Splitting the Electric Baby

A Methodology for Allocating Greenhouse Gas Emissions Reductions within the Electricity Sector

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Abstract

This paper presents a methodology for allocating greenhouse gas emissions reductions within the electricity sector. More narrowly, this paper addresses an issue that arises when certain emissions reductions result from decreasing the greenhouse gas intensity of electricity (i.e. reducing the pounds per MWh of generated electricity through policies like a renewable portfolio standard), while other simultaneous emissions reductions result from reducing the megawatt-hours consumed from the electric utility through energy efficiency. This paper presents an analytical solution to these issues that provides a foundation for a modeling methodology that properly allocates greenhouse gas emissions reductions within the electricity sector.

1. Introduction

A commonly used method for measuring greenhouse gas emissions is to multiply the total level of a particular activity (e.g., electricity consumption) by an emissions factor[1] associated with the same activity. This relationship is fundamental to estimating greenhouse gas emissions across sectors as diverse as electricity, natural gas, transportation, water, and even wastewater. However, though the relation may be simple and efficient for measuring total greenhouse gas emissions, it has limitations when used to estimate the emissions reductions[2] associated with a particular policy or activity. This paper highlights such a limitation found within the electricity sector. Specifically, this paper focuses on how to allocate greenhouse gas emissions reductions when certain policies reduce the rate of

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[1] In general, an emissions factor refers to a quantity of greenhouse gas emissions per unit of activity. For example, emissions factors for electricity are commonly presented with units of pounds of carbon dioxide equivalent per megawatt-hour of electricity consumed (lbs CO_2e/MWh).

[2] Generally, and for the purposes of this paper, emissions reductions refers to reductions in greenhouse gas emissions resulting from a greenhouse gas mitigation measure (e.g., a renewable portfolio standard, energy efficiency measures, etc.)

emissions (i.e. the emissions factor) while other policies reduce the level of activity (i.e. the amount of commodity consumed).[3] For example, one way to reduce greenhouse gas emissions in the electricity sector is to require utility companies to purchase a percentage of their electricity supply from renewable resources. The Renewable Portfolio Standard (RPS) in California requires electric utilities and energy service providers to supply 33% of their electricity from renewable sources by the year 2020.[4] Another policy approach to mitigate greenhouse gas emissions associated with electricity generation is to implement measures that result in lower electricity consumption. This commonly includes providing incentives for homeowners to do energy efficiency retrofits.

The fundamental issue in allocating greenhouse gas emissions reductions within the electricity sector is that not all mitigation measures reduce emissions in the same way. RPS policies reduce emissions by reducing the emissions factor (a rate), while energy efficiency measures reduce emissions by reducing the total amount of consumed electricity (a quantity).

2. Illustration of the Problem

This section illustrates the problems surrounding allocating greenhouse gas emissions reductions when certain mitigation measures affect the emissions factor (a rate) and other mitigation measures affect consumption (a quantity). When the various mitigation measures are considered sequentially, inaccurately favoring either rate-related measures or quantity-related measures is unavoidable.

For the purposes of illustration, assume the following:

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[3] Certain greenhouse gas mitigation measures affect greenhouse gas emissions simultaneously, and not independently from one another. Properly allocating reductions in greenhouse gas emissions between various greenhouse gas mitigation measures is both important and not necessarily straightforward.

[4] http://www.cpuc.ca.gov/PUC/energy/Renewables/

1. The electricity emissions rate before any mitigation is implemented is 500 lbs CO_2e/MWh (unmitigated electricity emissions rate[5]);
2. the RPS policy reduces the unmitigated electricity emissions rate by 100 lbs CO_2e/MWh;
3. the annual quantity of electricity consumption for a single residential home before any mitigation is 6 MWh (unmitigated electricity consumption); and,
4. if the same residential home undergoes an energy efficiency retrofit, then annual electricity consumption for that home will be reduced by 1 MWh.

Since this hypothetical involves both a mitigation measure affecting a rate (RPS) and a mitigation measure effecting consumption (efficiency retrofit), an issue arises regarding how to properly allocate the emissions reductions. If the effects of both mitigation measures are determined sequentially, then there are at least two possible calculation methods. The first method considers the effects of RPS *before* considering the effects of the efficiency retrofit ("Method 1"), and the second method considers the effects of RPS *after* considering the effects of the efficiency retrofit ("Method 2"). Each method yields the same total reduction. The focus here is how to allocate that total reduction.

