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ABSTRACT

This paper discusses the development and implications of American National Standards designed to evaluate the long term CO_2e emissions in buildings. Standards for both residential and commercial buildings that evaluate CO_2e impact using hourly energy use to project long term CO_2e emissions are discussed. The fact that the accounting methodology is hourly instead of annual is of significant importance as both building energy use and the emission intensity of the electricity utility grid vary by time of day and season. Additionally, on-site fuel choices have large impacts, especially with respect to forecasting long term emission impacts. As carbon emissions in electric utility grids are reduced through the use of renewable resources, energy storage and distributed energy resources, the impact of on-site combustion fuels on long-term emission forecasts becomes increasingly preponderant. Since buildings last for many decades, forecasting the future electricity grid is critically important. Electric-sector planning models can be used to create forward-looking emission metrics that are useful to the building community in long term building energy emission forecasting and in understanding how the grid may evolve over time. The development of the 2021 Cambium database by the U.S. National Renewable Energy Laboratory (NREL) satisfies this need for future electricity grid forecasting for the U.S. Similar databases should be developed for other grids. There are also U.S. Environmental Protection Agency (EPA) Greenhouse Gas (GHG) Protocol Scope 3 implications embedded in the use of these standards.

This paper discusses two American National Standards that were developed to address CO_2e emissions emanating directly from building energy use – one for residential dwelling units and the second for commercial buildings. Both are intended to evaluate the CO_2e implications of current and future building energy design decisions, where CO_2e includes methane (CH_4) and nitrous Oxide (N_2O) as well as carbon dioxide (CO2) GHG emission equivalents. The U.S. Residential Energy Services Network (RESNET) has incorporated a CO_2e Index in ANSI/RESNET/ICC Standard 301, which is used by ASHRAE Standard 90.2 to determine compliance for residential dwelling units and ASHRAE is incorporating a zero carbon emission factor (zCEF) for compliance with ASHRAE Standard 189.1 for commercial buildings. Both standards utilize the Cambium database to forecast future electricity grid emissions. Both standards use combined pre-combustion plus combustion long-run marginal CO_2e emissions rates ($LRMER\_CO_2e$) applied against hourly energy use to evaluate long term emissions. Both standards assume the NREL low-cost renewable energy scenario for determining the future fuel mix of the electric grid. Both Standards also use the Cambium Generation and Emission Assessment (GEA) regions for geographic grid sensitivity.

INTRODUCTION

The Sixth Assessment Report (AR6) of the Intergovernmental Panel on Climate Change (IPCC) is the direst warning to date of the potential for catastrophic impacts of climate change on the ecosystems of the planet. These climate and ecosystem impacts may result in "irreversible change." Different people respond to information of this sort in different ways. While many people find this IPCC report and its predecessors compelling enough to inspire action, other people are more strongly motivated by stories and examples.

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In this spirit we also observe that climate change affects each of us individually. Two authors of this paper recently experienced first-hand impacts or threats from climate change. One author experienced this at 11 am on September 9, 2020 when the view in the photo confronted him from his home: a dark orange sky (the picture shows the true color) that made midday look like late twilight.

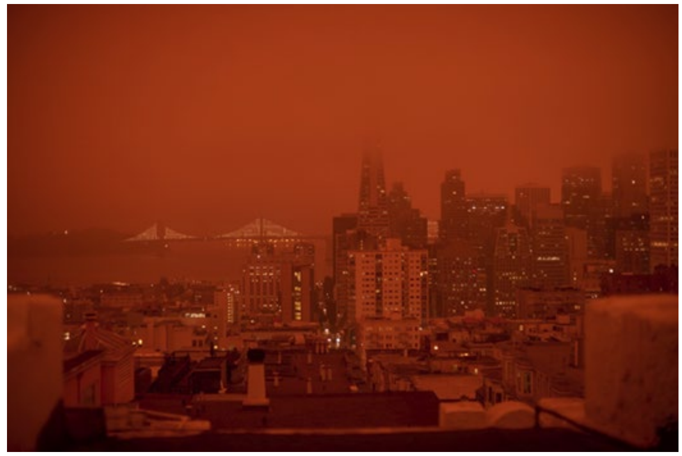

Photo credit: David B. Goldstein 2022

On the next day the smoke – from wildfires 500 miles away linked to climate change (Denchak and Turrentine 2021) – descended to breathing level and produced some two weeks of extremely unhealthy air, extending from north of Portland, Oregon to Los Angeles, California (Limaye 2020).

