. Now that at least one database of this type is readily available, it is no longer true that it is "difficult or impossible" to use ideally calculated marginal emissions factors for *OM*.

[6]The GHG Protocol guidelines notes that "[a]ccurately calculating both BM and OM emissions requires defining the boundaries within which electricity generation is displaced or avoided" (Broekhoff, 2005). In the United States, electricity is dispatched by the Balancing Authority or Independent System Operator. However, eGRID subregions often do not in fact match actual balancing authority or ISO borders but rather "transmission/distribution/utility service territory" borders (United States EPA & Associates, 2015).

Figure 1: Regions in our analysis

U.S. States	eGRID subregion	Gridbalancing Region
Roughly TX	ERCOT WECC	ERCOT
Roughly CA	California NPCC	Cal ISO
MA, CT, VT, NH, ME, RI	New England	ISO New England

We now calculate the foregone emissions per MWh from adding solar or wind farms to the electricity grid at a random location within these areas. To get generation profiles for wind and solar generation we use tools freely available from the Department of Energy and NREL respectively. We then take those profiles and compare them to the marginal emissions generated from fossil fuel generators most likely to be displaced by increased wind and solar generation when the wind blows and the sun shines using techniques akin to those in the economics literature discussed above. The results for wind and solar using the two methods are shown in Table 1.

Table 1: CO_2 emissions mitigated annually (tonnes per MWh)

Region	Wind (conventional)	Wind (marginal)	Solar (conventional)	Solar (marginal)
TX	0.5185	0.5327	0.5185	0.5302
CA	0.2950	0.4358	0.2950	0.4182
New England	0.2893	0.3651	0.2893	0.3648

The results are substantially different for some regions, as shown in Table 2 (values are marginal minus conventional results, divided by conventional).

Table 2: Emissions Difference tonnes CO2 per MWh

Region	Wind	Solar
TX	2.75%	2.26%
CA	47.75%	41.78%
New England	26.2%	26.07%

It is clear that for some regions, like Texas, there is little difference between using average and marginal emission factors. These are regions in which the marginal fuel happens to have roughly the emissions intensity of the total fuel mix. In Texas, for example, the lion's share of fossil fuel generation comes from a single source: natural gas. Yet for other regions like California and New England, the differences can be substantial. In New England, for example, the marginal generating unit which is "edged out" by wind or solar is generally a natural gas fired power plant, and is much dirtier than the average mix of coal, hydro, nuclear and large combined cycle natural gas plants which provide baseload electricity generation. In a region like TVA, results are similar to CA and New England because the fuel mix is varied.

Not only does this exercise show important accounting differences between the two methodologies within regions, but it also reveals large difference across regions. This has critical importance for efficiently reducing carbon footprints: carbon emissions are a uniformly mixing pollutant. Put another way, the atmosphere is equally impacted by a ton of carbon whether it is emitted in Tennessee or California. As a result, according to this model adding 1 MW of wind capacity in Texas reduces global carbon by significantly more than the same 1 MW in New England. The implication is that all else being equal, a 1 MW wind farm in California would be worth more RECs than an identical wind farm in New England if emissions are being counted accurately. Yet the traditional accounting method misses this.

This result has far-reaching implications for REC prices and investment in renewables. If watch-dogs like Greenpeace, firms like Microsoft, and states across the U.S. adopted "marginal" emissions accounting it would lead to the renewable projects which in reality reduce the most carbon. As a result, investors would receive a larger return for investing in those areas. The end result would be more carbon reduced, at a lower cost. The result is not surprising: better information leads to better decision making.

5   Implementing Marginal Accounting

We've noted that marginal carbon accounting can provide the right market signals to renewable energy investors and maximize carbon reductions, and shown that the potential emissions reductions from adopting such an approach can be significant. This section describes two different ways that the principles we outline here could be implemented in practice. To do so requires a very brief background on the legal and institutional structure of how renewable energy is currently counted under a market based approach.