2.1. Method 1: Rate First, Quantity Second

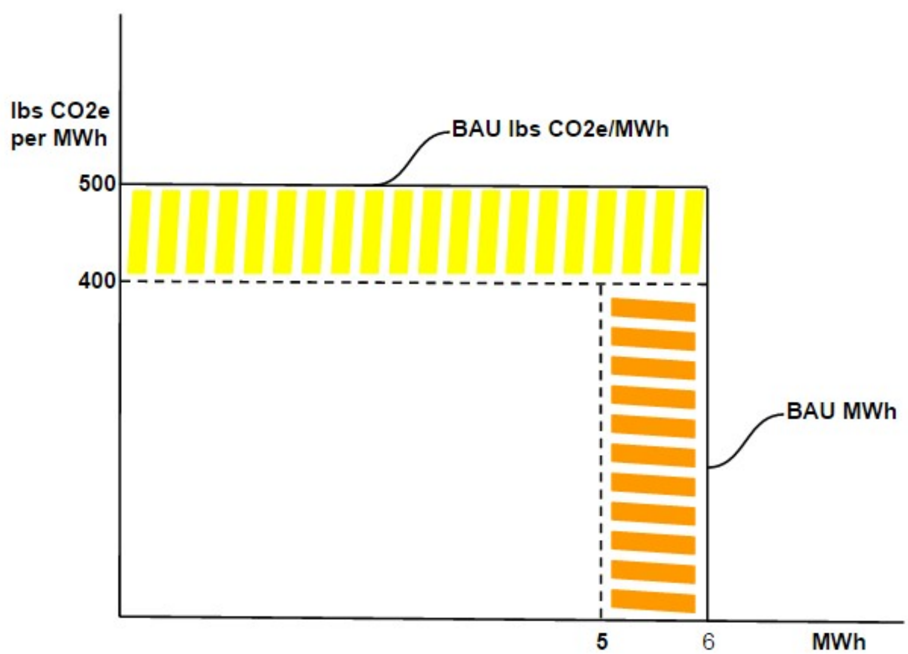
In Method 1, the effects of RPS are considered *first* (independent of the effects of the efficiency retrofit). In this scenario, the emissions reductions due to RPS are calculated as a function of the *unmitigated* annual electricity consumption. Using the above assumptions, the emissions reductions due to RPS within our single residential home are 600 lbs CO_2e/MWh per year (100 lbs

5 The "unmitigated electricity emissions rate" and the "business-as-usual emissions rate" are used interchangeably and both refer to the value of electricity emissions factor before considering the effects of any greenhouse gas mitigation measure.

CO_2e/MWh x 6 MWh) and the emissions reductions due to the efficiency retrofit are 400 lbs CO_2e/MWh per year (400 lbs/MWh x 1 MWh). Summing the emissions reductions for both mitigation measures results in total emissions reductions of 1000 lbs CO_2e per year.

Method 1 will overestimate the effects of RPS and an understatement of effects of the energy efficiency measure. Figure 1 below illustrates this graphically. The electricity emissions rate is on the vertical axis and the electricity consumption is on the horizontal axis. Using Method 1, the yellow box shows reductions attributable to RPS, and the orange box shows reductions attributable to the efficiency retrofit.

Figure 1: Allocation of Greenhouse Gas Emissions Reductions Between RPS and Efficiency Measures Using Method 1

