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Design to Thrive

The Carbon Balance Index: a simple metric for progress toward zero-net carbon

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In North America, "Architecture 2030" has established targets for reducing building fossil fuel use to zero by 2030, now called "zero net carbon" (ZNC). This paper introduces the Carbon Balance Index (CBI) as a simple metric that allows performance comparison along a spectrum from typical buildings that depend entirely on fossil fuels to those that export energy, comparing a range of carbon performance. CBI assesses greenhouse gas production (as CO_2 equivalent) relative to a typical building's carbon use intensity (CUI), using EUI data categorized by climate and building type. CUI is equal to the building's EUI times a CO_2e conversion factor/s based on fuel type/s used. CBI is defined as the designed building's net CUI divided by the CUI of a typical building, expressed as a percentage. The methods for calculating CUI benchmarks, the designed building's CUI and CBI are explained in simple terms. Building on earlier work on the Energy Balance Index (EBI), the CBI and EBI targets, curves and zero points are compared. Carbon-neutral buildings have CBI = 0. Positive CBI means some fossil fuels are used and carbon is produced, while negative CBI projects "consume" carbon by exporting excess energy and offsetting fossil grid energy.

Keywords: zero net carbon, carbon-neutral, carbon use intensity, energy balance index, carbon metric

Introduction

There are many definitions for net-zero carbon buildings (Riedy, et al, 2011), zero emissions buildings (RCOZEB, 2017), net-zero energy (Sartori, et al, 2012), among many others. What seems like a simple concept, "zero carbon," can get complicated with issues of lifecycle boundary, operation and construction carbon, building type, climate, grid source energy types and interconnections, spatial boundaries, etc. The question might then be, "Why do we need the subject of this paper, a new carbon metric for buildings?" The reason is not so much about building science precision as it is about the urgency of climate change and expediency of simplicity. As Simon Sinek (2015) puts it, "Simple ideas are easier to understand. Ideas that are easier to understand are repeated. Ideas that are repeated change the world." In this realm, we need simple.

In the North America, the Architecture 2030 organization has done a good job at making the challenge for the building community clear and simple with their 2030 Targets. The "2030 Challenge" sets targets, shown in Fig. 1, for designers to reduce fossil fuel use incrementally, culminating in *carbon-neutral* building performance by the year 2030 for all new construction and major renovations (Arch 2030, 2011).

At PLEA 2016, DeKay and Giddings (2016) presented the *Energy Balance Index* (EBI) to assesses energy performance relative to a typical building's *Energy Use Intensity* (EUI) based on climate and building type. The EBI shows that, depending on the level of imported renewables, the 2030 target of "carbon-neutral" can achieve a performance level of *site net-zero energy*, or in some cases something 20% short of that target. The paper finished with