Within the past two years, industry, government and environmental groups agreed upon a framework to recognize claims on the environmental attributes of renewable energy. Environmental attributes, like RECs, are denominated in MWhs of renewable energy generation. That is, each MWh of renewable energy which is generated from a windmill or a solar panel is counted and it generates an asset called a REC which is 1 MWh of renewable energy.[7]

There are two important technical issues with this system. First, the REC has a year associated with it: for example, a windfarm in TN which produces 1 MWh of electricity in 2016 creates a 2016 REC. Legally, the holder of that REC is entitled to the benefits associated with that 1 MWh of renewable energy. For example, utilities under renewable portfolio standards (RPSs) or firms with renewable targets might acquire RECs to meet energy targets.

Second, as a result of this system, a REC created at different hours of the day or in different regions are counted identically. This is problematic for the reasons described above: explicitly RECs are an instrument that currently allows for a "zero" GHG emissions claim from the purchase of electricity. Implicitly, though, this counts all RECs as offsetting CO_2 averaged over the entire nation's grid across all hours of generation rather than the ideal of using marginal emissions accounting. The U.S. Environmental Protection Agency (EPA) has acknowledged that this is problematic in the context of the clean power plan.[8] To that end, the EPA has created Emission Rate Credits (ERCs) which try to normalize for emission rates across different regions.

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[7]For some current industry best practices see http://media.virbcdn.com/files/62/53dc80177b9cc962-RE100CREDIBLECLAIMS.pdf
[8]See http://resource-solutions.org/site/wp-content/uploads/2015/10/Renewable-Energy-In-the-EPA-CPP-2.pdf, https://www.epa.gov/cleanpowerplan/fact-sheet-energy-efficiency-clean-power-plan and http://environment.law.harvard.edu/wp-content/uploads/2015/08/Emission-Rate-Credits-in-the-Clean-Power-Plan.pdf for descriptions.

Given that many firms and governments are counting renewable energy denominated in MWhs and ideal carbon accounting is denominated in offset CO2, any accounting system must be able convert the information regarding CO2 offset to MWhs which are the unit of account for firms and states. While this seems troublesome, it is actually straightforward to do using conversion factors with some straightforward properties. Intuitively, this is similar to any firm and employee counting overtime hours worked at 1.5 times the normal wage rate or holiday hours at 2 times the normal wage rate.

There are two characteristics which must be present in conversion factors which weight MWh of renewable generation by offset emissions using marginal accounting. First, the conversion factors must weight renewable generation which offsets more carbon intensive fossil fuel generation greater that renewable generation which offsets cleaner generation. Second, the after using conversation factors, to make accounting tractable under the current system the sum of actual total renewable generation must equal the sum of weighted total renewable generation after using conversion factors.

A good way to see how this works is with an example. Assume there are three locations (**a**, **b** and **c**) each of which generate 1 MWh of renewable electricity. Assume that each MWh of generation displaces different mixes of fossil fuels ranging from relatively dirty to relatively clean. For example, assume that the CO2 displaced in locations a, b and c are 1.5, 1 and .8 tonnes of CO2 respectively.

Under current MWh accounting rules this generation counts for 3 MWhs in RECs. Under marginal carbon accounting, it actually offsets 3.3 tonnes of CO2. In total the 3MWhs of generation had an average offset of 1.1 tonnes of CO2. However, in location **a**, the carbon offset was much larger than in location **c** (1.5 > .8). That can be reflected in the RECs accounting if the proportion of RECs accruing to location **a** as a percentage of the total is the same as the proportion of emissions offset in location **a** as a percent of the total. Specifically, an accurate MWh denominated accounting system for each location should be:

Table 3: Converting average accounting RECs to marginal accounting RECs

Location	Ratio	Conversion Factor	Converted REC MWhs
a	$\dfrac{X_a REC}{3REC} = \dfrac{1.5 \text{ tons } CO2}{3.3 \text{ tons } CO2}$	$X_a=1.36$	1.36
b	$\dfrac{X_b REC}{3REC} = \dfrac{1 \text{ tons } CO2}{3.3 \text{ tons } CO2}$	$X_b=.91$	.91
c	$\dfrac{X_c REC}{3REC} = \dfrac{.8 \text{ tons } CO2}{3.3 \text{ tons } CO2}$	$X_c=.72$	.73

NOTE: In this example 1.36 + .91 +.73 = 3. If total generation were different (e.g., 3, 4 and 5 for locations, a, b and c) then while the conversion factors remain identical, converted RECs would sum to 12 after normalization (e.g., multiplying 4.08, 3.64, 3.65 by 12/11.37 = 1.055 yields 4.31, 3.84, 3.85 which sums to 12).