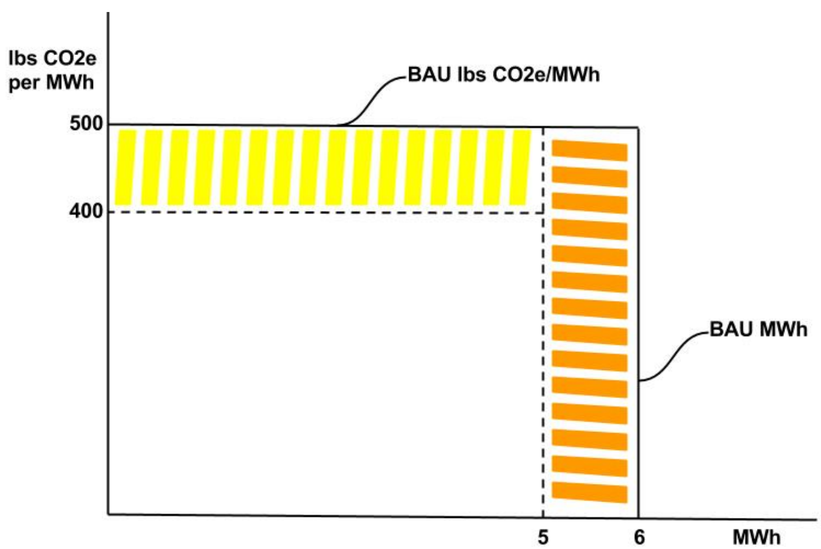


2.2. Method 2: Quantity First, Rate Second

In Method 2, the effects of the efficiency retrofit are considered *first* (independent from the effects of RPS). Here, the emissions reductions attributed to energy efficiency are determined by multiplying the *unmitigated* electricity emissions factor by the reduction in consumed electricity. This would result in emissions reductions of 500 lbs CO_2e for energy efficiency (1MWh reduction x 500lbs/MWh unmitigated electricity emissions rate) and 500 lbs CO_2e for RPS (100 lbs CO_2e/MWh x 5MWh of mitigated electricity consumption). Again, the sum of the emissions reductions for both measures equals 1000 lbs CO_2e per year.

Method 2 will yield an overestimate of the effects of the efficiency retrofit and an understatement of the effects of the RPS. Figure 2 below shows this graphically. The emissions rate is on the vertical axis and the electricity consumption is on the horizontal axis. Here using Method 2, the yellow box shows reductions attributable to RPS, and the orange box shows reductions attributable to the efficiency retrofit.

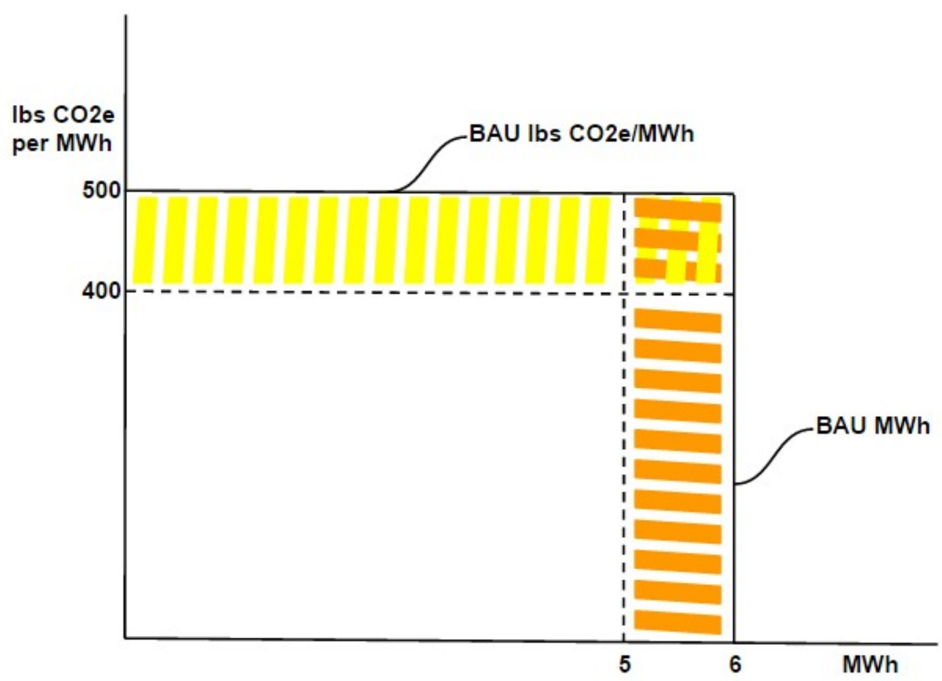
Figure 2: Allocation of Greenhouse Gas Emissions Reductions Between RPS and Efficiency Measures Using Method 2



2.3. The Problem

The issue is that when the emissions reductions for the two types of mitigation measures (rate reducing measures and quantity reducing measures) are determined sequentially, neither is accurate. The measure type calculated first will overestimate emissions reductions, and the measure type calculated second will underestimate emissions reductions. Figure 3 below highlights the issue graphically. If the effects of RPS are calculated first, then the emissions reductions defined by the upper right box (both yellow and orange) are attributed entirely to RPS. Conversely, if the effects of the efficiency retrofit are considered first, then the same emissions reductions defined by the upper right box are entirely attributed to the efficiency retrofit.

Figure 3 Illustration of the Problem



The tables below summarize the results from Method 1 and Method 2. Notice that both methods yield the same overall greenhouse gas emissions.