Climate change is not a distant threat affecting strangers across the ocean. It is a crisis that has already arrived on our doorsteps.

As a professional society, ASHRAE has taken the strong position that "Climate change is the most formidable environmental challenge ever faced by society" (ASHRAE June 27, 2018). It has also taken the position that opportunities exist within the HVAC&R industry to provide solutions to reduce GHG emissions, including demand reduction, building energy efficiency and renewable energy. Among the actions that ASHRAE recommends is the development of improved GHG emissions performance metrics for determining emissions performance of building operations and the development of standards supporting the minimization of GHG emissions in the building sector. This ASHRAE position is now directly expressed in the development of GHG emissions criteria within ASHRAE Standard 189.1 (ANSI/ASHRAE/ICC/USGBC/IES Standard 189.1-2017).

Climate change is driven in large part by carbon dioxide emissions and in the U.S. some 36 percent of these emissions result from burning fossil fuels to power, heat, and cool buildings, with more than 20 of that 36 percent from residential buildings **(**Langevin, Harris and Reyna 2019**)**. This 36 precent figure is about the same as the global fraction of emissions from buildings. All of these figures are approximate because they depend on specific resolutions of the issues of how to count emissions that are addressed in this paper.

The Residential Energy Services Network, Inc. (RESNET) promulgates ANSI/RESNET/ICC 301, "Standard for the Calculation and Labeling of the Energy Performance of Dwelling and Sleeping Units using an Energy Rating Index." The RESNET 301 Standard now incorporates a CO_2e Index that assesses the GHG emissions performance of residential dwelling units. This RESNET 301 Standard is used by ASHRAE Standard 90.2 to determine residential energy performance compliance. The 90.2 SSPC is now considering how it will use the CO_2e Index to complement the Energy Rating Index that is used to determine compliance with the 90.2 Standard.

REDUCING BUILDINGS' CONTRIBUTION TO CLIMATE CHANGE

Improving our buildings or other parts of our economy – to reduce or eliminate these emissions is called "Decarbonization." Decarbonization of our buildings is critical if we hope to meet the climate goal of reducing U.S. emissions by well over half by 2030 (IEA 2021 and Goldstein 2018).

Decarbonization of buildings can be achieved through:

- Increasing the energy efficiency of our buildings,
- Adding renewable energy to a facility or the grid,
- Changing the time at which electricity is consumed so that most, or all of it, can be supplied by renewables – like solar and wind power, and
- Changing from a fuel with higher emissions to electricity (Mejia-Cunningham 2021)

Decisions have often been guided by generic studies of historical annual average emissions, or simple heuristics. There is a need for more sophisticated and consistently-applied data, methods and standards to improve our ability to compare across a variety of Decarbonization measures.

A number of considerations are important in the development of standards and procedures for evaluating the long-term GHG emissions in buildings. Of particular importance are the following:

- Determination of the upstream pre-combustion GHG emissions of primary fuels
- Development of rational scenarios for potential changes in electricity generation systems
- Forward-looking electric utility levelized long-run marginal emission rates
- A framework into which the evaluation methodology can be inserted

FORWARD-LOOKING ELECTRIC UTILITY EMISSIONS

When estimating the GHG emission impacts of design and operational choices for electricity consumption in buildings, it is best to look forward. There are two reasons. First, in regions where the electrical grid is undergoing transformation, the intensity of emissions from electricity may change meaningfully over the lifetime of a building (a condition that applies to many areas of the world, as the goals set by the UNFCCC require a rapid acceleration of already-aggressive investments in renewable electricity generation (IEA 2021)). Second, choices about the timing and magnitude of electricity consumption in buildings can influence which electric generators are built. For example, electrifying services in buildings and preferentially adding load during times with high-quality renewable resources (i.e., when the sun is shining and the wind is blowing) can induce more non-emitting generators to be built. This is particularly relevant for jurisdictions that have certain types of clean energy polices – such as Renewable Portfolio Standards in the United States, which are legally binding requirements to serve a certain percentage of the electric load from renewable sources. The structure of this standard implies that each new kWh of load will cause the construction of sufficient new capacity in renewable energy to supply the required percentage of consumption.