Table 3 shows the two critical aspects of creating conversion factors described above. First, it up-weights generation in areas that offset carbon at above the average emissions rate (e.g., 1.5>1.1) and down-weights others. Second, the total number of MWhs remains the same (e.g., 1.36+.91+.73 = 3). Note that the technological innovation of measuring marginal emissions provides displacement rates which make this

possible (e.g., 1.5, 1 and .8). This is not fundamentally new and marginal emission rates have been around for years conceptually; the innovation is getting unbiased and finer granularity estimates.

The above system isn't the only way to implement marginal emissions to states and firms seeking to implement marginal emissions accounting. One alternative to a system like the one described above is to begin denominating RECs and renewable generation in terms of CO_2 offset from their generation. There would be costs and benefits to doing so. On the benefits side, it would be more straightforward if the goal is to count offset CO_2 equivalent. Conversion factors would change with both fuel prices and as the composition of power plants changes. As a result, conversion factors would have to be updated yearly. On the cost side, it would require new machinery and thinking on the part of industry participants in addition to a market maker which facilitates trades. Further, it is in some senses easier to perform quality control if renewable generators report hourly generation rather than hourly emissions offset which they themselves monitor. That said, the quality control imperative could be addressed by other means as well, such as random auditing.

Both MWh denominated marginal accounting with conversion factors and CO_2 denominated marginal accounting are possible. Either system would send the right signals to the market to align social and investor goals. As a result, either system solves the market shortcomings associated with the current approach since they leverage the recent innovation in measuring marginal emissions. The magnitudes are non-trivial: the above examples show that marginal emission accounting can give roughly 40% differences in emission offsets. For simplicity, assume that 20% of the revenue of a new windfarm is from selling the renewable attribute. The implication is that marginal accounting changes the return of investing in different locations by 8% (e.g., 8% = 20% * 40%), which is non-trivial.

Enforcement of Marginal Accounting & Additional Opportunities

Enforcing compliance with the above system is similar to enforcing what is currently in place. Power purchase agreements, state municipal level REC regulatory bodies and environmental watchdogs already mandate monitoring of hourly renewable generation profiles for solar and wind energy. Marginal accounting could possibly improve this process by having renewable generators report generation profiles in a uniform standard to a set of institutions which measure marginal emissions offset by renewable generation. The institutions, like WattTime.org, would be overseen by independent academic, NGO and government scientific panels much like EPA's current air dispersion models already are. RECs would be counted exactly as they are today after both generation profiles, but also after they are converted via marginal accounting.

There are four additional opportunities associated with a marginal accounting system, both of which would improve the signal to noise ratio further. First, currently RECs are associated with a wind or solar farm and a year but not a date nor hour. That can change to a system much like how the EPA handles the ethanol mandate with time stamped Renewable Identification Numbers (RINs) earned by transportation fuel blenders at minimal cost. This additional information allows for even more precision in monetizing actual carbon offset by renewable generation rather than noisy approximations.

Second, balancing concerns from renewables can impose external costs to the electrical grid. Renewable capacity is intermittent: PV panels produce power when the sun shines and turbines spin when the wind blows. Since system operators can't choose when the wind blows and the sun shines, as investors build additional renewable capacity it means there must be a supply of "ready to go" capacity which immediately generates if renewable suddenly stop producing due to short term weather conditions. Currently renewable investors aren't responsible for the additional costs to the system of increased capacity. Marginal accounting can quantify the

extent to which this effect influences dispatch behavior and therefore the emissions benefits of new renewable energy projects.