Table 1 Comparison of Methods

Method 1		
Emissions Reductions Due to RPS	600 lbs CO_2e	Overestimate
Emissions Reductions Due to Efficiency Retrofit	400 lbs CO_2e	Underestimate
Total Emissions Reductions	1000 lbs CO_2e	Accurate

Method 2		
Emissions Reductions Due to RPS	500 lbs CO_2e	Underestimate
Emissions Reductions Due to Efficiency Retrofit	500 lbs CO_2e	Overestimate
Total Emissions Reductions	1000 lbs CO_2e	Accurate

The problem evolves from the original decision to measure total emissions reductions in terms of the product of a rate and a sum.[6] Invariably, the two are dependent variables, and are inseparable. However, inaccuracy in the allocation of emissions reductions can be minimized. The following sections derive more accurate expressions for the emissions reductions associated with the two key emissions reductions components (RPS, which is a rate; and efficiency measures, which are quantities).[7]

3. Analytical Derivation of Method 1 and Method 2

This section presents analytical derivations for Method 1 and Method 2 explained earlier. Both Method 1 and Method 2 define greenhouse emissions levels over time as a function of an emissions rate (lbs CO_2e/MWh) and a consumption level (MWh). Method 1 considers the effects of

[6] Note that both Method 1 and Method 2 arrive at the correct *total* emissions reductions (the sum of the emissions reductions due to RPS and the emissions reductions due to the efficiency retrofit); it is the allocation of emissions reductions between the two mitigation measure types that is inaccurate.
[7] Specifically, the following sections derive expressions that quantify (1) the emissions reductions entirely attributable to rate-related measures like RPS, and (2) the emissions reductions that are entirely attributable to consumption-related measures like an efficiency retrofit, and (3) expressions that allocate the emission reductions that are inseparably a function of both the rate-related and consumption-related measures.

rate-based mitigation measures[8] (e.g. RPS) before considering the effects of consumption-based mitigation measures[9] (e.g., energy efficiency measures). Conversely, Method 2 considers the effects of consumption-based mitigation measures before considering the effects of rate-based mitigation measures.

3.1. Derivation of Method 1

Method 1 and Method 2 begin by defining the foundational emissions measurement relation in terms of the electricity sector.

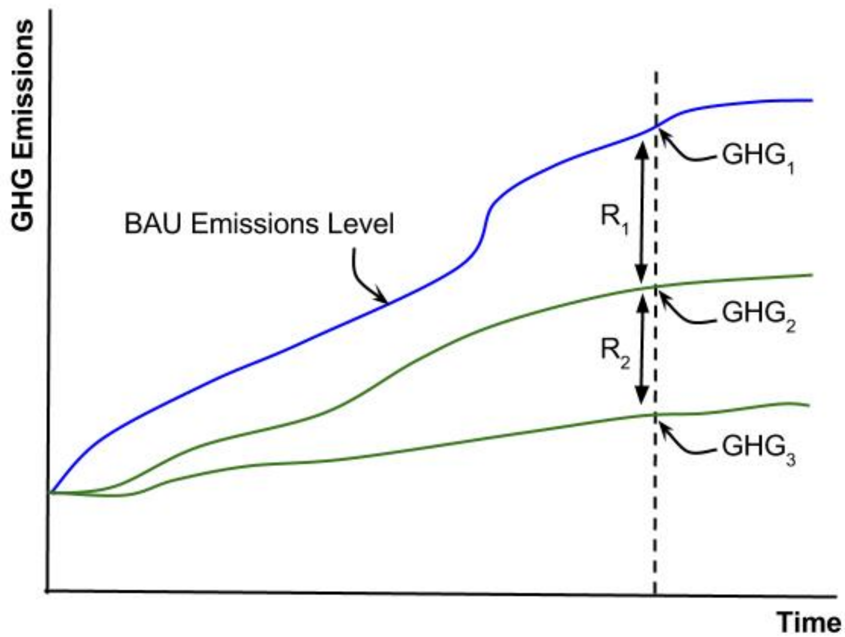
$$GHG_1 = NC$$

where N is the baseline electricity emissions factor, in terms of pounds of carbon dioxide equivalent per MWh, and C is the total business-as-usual consumption (MWh). With the business-as-usual emissions level defined, the next step is to determine the reductions in greenhouse gas emissions due to the rate-based measures ("RB measures"), as well as the quantity-based measures ("QB measures"). Figure 4 graphically illustrates the key components in both Method 1 and Method 2.

For simplicity's sake, we derive Method 1 using a single RB measure (RPS), and a single QB measure (residential efficiency retrofits). In practice, the effects of many mitigation measures can be aggregated into groups comprising entirely RB measures and entirely QB measures. The relationships that are identified and quantified here apply regardless of the size of the RB group or CB group.