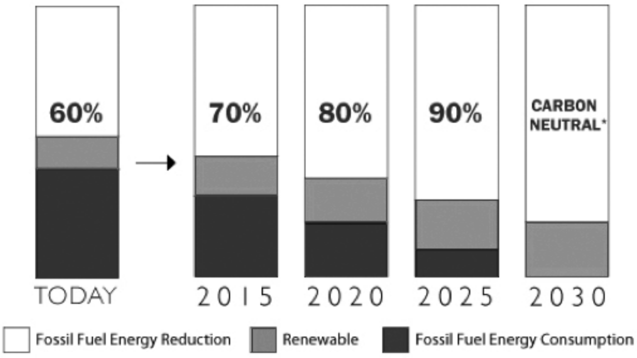

FIGURE 1: Targets for fossil fuel reduction

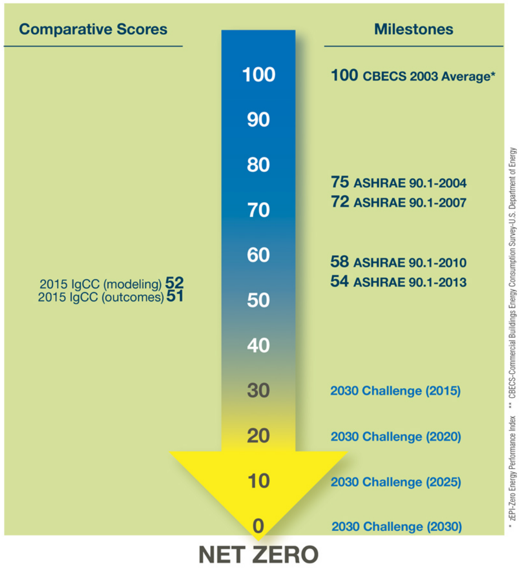

FIGURE 2. zEPI Scale from NBI

outlining the need for and giving a preliminary definition of the *Carbon Balance Index* (CBI), now developed further in this paper.

The Issues and Need for a Carbon Index

The need to define an index for carbon performance in buildings came about in part because of numerous related definitions, and the desirability of understanding the relative carbon performance or one building to another, rather than simply the absolute production or consumption value of greenhouse gases. For example, the US EPA's Target Finder allows a relative score for energy, but reports carbon use in "total GHG Emissions," (metric tons CO_2e). This is in contrast to Energy Use Intensity (EUI), which is expressed in energy per unit of floor area per year, and can thus be compared with benchmarks and with other buildings similar in case. Like for energy use, there is a need for measuring carbon on a "more stable, absolute scale that would be used to benchmark buildings, as opposed to the typical percent-better-than-code metric" (NBI, 2017).

Recently, Architecture 2030, along with the New Buildings Institute (NBI, et al, 2016) defined *Zero Net Carbon* (ZNC) as "a highly energy efficient building that produces on-site, or procures, enough carbon-free renewable energy to meet building operations energy consumption annually." In defining "net zero" as linked to carbon and delinked from the building's site boundary, the NBI's coalition has 1) Put the focus on operational energy and carbon, 2) Established a simple legible approach for the complex issues of energy and carbon balance, and 3) Focused the building community on making progress toward solving climate change that is widely inclusive of many building types and site contexts. It aligns with Architecture 2030's emphasis on cities and urban buildings, which in many cases lack good access to solar energy. This is all good, *and* there are problems, the main one being that there is no way to align carbon and energy at any other place on the implied ZNC scale.

Figure 2 shows the *Zero Energy Performance Index* (zEPI) scale as promoted by the New Buildings Institute (2016). Note that this is an *energy* scale with 100 set at the EUI of a benchmark building and zero for "net-zero" energy, with the year 2030 target, which is "carbon-neutral," meaning no fossil fuels used in building operation, aligned to zero. This

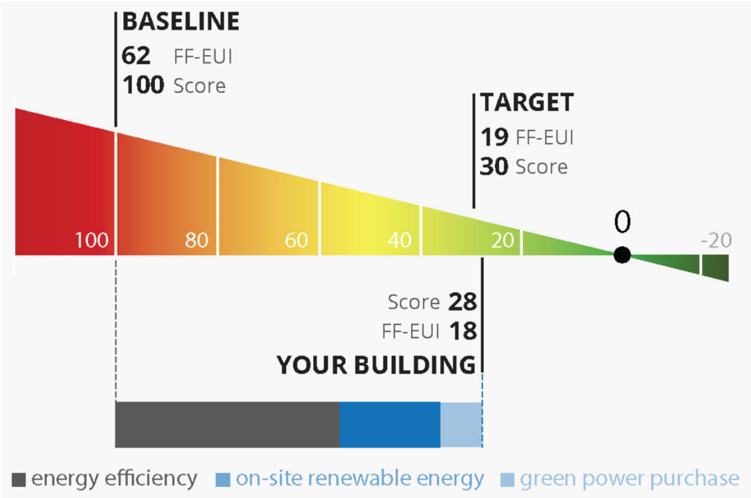

FIGURE 3: The "Zero Scale" by Arch 2030

"net-zero" definition allows imported renewables and so is *not* "site" net-zero energy or carbon. The new Architecture 2030/NBI definition of ZNC also aligns with zero on the zEPI scale, essentially conflating energy and carbon—simple, but rather, too simple.