Third, there is a fundamental difference between increasing renewable generation and reducing emissions. For example, in regions like California with explicit and binding carbon caps, adding additional renewables doesn't directly impact total carbon since any carbon reduction anywhere in the state allows an increase somewhere else.[9] These are crucial additionality considerations for any emissions accounting framework, and are simpler to accurately account for in a system where the causal impact of each renewable generated MWh on fossil fuel emissions is accounted for.

Fourth, marginal emissions are not constant over time and can change with fossil fuel prices, installed generation capacity and the network of transmission lines. For example, long run investment decisions for renewables with marginal accounting is somewhat different than short run REC purchasing decisions. Just as high frequency traders use very different statistical models from "fundamental" or "long position" investors to value stocks, the measurement techniques currently used by WattTime.org might be less useful for forecasting marginal emission profiles 10- 15 years into the future, which is a more appropriate timeline for longer run investments. Any short run model estimating marginal emissions-which is most of the models with nationwide coverage-needs to be updated as prevailing market conditions change.

Finally, in this paper we've only focused on better accounting for emissions offset from renewable generation but there is a larger question of the right carbon footprint any firm or state should offset. If a firm consumes 100 MWhs of electricity in a coal burning region its carbon footprint is different than 100 MWhs of electricity consumed in a hydroelectric region. Denominating all electricity consumption in MWhs, rather than location based account associated with eGRID regional emission rates, can therefore be problematic. This consumption side of the market is subject to the same conceptual issues as those discussed above: to reach a certain level of "green" firms and states with clean generation profiles ought to be rewarded commensurately.

6. Discussion

The recent explosion of new marginal emissions analysis techniques in academia means it is now possible for analysts to directly measure the emissions impacts of renewable energy projects using the "ideal" form of the GHG Protocol for Grid-Connected Electricity Projects. There is an intuitive theoretical foundation for why these techniques should provide more accurate carbon accounting than the conventional workaround frameworks commonly in use today. A couple of simple examples show the impact of upgrading to more accurate techniques is not small. The market implications are far reaching because more accurate accounting can lead to more accurate price signals being sent to the investment market.

One interesting conclusion of this exercise is that the conventional model can underestimate the carbon benefits of newest renewable energy facilities. This is largely due to the fact that the conventional approach implicitly treats new renewable energy projects as if they were equally likely to displace highly emitting sources (such as gas and coal plants) and zero- carbon sources (such as nuclear facilities, wind, and hydro). Yet with the exception of hydro, nearly all zero-carbon resources are at the very bottom of the dispatch order, with zero or even lower effective marginal cost. Put another way, cleaner plants are often generating regardless of what demand for electricity is because, conditional on being built, they are cheap to operate. It strains credulity to

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[9]In states with carbon caps, renewable generation serves to decrease compliance costs of the cap by lowering permit prices. Similar complications exist for states with renewable portfolio standards (RPSs) and the U.S. EPA's Clean Power Plan (CPP).

suggest that a new renewable energy facility would be just as likely to displace energy from these facilities as from a high-cost plant which is frequently on the margin.

If REC purchasers and watchdogs begin indexing RECs created by the marginal rather than traditional accounting techniques it would also reduce the abatement cost per ton of carbon dioxide for companies buying renewable energy. The new techniques, because they capture hour-by-hour variation in local marginal emissions intensity, allow for analysts to distinguish between the emissions impacts of otherwise identical facilities based on the time and place that they generate electricity. In some cases, this variation can be very significant. Honest carbon accounting leveraging the recent advances could enable companies to deliberately site new renewable facilities at locations where they will displace the dirtiest energy possible. Thus, there is a very real social cost - higher carbon emissions at a higher cost - to inaccurate carbon accounting. This is a clear example where state level policy makers, in addition to national watchdogs and firms, can improve welfare by formally adopting better accounting practices.

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Appendix 1: Carbon Accounting Details

In this section we formalize and describe the accounting technique described in the GHG Protocol for renewable energy project accounting. The overall goal of the technique is to identify BE_T, the baseline emissions mitigated by a new renewable power plant in region r during time T (e.g. one year).