[8] "Rate-based mitigation measures" is abbreviated to "RB measures" throughout the remainder of the paper.
[9] "Consumption-based mitigation measures" is abbreviated to "CB measures" throughout the remainder of the paper.

Figure 4: Business-As-Usual GHG Emissions Level, GHG Reductions, and the Mitigated GHG Emissions Level



In Method 1, emissions reductions resulting from the RPS are determined first. The reductions due to RPS are,

$$R_1 = (N * \%_{RPS})C = \%_{RPS}NC$$

where R_1 is the reduction in greenhouse gas emissions considered *first*. In Method 1, R_1 refers to the reductions due to the Renewable Portfolio Standard. $\%_{RPS}$ is the fraction of electricity provided by renewable energy resources.

Therefore,

$$GHG_2 = GHG_1 - R_1 = (1 - \%_{RPS})NC$$

Next, the reductions in emissions due to energy efficiency measures are determined.

$$R_2 = N(1 - \%_{RPS})\lambda$$

where R_2 is the reduction in greenhouse gas emissions considered *second* (sequential to R_1), and λ is equal to the sum in MWh of the total energy offset by energy efficiency measures. R_2 must be a function of $(1 - \%_{RPS})$ to avoid allocating more emissions reductions than where actually reduced.

Notice,

$$GHG_3 = GHG_2 - R_2 = (1 - \%_{RPS})NC - (1 - \%_{RPS})N\lambda$$

which can be simplified to:

$$GHG_3 = N(1 - \%_{RPS})(C - \lambda)$$

The above expression represents the total greenhouse gas emission levels after reductions due to the Renewable Portfolio Standard and energy efficiency measures have been considered. Notice that the expression comprises three primary components: (1) the electricity emissions factor N, (2) the electricity emissions factor reduction component $(1 - \%_{RPS})$, and (3) the net consumption value $(C - \lambda)$.

Of crucial importance to this derivation is the observation that the expression representing GHG_3, while correct, was arrived at by making one key assumption. The reductions in emissions resulting from the Renewable Portfolio Standard were considered *before* the reductions in emissions resulting from energy efficiency measures. This election necessarily creates a second possible method for determining GHG_3, where the reductions in emissions resulting from the Renewable Portfolio Standard are considered *after* the reductions in emissions resulting energy efficiency measures.

As noted before in Section 2.3, if the effects of energy efficiency measures are considered *before* the effects of the RPS, the expression for GHG_3 will remain the same. That is, the total greenhouse gas reductions using either method are the same. However, there is great value in performing the derivation for the alternate method because it establishes a range of values for the reductions attributable to the renewable portfolio standard, as well as a complimentary range of reductions attributable to efficiency measures.

3.2. Derivation of Method 2

As noted, the initial emissions level is the same in both methods because it is the product of the baseline electricity emissions factor and the total consumption.

$$GHG_1 = NC$$

Here, R_1 is again defined to be the reduction in emissions considered *first*, however now the reductions resulting from energy efficiency measures are considered first.

$$R_1 = N\lambda$$

Again as in Method 1, notice:

$$GHG_2 = GHG_1 - R_1 = N(C - \lambda)$$

Next the reductions due to the Renewable Portfolio Standard are considered.

$$R_2 = (N * \%_{RPS})(C - \lambda)$$

where, again as in Method 1, R_2 is the reduction in greenhouse gas emissions considered *second* (sequential to R_1).

Notice,

$$GHG_3 = GHG_2 - R_2 = N(C - \lambda) - (N * \%_{RPS})(C - \lambda)$$

which can be simplified to:

$$GHG_3 = N(1 - \%_{RPS})(C - \lambda)$$

As expected, the final result for GHG_3 is the same in both Method 1 and Method 2. However, having only completed the basic derivation for GHG_3, accurate expressions for the emissions reductions due to the Renewable Portfolio Standard, and efficiency measures remain to be determined.

4. A Method for Allocating Emissions Reductions

A necessary consequence of considering the reductions due to the Renewable Portfolio Standard efficiency measures sequentially, is that the component considered second will be smaller than if the same component had been considered first.