During the writing of this paper, Architecture 2030 (2017) released the "Zero Scale," shown in Fig. 3, along with an on-line tool to replace the EPAs Target Finder, a zEPI-like linear scale based on fossil fuel EUI (FF-EUI). It upgrades the previous approach to the 2030 Targets by making clear the role of on-site renewables and sets ZNC at zero. It is, however, not a carbon scale but, rather, a fossil energy scale—for the main reason that it makes no distinctions among the GHG impacts of various fuels. For example, the CO2*e* of grid-supplied electricity and natural gas are treated equally by the surrogate measure of total fossil fuel use.

Dekay and Giddings (2016) showed that because Architecture 2030's guidelines for its influential 2030 Targets allows 0-20% of the fossil fuel reduction target to be met by imported off-site renewables, a confusion can arise about the meaning of the year 2030 "carbon-neutral" target and terms like net-zero energy, site net-zero carbon, etc. The ZNC solves the confusion about the meaning of zero carbon in the 2030 Targets, by allowing on-site or procured renewables to balance the scale. It does not however, allow users an easy way to calculate something comparable to the 2030 targets for fossil fuel use, which is tied to benchmark EUI for a building type and climate, or offer how to extend these into the future. The ZNC/zEPI approach also collapses the distinction between the emissions offset value of on-site renewables, which have no grid losses or transportation fuel consumption, and off-site renewables, which do (See Table 1). This paper and its CBI solve all three of the above problems. The *Carbon Balance Index* allows performance comparison along a spectrum from typical buildings that depend entirely on fossil fuels to those that export energy, comparing a range of carbon performance.

TABLE 1 Emissions factors for grid-supplied and renewable electricity in the US and Canada
Sources: Environment Canada, Natural Resources Canada, and ASHRAE

CANADA CO_2e EMISSIONS, NATIONAL AVERAGES	
Fuel Type	**Emissions Rate CO_2e lbs / kWh (kg / kWh)**
Electricity, grid displaced	N/A
Electricity, off-site renewable	–0.441 (–0.200)
Electricity, Canada, average	0.441 (0.200)

USA CO_2e EMISSIONS, NATIONAL AVERAGES	
Fuel Type	**Emissions Rate CO_2e lbs / kWh (kg / kWh)**
Electricity, grid displaced	–1.835 (–0.083)
Electricity, off-site renewable	–1.670 (–0.758)
Electricity, USA, average	1.670 (0.758)

Method

Carbon Use Intensity Benchmark

The CBI is a way to compare a building's greenhouse gas production, as CO_2 equivalent (CO_2e) relative to a typical building's *Carbon Use Intensity* (CUI), using EUI data categorized by climate and building type. In the same way that EUI is widely used to describe and compare a building's energy performance, the Carbon Use Intensity (CUI) method was expanded by DeKay and Brown (2014, p 280–291), based on work developed by Bryan (2009). The CUI, with units of CO_2e lbs/ft^2/yr (or CO_2e kg/m^2/yr) is used as the basis to develop the CBI, accounting for the relative impacts of different fuels and renewables on CO_2e. CUI is equal to the building's EUI times a CO_2e conversion factor/s based on the emissions rate of the fuel type/s used. To convert site EUI to Carbon Use Intensity (CUI) multiply by the CO_2e conversion factor:

$$\text{CUI} = \text{EUI} \times CO_2e \text{ conversion factor}$$

EPA's Target Finder tool (2012) gives the typical percentage mix of gas and electricity use for the building's region. These percentages can be used along with the average building EUI to establish a benchmark CUI (Bryan, 2009). "The total CUI is the sum of CUIs for each fuel used. For example, if the building uses some natural gas and some electricity, as many buildings do, then the EUI attributable to each fuel is used to find a CUI for gas and a CUI for electricity and then these are added to get the total building CUI" (DeKay & Brown, 2014, p281). Table 2 shows an excerpt from CUI targets published in *Sun, Wind & Light* by US climate zone and building type. They provide similar calculations for residential and non-residential buildings in the US and Canada, using a variety of emissions factors from EPA, NRC Canada, and ASHRAE.