Such forward-looking phenomena can be captured with power sector models and summarized for the building industry in accessible, actionable metrics, such as a long-run marginal emission rate (LRMER). A LRMER is a forward-looking estimate of the rate at which emissions are expected to be induced or avoided by changes in electricity demand. It incorporates both the projected changes to the electric grid, as well as the potential for a building's load to influence the operation and investments on the grid (i.e., the building and retiring of capital assets, such as generators). The LRMER is distinct from the short-run marginal emission rate, which treats grid assets as fixed, and therefore does not incorporate how electric loads can influence capital assets. By omitting new capacity, a short-run approach can overestimate the emissions from electrification and miss important diurnal trends (Gagnon and Cole 2022).

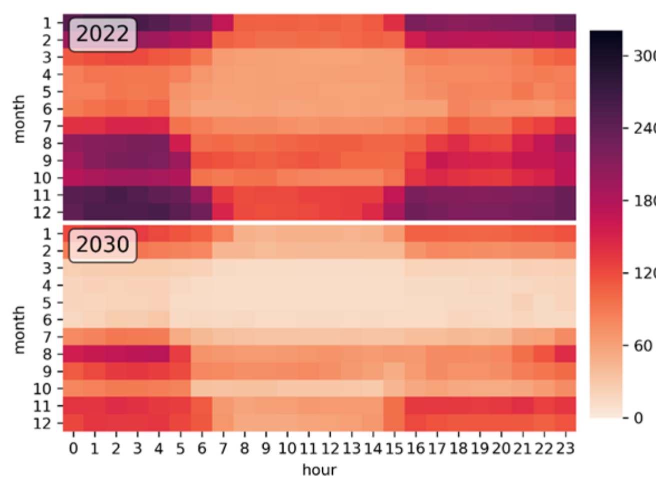

Figure 2: Example LRMERs for the California, U.S., from the Low Renewable Energy Cost scenario of the 2021 Cambium data set. The top panel are values starting in 2022 and the bottom for 2030, both levelized for a 20-year lifetime with a 3% discount rate. Units are kg of CO_2e per MWh of electricity consumption, considering both combustion and precombustion.

Two examples of LRMER values are given in Figure 2, for the state of California in the U.S., for analyzing an electric load installed in either 2022 or 2030. Recall that these values are an estimate of the rate at which CO_2e emissions would be induced or avoided by a change in end-use electricity consumption – i.e., it is not a description of the current emissions intensity of the grid, but rather an estimate of the emissions consequences of changes in electricity consumption. Two phenomena are apparent: First, the values decrease meaningfully over time. Secondly, there are prominent diurnal and seasonal trends, caused by the projected role of wind and solar generators in the evolution of the local electric sector– adding or shifting load to hours with abundant renewable generation is projected to induce less emissions, as demand during those hours would be served in greater proportion by non-emitting generators.

The types of factors exemplified by Figure 2 can be used to guide building design choices – multiplying these factors by the changes in load of an electrified HVAC system or alteration of an energy efficiency measure estimates the greenhouse gas emissions impacts of the alternatives, helping guide the related choices.