For example, the reductions due to the Renewable Portfolio Standard were considered first in Method 1, and second in Method 2.

$$\text{Method 1, Reductions due to RPS} = \%_{RPS}NC;$$

$$\text{Method 2, Reductions due to RPS} = \%_{RPS}N(C - \lambda)$$

Notice, the apparent reductions for the same mitigation measure are larger in Method 1, where they were considered first:

$$\%_{RPS}NC > \%_{RPS}N(C - \lambda)$$

The same phenomenon expectedly appears for the reductions resulting from energy efficiency measures. Reductions from efficiency measures were considered first in Method 2, and second in Method 1.

$$\text{Method 2, Reductions due to Energy Efficiency } = N\lambda;$$

$$\text{Method 1, Reductions due to Energy Efficiency} = (1 - \%_{RPS})N\lambda$$

Notice again, the apparent reductions for the same mitigation measure are larger in Method 2, where they were considered first:

$$N\lambda > (1 - \%_{RPS})N\lambda$$

The two expressions for each of the two emissions reductions components are useful in that they establish a range for allocating the emissions reductions. The larger of the two expressions for each component represents a maximum value, and the smaller of the two expressions for each component represents a minimum value.

For the Renewable Portfolio Standard emissions reduction component:

$$Max\ Value = \ \%_{RPS}NC$$

$$Minimum\ Value = \%_{RPS}N(C - \lambda)$$

and for energy efficiency emissions reduction component:

$$Max\ Value = \ N\lambda$$

$$Minimum\ Value = (1 - \%_{RPS})N\lambda$$

An easy check to confirm that the expression for the maximum and the minimum for each emissions reductions component is correct is to set their ranges equal to each other.

The range for the Renewable Portfolio Standard emissions reduction component is,

$$Range_{RPS} = \%_{RPS}NC - \%_{RPS}N(C - \lambda) = \%_{RPS}N\lambda$$

and the range for energy efficiency emissions reduction component is,

$$Range_{EE} = N\lambda - (1 - \%_{RPS})N\lambda = \%_{RPS}N\lambda$$

Checking that the ranges of the two reduction components are equal confirms the mathematics, but also aligns with intuition. Notice the range is comprised of two expected components: (1) the amount by which the electricity emissions factor has been scaled by the Renewable Portfolio Standard $(\%_{RPS}N)$, and (2) the amount by which the consumption has been reduced λ. With upper and lower limits established for both of the emission reduction components, the next step is to allocate the range between the two components.

4.1. Allocating the Range Between the Two Types of Mitigation Measures

The next step in the derivation is to determine what proportion of the range to allocate to each of the emission reduction components.

Stepping back from the derivation, it should be clear that in going from the business-as-usual greenhouse gas emissions level GHG_1 to the mitigated greenhouse emissions level GHG_3, the reductions are real. For each MWh of electricity actually consumed, the decreased amount of actual emissions released into the atmosphere are a result of either the Renewable Portfolio Standard, or efficiency measures, individually or in the aggregate. When considered on a large-scale, all of the effects of the Renewable Portfolio Standard and efficiency measures are considered in the aggregate.

In view of the aggregate perspective and on larger scales, the range identified by the two primary methods should be allocated according to the relative weight of each reduction component. In other words, if there were no Renewable Portfolio Standard, then the reduction component for efficiency measures would be equal to $(1 - \%_{RPS})N\lambda$, where $\%_{RPS}$ is zeroed out. This case would result in entire range being allocated to efficiency measures, resulting in total reductions equal to $N\lambda$ (the maximum value).

However, for cases where neither of the two reduction components equal to zero, it becomes necessary to develop expressions that weigh the relative contribution of each component. Below is a method to achieve this goal.

First, the weight of each emissions reductions component is expressed as a fraction of its related business-as-usual variable.

$$i_1 = (1 - \%_{RPS}); \;\; i_2 = \frac{C - \lambda}{C}$$

where i_1 is the weighting factor for the Renewable Portfolio Standard component, and i_2 is the weighting factor for the energy efficiency component. Weighting the factors in this way has two immediate benefits. First, each weighting factor accurately captures the extent to which the reduction factor affects the related variable (where the related variable for $\%_{RPS}$ is the electricity emissions factor N, and the related variable for λ is the total consumption C). Second, i_1 and i_1 both scale from zero to one, thereby allowing direct relative weighting.