Analysts may divide T into sub-periods t, e.g. 8760 hourly periods in a year. BE_T is the sum of emissions in all sub-periods t. Each such sub-period's emissions total is found by multiplying the baseline emissions rate ER_{rt} (in tonnes carbon dioxide equivalent per megawatt-hour) by GEN_t, the electricity generated by the project's electricity output (in megawatt-hours) over that time period t. This is formalized as:

$$BE_T = \sum (ER_{rt} \times GEN_t) \qquad (1)$$

Accurately measuring GEN_t is a relatively straightforward exercise based on actual or forecast electricity production. The key to accurate carbon accounting is therefore a quality measure of the baseline emissions rate (ER_{rt}). This rate in turn depends on two factors:

First, construction of a new power plant will have immediate impacts on output levels from other nearby power plants, who will no longer need to produce as much energy. This is represented as the Operating Margin Emissions Factor, OM_{rt}.

Second, constructing a new power plant has a longer-term impact on the construction of other new power plants on the grid. The Protocol notes that when a new renewable energy plant is built, "another potential power plant either may not need to be built or can be reduced in size" (Broekhoff, 2005, p.13). These effects on incremental new capacity displaced by a new project and its associated generation are referred to as the Build Margin (BM).

In mathematical terms, the calculation of ERrt is thus:

$$ER_{rt} = \omega BM + (1 - \omega)OM_{rt} \qquad (2)$$

where ω is a factor representing the weight (between 0 and 1) representing the share of emissions that are "allocated" to the Build Margin.

Currently there is no single widely agreed upon method for determining an appropriate value of ω, and the Protocol offers only limited qualitative guidance on calculating BM. Developing a more detailed standard around those factors would be a matter of developing an industry consensus where none currently exists, and is outside the scope of this paper.

However, precisely estimating the Operating Margin Emissions Factor, OM_{rt} is a precisely answerable scientific exercise. It involves measuring the displacement of a new power plant on existing plant production. Perhaps due to this greater scientific clarity, conventional methods frequently focus primarily on estimating OM_{rt}. Therefore, the proper estimation of OM_{rt} is arguably the single most important factor for accurate emissions accounting.

Appendix 2: Stylized Example Details

In this appendix we describe additional characteristics of the renewable energy projects we analyzed to compare emissions accounting techniques. To assure the fairest apples-to-apples comparison, we analyze hypothetical power plants so that we can keep the different example plants of each fuel type artificially identical in all respects except their location. We analyze them using the following technique: First, we calculate the baseline emissions BE mitigated in time period T as follows:

$$BE_T \; = \sum (ER_{rt} \times GEN_t) \qquad\qquad (3)$$

Where baseline emissions rate, ER_{rt}, is a sum of BM and OM_{rt} with weight ω on BM (equation 2). As discussed above, in practice analysts frequently focus primarily on estimating OM_{rt}, the operating margin and it is arguably the single most important factor for accurate emissions accounting. Thus we estimate BE_T solely using OM_{rt} for the purpose of this comparison:

$$BE_T \approx \sum (OM_{rt} \times GEN_t) \qquad\qquad (4)$$

Next we define a time period T. For simplicity of the example, we use one year, the time period 2015. We divide the 2015 into 8760 hourly sub-periods t. Because the eGRID data are only available on an annual basis, OM_{rt} for total emissions analysis is a constant value for each region, r. For marginal emissions analysis, OMrt is variable for every hour, so we use that.

To get sample values for GEN_t, the electricity generated by the project's electricity output (in megawatt-hours) in one hour, we generate two annual production profiles for hypothetical wind and solar power plants. For this we use *PVWatts* by the National Renewable Energy Laboratory for the solar facility and the *WIND Toolkit* by the Department of Energy for the wind farm.[10]

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[10]We used common parameters for these hypothetical plants: Solar Plant (from PVWatts): 1-Axis Tracking, South Facing, Capacity Factor 23.7 percent. Wind Plant (from WIND Toolkit): NREL Sample Site ID 2235, Power Curve 3, Capacity Factor 43 percent.