The LRMER values in Figure 2 are from the publicly available Cambium data sets (Gagnon, Hale and Cole), which are created by the U.S. National Renewable Energy Laboratory. These values are calculated by employing power sector models (ReEDS, an NREL-built capacity expansion model that projects the structural evolution of the power sector and PLEXOS, a commercial production cost model that simulates the hour-to-hour operation of the evolving grid). Combined, these models project potential futures of the power sector, assuming that the grid will be built and operated to minimize costs subject to policy and operational constraints. The LRMER values themselves are calculated by running both of the models twice, holding every assumption about the future constant except adding an increase in electricity demand in the second set of runs. By comparing the generation mixtures in the "baseline" model run and the "perturbed" model run, we can estimate what generation types will be induced by increased load (or avoided by decreased load). More detailed documentation can be found in (Gagnon, Frazier, Cole and Hale 2021). There is significant uncertainty in such forward-looking projections, so the Cambium data sets contain LRMER values for multiple potential futures (e.g., relatively higher or lower costs of renewable generation), and users are encouraged to analyze their design and operational choices in light of the range of possible values.

This process can be replicated in other countries, to create LRMER values for places beyond the U.S. This can be done by employing similar power sector models and using them to estimate how a change in load may induce changes in the operation and structure of the grid. For example, (Hawkes 2014) used a model of the British electricity system to calculate LRMER factors for that region. Alternatively, (Vandepaer, Tryer, Mutel, Bauer and Amor 2018) gives an example of how one might draw from existing electric sector projections to estimate long-run electricity mixtures. Heuristics may also be appropriate. The Greenhouse Gas Protocol's Guidelines for Quantifying GHG Reductions from Grid-Connected Electricity Projects (Broekhoff) describes a heuristic method that involves estimating an "operating margin" (roughly, generation from existing generators) and a "build margin" (roughly, generation from new generators) and combining them with weights. Heuristics can be particularly appropriate in regions with certain types of electric-sector policies. If a region has a policy that mandates that a certain fraction of electric load is met with non-emitting generation, for example, that may facilitate a reasonably accurate estimate of how changes in electric demand would change electric-sector emissions without having to use a power sector model. Whether produced with heuristics or models, the resulting metrics can then be used to guide decisions in the buildings sector.

RESNET STANDARD 301-2022 AND ASHRAE STANDARD 90.2

RESNET is a Non-Governmental Organization (NGO), which is an ANSI-accredited Standards Development Organization focusing on the energy performance of residential buildings. The RESNET Standard applicable to this discussion is ANSI/RESNET/ICC 301-2022, Addendum B. This addendum establishes a CO_2e Index for residential dwelling units.

While the methodology used for this Addendum is intended for asset ratings of residential buildings, it is equally applicable to operational ratings and to nonresidential buildings. It is also usable, possibly with some small adjustments based on local low-voltage distribution, for industrial energy users.

RESNET 301 Standard defines CO_2e as the summation of the upstream pre-combustion GHG emissions of CO_2, CH_4 and N_2O plus the combustion emissions for those same gases. The building fuel emission values are taken from the literature (Deru and Torcillini; Littlefield, et al.) and are modified by the IPCC Sixth Assessment Report (AR6) Global Warming Potential (GWP) values for the 100-year time horizon, which are 1.0 for CO_2; 29.8 for CH_4; and 273 for N_2O.

For forward-looking electric utility emissions, the Cambium database is used to determine the levelized, long-run marginal emission rates (LRMER) for the combined pre-combustion plus combustion emission rates for the low renewable cost scenario, levelized over the 25-year period of 2025 through 2050. Month-hour averages are used to create the 8760 hourly emission rates that are applied against the projected hourly electric energy uses in dwelling units that are rated in accordance with the RESNET 301 Standard.

The Cambium database is comprised of 134 utility balancing areas that are assigned to 20 Cambium Generation and Emission Assessment (GEA) regions across the contiguous U.S shown in Figure 3. These Cambium GEA regions mimic the EPA eGRID sub-regions (which are often used for retrospective emissions assessments). The principal and important distinctions are that the Cambium data consider the forward-looking changes in electricity generation and are hourly projections that can be applied against hourly energy use data to evaluate the long-term, time-of-day CO_2e impacts of energy use in buildings. This lends itself to a number of valuable benefits, including the evaluation of thermal and energy storage impacts that shift energy use from times of more intensive emissions to times of less intensive emissions.