TABLE 2. Median Carbon Use Intensity (CUI) targets, USA commercial buildings
CO_2e lbs/ft^2/yr, excerpt of table (DeKay & Brown, 2014)

ASHRAE Climate Zones	City	Small Office 5500 sf / 1st			Medium Office 53628 sf / 3 st			Large Office 498588 / 12 st			Medical Office 40946 / 3 st			Primary School 73960 / 1 st			Secondary School 210887 / 2 st			Hospital (general medical & surgical) 241351 5 st			Senior Care Facility 20025 SF (1)			Hotel (small) 43200 / 4 st		
		med	70%	90%	med	70%	90%	med	70%	90%	med	70%	90%	med	70%	90%	med	70%	90%	med	70%	90%	med	70%	90%	med	70%	90%
1A	Honolulu, HI	25.3	7.6	2.5	35.7	10.7	3.6	42.1	12.6	4.2	57.1	17.1	5.7	18.3	5.5	1.8	28.4	8.5	2.8	82.3	24.7	8.2	49.5	14.8	4.9	25.8	7.7	2.6
1A	San Juan, PR	24.8	7.4	2.5	35.3	10.6	3.5	41.5	12.4	4.1	55.8	16.8	5.6	12.7	3.8	1.3	22.4	6.7	2.2	82.1	24.6	8.2	49.1	14.7	4.9	25.6	7.7	2.6
1A	Miami, FL	25.9	7.8	2.6	36.7	11.0	3.7	43.1	12.9	4.3	62.9	18.9	6.3	13.2	4.0	1.3	25.0	7.5	2.5	84.2	25.3	8.4	51.4	15.4	5.1	27.4	8.2	2.7
2A	Houston, TX	24.5	7.3	2.4	35.3	10.6	3.5	41.3	12.4	4.1	49.8	14.9	5.0	22.1	6.6	2.2	28.4	8.5	2.8	79.2	23.8	7.9	47.7	14.3	4.8	25.4	7.6	2.5
2B	Phoenix, AZ	26.3	7.9	2.6	37.2	11.2	3.7	43.4	13.0	4.3	62.3	18.7	6.2	21.8	6.5	2.2	32.4	9.7	3.2	82.9	24.9	8.3	51.0	15.3	5.1	27.8	8.3	2.8
3A	Atlanta, GA	22.9	6.9	2.3	33.7	10.1	3.4	39.7	11.9	4.0	38.7	11.6	3.9	22.1	6.6	2.2	23.2	7.0	2.3	73.9	22.2	7.4	44.2	13.3	4.4	23.7	7.1	2.4
3B-CA	Los Angeles, CA	18.2	5.5	1.8	28.7	8.6	2.9	34.9	10.5	3.5	24.9	7.5	2.5	19.7	5.9	2.0	16.6	5.0	1.7	67.7	20.3	6.8	37.5	11.3	3.8	17.8	5.3	1.8

Carbon Balance Index Defined

CBI is defined as the designed building's net CUI (after accounting for renewables) divided by the CUI of a typical building, expressed as a percentage:

$$\text{CBI} = (\text{CUI}_{Design}) \div \text{CUI}_{Typ.} \times 100\%$$

The task then is to find both the building design's CUI and that of a benchmark building. The CUI_{Typ} can be calculated as described above or found in *Sun, Wind & Light's* "Emissions Targets" chapter. A similar method can be done for any country with median data for building EUI by class and climate.