Next, we weigh the two weighting factors against each other, thereby allowing the range to be allocated. Let,

$$a = \frac{i_1}{i_1 + i_2}, \qquad and \qquad b = \frac{i_2}{i_1 + i_2} \qquad where\ \ a + b = 1$$

So, the fraction of the range allocable to the Renewable Portfolio Standard emissions reduction component is,

$$a(\%_{RPS} N\lambda) \quad where \quad a = \frac{(1 - \%_{RPS})}{(1 - \%_{RPS}) + \frac{C - \lambda}{C}}$$

and the fraction of the range allocable to energy efficiency reduction component is,

$$b(\%_{RPS} N\lambda) \quad where \quad b = \frac{\frac{C - \lambda}{C}}{(1 - \%_{RPS}) + \frac{C - \lambda}{C}}$$

With expressions for how to allocate the range between the two reduction components, final expressions can be determined.

4.2. Final Expressions for the Two Type of Mitigation Measures

There are two ways to express each of the reduction components. Each can be expressed as the maximum value less the allocated range, or the minimum value plus the allocated range. For simplicity and consistency, the former is chosen.

$$\text{Effect of RPS} = \%_{RPS} NC - a(\%_{RPS} N\lambda) \quad where \quad a = \frac{(1 - \%_{RPS})}{(1 - \%_{RPS}) + \frac{C - \lambda}{C}}$$

$$\text{Effect of EE } = N\lambda - b(\%_{RPS}N\lambda) \quad where \quad b = \frac{\frac{C-\lambda}{C}}{(1-\%_{RPS}) + \frac{C-\lambda}{C}}$$

The above two expressions represent final solutions. Each respectively measures the reductions in emissions resulting from either the Renewable Portfolio Standard, or from energy efficiency measures. The range of values for each reduction component resulting from the two calculation methodologies is allocated between the components according to relative weight. Using this range allocation structure maximizes accuracy. The accuracy is discussed in detail in Section 4.4.

4.3. Final Check

Checking the final solutions is straightforward. Beginning with the proposition that the final emissions level will equal the business-as-usual emissions level less the effects of RPS and energy efficiency allows direct substitution of our solutions.

$$GHG_3 = GHG_1 - (\text{Effect of RPS}) - (\text{Effect of Energy Efficiency})$$

Next, the solution expressions are substituted and manipulated:

$$GHG_3 = NC - \left(\%_{RPS}NC - a(\%_{RPS}N\lambda)\right) - \left(N\lambda - b(\%_{RPS}N\lambda)\right)$$

$$GHG_3 = NC - \%_{RPS}NC + a(\%_{RPS}N\lambda) - N\lambda + b(\%_{RPS}N\lambda)$$

Since $a + b = 1$,

$$a(\%_{RPS}N\lambda) + b(\%_{RPS}N\lambda) = \%_{RPS}N\lambda$$

The solution simplifies:

$$GHG_3 = NC - \%_{RPS}NC - N\lambda + \%_{RPS}N\lambda$$

$$GHG_3 = N[C - \%_{RPS}C - \lambda + \%_{RPS}N\lambda]$$

$$GHG_3 = N[C(1 - \%_{RPS}) - \lambda(1 - \%_{RPS})]$$

Finally, the final emissions level GHG_3 is shown to be equal to solutions derived in Method 1 and Method 2 above.

$$GHG_3 = N(1 - \%_{RPS})(C - \lambda)$$

4.4. Real-World Application

The following presents a basic illustration of the above principles using real-world values for key variables. Assume the following values:

Key Variable	**Value**
N (Business-as-Usual Electricity Emissions Factor)	725 lbs CO_2e/MWh
$\boldsymbol{\%_{RPS}}$ (Percent of Delivered Electricity Generated from Renewable Resources)	20%
C (Total Business-as-Usual Consumption)	9 Million MWH
$\boldsymbol{\lambda}$ (Total MWh offset by Energy Efficiency Measures)	1 Million MWh

The business-as-usual greenhouse gas emissions level GHG_1 is the same in Method 1 and Method 2:

$$GHG_1 = NC = 2.9\ MMT\ CO2e$$

Using Method 1 and our defined values, we can calculate the apparent emissions reductions allocations for the RPS component and for the energy efficiency component:

$$\text{Reductions due to RPS} = \%_{RPS}NC = 596{,}026\ MMT\ CO2e$$

$$\text{Reductions due to Energy Efficiency} = (1 - \%_{RPS})N\lambda = 264{,}901\ MMT\ CO2e$$

Now using Method 2 and our defined values, we can calculate the different apparent emissions reductions allocations for the RPS component and for the energy efficiency component:

$$\text{Reductions due to RPS} = \%_{RPS}N(C - \lambda) = 529{,}801\ MMT\ CO2e$$

$$\text{Reductions due to PV and Energy Efficiency} = N\lambda = 331{,}125\ MMT\ CO2e$$

Notice, as shown above, for each reduction component the apparent emissions reductions is larger when the component is considered first and smaller when the same component is considered second.