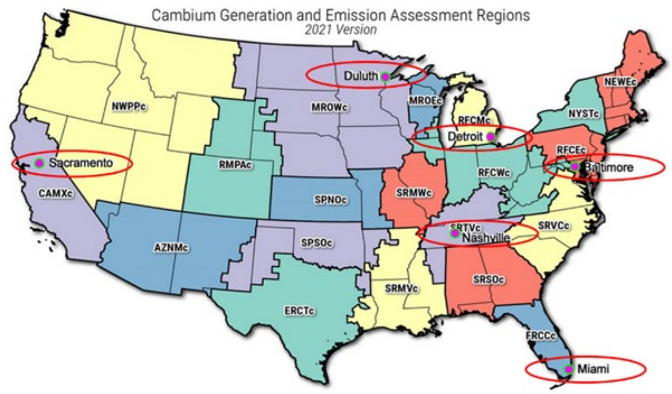

Figure 3. Cambium GEA Regions showing city location for six simulation examples.

The CO_2e Index utilizes these Cambium data to compare the projected emissions of a Rated dwelling unit with the emissions of a CO_2e Index Reference dwelling unit. The CO_2e Index Reference dwelling unit has the same geometric configuration as the Rated dwelling unit. The Reference dwelling unit is configured to have the enclosure energy features required by the 2006 International Energy Conservation Code (IECC) and the equipment and appliance efficiency characteristics of the minimum U.S. federal standards in 2006. The CO_2e Index Reference dwelling unit uses electricity for all energy end uses.

The CO_2e Index is calculated using the following equation:

$$CO_2e\ Index = \frac{ACO2}{(ARCO2 \times IAF_{RH})} \times 100$$

where:

ACO2 = total annual hourly CO_2e emissions of the Rated Home, lbs/y (kg/y)

ARCO2 = total annual hourly CO_2e emissions of the CO_2e Index Reference Home, lb/y (kg/y)

IAF_{RH} = Index Adjustment Factor for the CO_2e Index Reference Home, unitless

Using the EnergyGauge® USA software (v.7.0.03), the CO_2e Index calculations were exercised in the six locations illustrated in Figure 3: Detroit, MI; Nashville, TN; Baltimore, MD; Miami, FL; Duluth, MN; and Sacramento, CA. These particular location were selected because they represent the full range of GEA emissions encompassed by the Cambium database as illustrated in Figure 4 as well as a full range contiguous U.S. climatic conditions ranging from IECC Climate Zones 1 through 7.

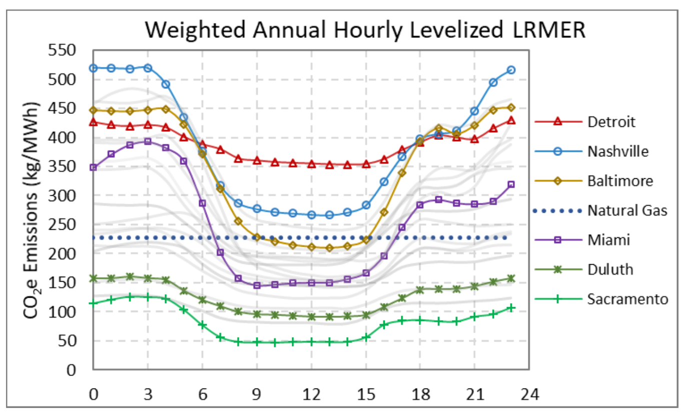

Figure 4. Weighted annual hourly levelized LRMER values for 20 GEA regions showing the range of cities examined in simulations.

Two-story, 2400 ft^2 (223 m^2), 3-bedroom, frame homes configured to comply with the minimum requirements of the 2018 IECC serve as the example simulations. Four equipment, lighting and appliance configurations are examined for each home:

Base: ERI Reference HVAC, DHW, Lighting and Appliances
HE: High Efficiency HVAC, DHW, Lighting and Appliances
PV: HE case with 4 kWp-dc PV system
PVbatt: PV case with 13.5 kWh battery storage

For each configuration scenario both an all-electric and a mixed-fuel home are simulated. The equipment efficiencies are Seasonal Energy Efficiency Ration (SEER)=16, Heating Season Performance Factor (HSPF)=.-9.6 and Uniform Efficieny Factor (UEF)=2.50 for the all-electric HE (High Efficiency) homes and SEER-16, Annual Fuel Utilization Factor (AFUE)=0.95, UEF 0.83 for the mixed-fuel HE homes. All appliances for the HE homes are minimum ENERGY

STAR qualified. Lighting in the HE homes is 90% high efficiency LED (90 lumens/watt) and 10% incandescent (15 lumens/watt).

The RESNET 301 Standard is the calculation procedure used in the U.S. for determining the Energy Rating Index (ERI) of a dwelling unit. The ERI is similar to the CO_2e Index in that it evaluates the relative energy performance of a Rated dwelling unit with respect to a 2006 vintage Reference dwelling unit in virtually the same manner as does the CO_2e Index. However, for the ERI, the Reference dwelling unit case has the same fuel type as Rated dwelling unit case. The ERI calculation procedure is also used by RESNET to calculate the HERS® Index, which is identical in value to the ERI but requires quality assurance oversight by RESNET.

Results of these simulations illustrate the correspondence between the ERI and the CO_2e Index across the full range of GEA regions and contiguous U.S. climatic locations. Tables 1 and 2 give the ERI and CO_2e Indices, respectively for the Rated Homes. It is clear from these two tables that the ERI scores are much more consistent across fuel types than the CO_2e Index scores.

Table 1. Energy Rating Index (ERI) for all Rated dwelling unit cases

Energy Rating Index (ERI - dimensionless)								
Location	Mixed-fuel homes				Electric Homes			
	gasBase	gasHE	gasPV	gasPVbatt	elecBase	elecHE	elecPV	elecPVbatt
Detroit	81	59	36	37	81	62	39	40
Nashville	76	53	26	27	76	54	27	28
Baltimore	78	58	30	30	78	57	31	32
Miami	78	52	21	21	77	51	20	21
Duluth	80	58	39	39	80	63	46	46
Sacramento	70	49	15	16	70	49	15	16

Table 2. CO_2e Index for all Rated dwelling unit cases

C0₂e Index (dimensionless)								
Location	Mixed-fuel homes				Electric Homes			
	gasBase	gasHE	gasPV	gasPVbatt	elecBase	elecHE	elecPV	elecPVbatt
Detroit	94	75	54	54	84	62	42	41
Nashville	86	64	44	41	81	56	37	34
Baltimore	92	71	55	51	82	59	43	40
Miami	102	67	45	40	88	57	34	30
Duluth	205	172	160	158	79	67	55	53
Sacramento	200	157	138	131	76	49	33	28

For two locations, Duluth and Sacramento, the CO_2e Index is very large for the mixed-fuel homes (highlighted in the tables). This occurs because, as shown in Figure 4, the reference case CO_2e emissions are quite small in these GEA regions. This results in the CO_2e emissions of the Rated dwelling unit case being much larger than the CO_2e emissions of the Reference dwelling unit case as shown in Table 3.

Table 3. Annual CO_2e emissions for Reference and all Rated dwelling unit cases

CO_2e Emissions (tons)									
Location	Reference Case	Mixed-fuel homes				Electric Homes			
		gasBase	gasHE	gasPV	gasPVbatt	elecBase	elecHE	elecPV	elecPVbatt
Detroit	9.48	8.94	7.09	5.15	5.10	7.97	5.88	3.94	3.92
Nashville	8.31	7.13	5.33	3.68	3.41	6.69	4.69	3.04	2.83
Baltimore	7.96	7.33	5.68	4.42	4.07	6.51	4.71	3.41	3.16
Miami	4.43	4.54	2.99	1.99	1.79	3.90	2.51	1.51	1.34
Duluth	4.07	8.34	7.00	6.51	6.41	3.23	2.72	2.23	2.16
Sacramento	1.56	3.13	2.46	2.15	2.05	1.19	0.83	0.52	0.44

ASHRAE STANDARD 189.1 AND zCEF

Standard 189.1 is a green building standard that is also the technical content of the International Green Construction Code (IgCC). The performance approach for compliance with this standard requires that the operational carbon emissions be estimated and shown to be less than the target emissions. The target emissions are set as a percentage of the emissions of a stable baseline building, which is defined in Appendix G of ASHRAE Standard 90.1 and roughly represents a building in compliance with the 2004 version of Standard 90.1. Standard 189.1 and the IgCC are updated every three years and with each update the target emissions are lowered.