Next, the range for each component is determined,

$$Range_{RPS} = \ \%_{RPS}NC - \%_{RPS}N(C - \lambda) = \%_{RPS}N\lambda = 66{,}225\ MMT\ CO2e$$

$$Range_{EE} = N\lambda - (1 - \%_{RPS})N\lambda = \%_{RPS}N\lambda = 66{,}225\ MMT\ CO2e$$

As expected, the ranges for both emissions reductions components are equal. The numerical example is useful as an illustration of just how significant the range can be. Here, using real-world values, the range is over 10% of the Renewable Portfolio Standard component, and over 20% of the energy efficiency component. Since the range represents maximum and minimum values for both components, there exists the possibility for significant overestimation or underestimation resulting from using either Method 1 or Method 2 to determine the apparent emissions reductions for either component.

Since the two emissions reduction components do not contribute to the overall emissions reductions equally, the range cannot be allocated equally between them. Using our analytical solutions derived above, the range can be allocated according to relative component weight. Again, our expressions for the weighted emissions reductions allocations are:

$$\text{Effect of RPS} = \%_{RPS}NC - a(\%_{RPS}N\lambda) \quad where \quad a = \frac{(1-\%_{RPS})}{(1-\%_{RPS}) + \frac{C-\lambda}{C}}$$

$$\text{Effect of Energy Efficiency} = N\lambda - b(\%_{RPS}N\lambda) \quad where \quad b = \frac{\frac{C-\lambda}{C}}{(1-\%_{RPS}) + \frac{C-\lambda}{C}}$$

Before solving for the final emissions reductions allocations, it's useful to note the weighting values. Here, $a = 0.474$ and $b = 0.526$, indicating that with the given set of real-world values, the energy efficiency measures have a greater weight in pulling the business-as-usual curve down towards the mitigated overall emissions level.

Finally, plugging our defined values into these expressions yields,

$$\text{Effect of RPS} = 564{,}657\ MMT\ CO2e$$

$$\text{Effect of Energy Efficiency} = 296{,}270\ MMT\ CO2e$$

The solution can be checked by calculating the final greenhouse gas level GHG_3 as derived in Method 1 and Method 2.

$$GHG_3 = N(1-\%_{RPS})(C-\lambda) = 2{,}119{,}205$$

Finally, taking the difference between our business-as-usual greenhouse gas emissions level for the electricity sector GHG_1 and the weighted emissions reductions components should yield the value for GHG_3 calculated above.

$$GHG_3 = GHG_1 - (\text{Effect of RPS}) - (\text{Effect of EE Measures})$$

$$GHG_3 = 2{,}980{,}132 - 564{,}657 - 296{,}270 = 2{,}119{,}205 \quad [MMT\ CO2e]$$

Thus, the weighted allocations of the emission reduction components are correct.

Notice the delta that results from using either Method 1 or Method 2 when real-world values are used for the input variables:

Method 1	**Apparent Allocation**	**Corrected Weighted Allocation**	**Delta**
RPS Component	596,264 MMT CO2e	564,657 MMT CO2e	- 5.3%
EE Component	264,901 MMT CO2e	296,270 MMT CO2e	+ 11.8%
Method 2	**Apparent Allocation**	**Corrected Weighted Allocation**	**Delta**
RPS Component	529,801 MMT CO2e	564,657 MMT CO2e	+ 6.6%
EE Component	331,126 MMT CO2e	296,270 MMT CO2e	- 10.5%

Notice that the variance in the apparent reductions resulting from energy efficiency measures spans ±10% using either Method 1 or Method 2. Further, while the selected real-world values used in this numerical example are not inconsistent with values found in many climate planning documents, the real-world values can justifiably vary quite considerably. Variance in the real-world values obviously can have a significant effect upon the overestimation and underestimation associated with attempting to use the apparent emissions reductions allocations from Method 1 or Method 2.

5. Conclusion

Climate planning documents regularly feature forecast greenhouse gas emissions curves that just barely hit a desired future emissions target. Further, interested parties frequently and contentiously debate underlying assumptions that comprise individual mitigation measures out to the very last decimal. For this reason, avoiding unnecessary uncertainty, oftentimes in excess of ±10%, is extremely important. The analytical solutions for allocating emissions reductions derived in this paper offer emissions and climate modelers a refinement over previous methodologies that increases accuracy and minimizes error.