The standard defines the zero-carbon emissions factor (zCEF) to be the ratio of carbon emissions of the proposed design to the carbon emissions of the baseline building. A zCEF of zero means that the operational carbon emissions of the proposed design are expected to be zero. A zCEF of 1.0 would mean that the proposed design emissions would be equal to the baseline building. Standard 189.1 references the energy efficiency requirements in Standard 90.1 but adds additional measures and makes some of the 90.1 requirements more stringent. More importantly, Standard 189.1 requires a minimum amount of renewable energy to be installed on site and/or procured from acceptable off-site generators. There are two terms that set the zCEF target:

1. The expected improvement in energy efficiency compared to the baseline building. This is expressed as a building performance factor (BPF) and represents the reduction of carbon emissions for the regulated components of building energy use, compared to the baseline building.
2. The renewable fraction (RF) which is the faction of building energy use that that should be met by on-site or off-site solar, wind, or other renewable energy systems.

These two terms (BPF and RF) are used in the following equation to set the target, based on the estimated GHG emissions of the baseline building, which are separated into those resulting from regulated energy use (GHGRBB) and unregulated energy use (GHGUBB). With each update of Standard 189.1 / IgCC, the BPF will be reduced and the RF increased.

$$zCEF_{TARGET} = \frac{[GHG_{UBB} + (GHG_{RBB} \times BPF)] \times (1 - RF)}{GHG_{UBB} + GHG_{RBB}}$$

The GHG emissions for both the proposed design and the baseline building are calculated by multiplying the electricity use, fossil fuel use and thermal energy use by an appropriate emissions rate. The electricity emissions rate is highly sensitive to the mix of electric generators used to produce the power and range from a low of 180 kg/MWh in the cleanest US grids to a high of 920 kg/MWh in the dirtiest electric grids. The emission rates for electricity, fossil fuels, and thermal energy all include not only the combustion emissions, but also the pre-combustion emissions related to extraction, process and delivery. Methane (CH_4) and nitrous oxide (N_2O) are considered in addition to carbon dioxide (CO_2). Methane leaks are a significant portion of the pre-combustion emissions for natural gas.

The zCEF concept is added in the 2023 version of Standard 189.1, but the requirement to model carbon emissions and compare them to a baseline has existed since the inception of the standard in 2009. The current emission rates are retrospective and based on the latest information from the US Energy Information Agency (EIA) and Environmental Protection Agency (EPA). However, the standards development committee is working with NREL to take a more forward-looking approach and incorporate long-run marginal emissions rates (LRMER). The intent is to add LRMER to the standard as a jurisdictional option to replace the use of the retrospective eGRID emission rates. The jurisdictional option will be especially important in areas of the US with a large contribution of renewable energy already on the grid or areas where significant growth is expected in the near term. The increased time granularity of LRMER, will encourage behind-the-meter energy storage and give proper credit to on-site solar contributions which often align with periods of low carbon intensity.

CONCLUSIONS

RESNET has developed a method for calculating greenhouse gas emissions from residential buildings in the United States that is suitable for encouraging building designs that minimize cumulative greenhouse gas emissions in line with the goals set by the IPCC. ASHRAE is developing parallel methods. Both methods are capable of being expanded to address other categories of utility customers, to address operational ratings, and to work anywhere in the world. This paper has explained the methods used and the rationale for making the choices that were made.

Meeting climate goals will require metrics to allow comparison of what is being done now to what was planned as a way of guiding future decisions. The metrics described here allow the process of continual improvement to optimize residential buildings as well as other energy consuming entities for minimum societal greenhouse gas emissions.

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