Calculating CUI for a Building

To estimate the CUI_{Design}, the following steps are recommended (modified from Dekay and Brown, 2014, p289-91):

1) After *selecting CO_2e rates* for each fuel used from emissions factors data for your country or region, *calculate the source CUI for each fuel* by multiplying the site *Energy Demand Intensity* (EDI), which is the energy demand component of site EUI, for each fuel, by the CO_2e emissions rate for that fuel (from step 1), for example natural gas: site $EDI_{gas} \times CO_2e_{gas} = CUI_{gas}$, where, site EDI is in kWh/ft^2/yr (kWh/m^2/ yr), CO_2e is in lb CO_2e/kWh (kg CO_2e/kWh) for the fuel, and CUI is in lb CO_2e/ft^2/yr (kg CO_2e/m^2/yr).
2) *Find the total demand CUI for the building design* by adding together the CUI for each fuel. For example: $CUI_{gas} + CUI_{electric} = CUI_{demand}$
3) *Estimate the emissions savings from on-site renewables,* in CUI units, by multiplying the on-site renewable *Energy Production Intensity* (EPI) by the emissions rate for on-site renewables: $EPI_{on\text{-}site\ RE} \times CO_2e_{on\text{-}site\ RE} = CUI_{on\text{-}site\ RE}$. The emissions for renewables are negative and on-site renewables typically count for more emissions offset than do grid-supplied renewables. To do this step, one must know the amount of energy produces on-site.
5) *Estimate the emissions savings from off-site renewables,* in CUI units, by multiplying the off-site renewable EPI (such as from utility-generated wind power) by the emissions rate for off-site renewables: $EPI_{off\text{-}site\ RE} \times CO_2e_{off\text{-}site\ RE} = CUI_{off\text{-}site\ RE}$
6) *Find the net CUI* by subtracting credits for on-site (step 4) and off-site (step 5) renewable energy from the gross total CUI for the building demand (step 3): $CUI_{demand} - CUI_{on\text{-}site\ RE} - CUI_{off\text{-}site\ RE} = CUI_{design}$

The following additional interpretations apply: A net design CUI = 0 means a carbon neutral building by the *SWL* emissions targets criteria, while a net design CUI < 0 means a "carbon consuming building," which helps offset greenhouse gases generated by other buildings.

The *SWL Tools* spreadsheet (DeKay, 2016) facilitates the calculation of CUI and allows comparison against a benchmark building and reduction targets for carbon, similar to the 2030 Targets for fossil fuel reduction (See Fig. 4).

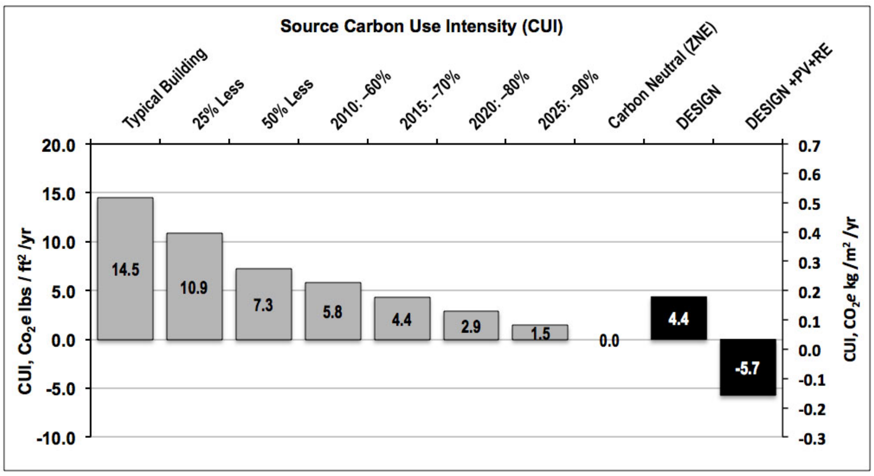

FIGURE 4. Comparative Carbon Use Intensity (CUI), from *SWL Tools* (DeKay, 2016)

Expanding on the 2030 Targets for Carbon

The CUI_{design} value as described above can then be used to find the Carbon Balance Index (CBI):

$$CBI = (CUI_{Design}) \div CUI_{Typ.} \times 100\%$$

If we take the CUI of a typical benchmark (base) building as a CBI value set at 100 and a zero net-carbon performance (ZNC) as zero, then we can establish a range of targets more or less calibrated to the 2030 Targets for fossil fuel use reduction, as shown in Fig. 5. To do this we

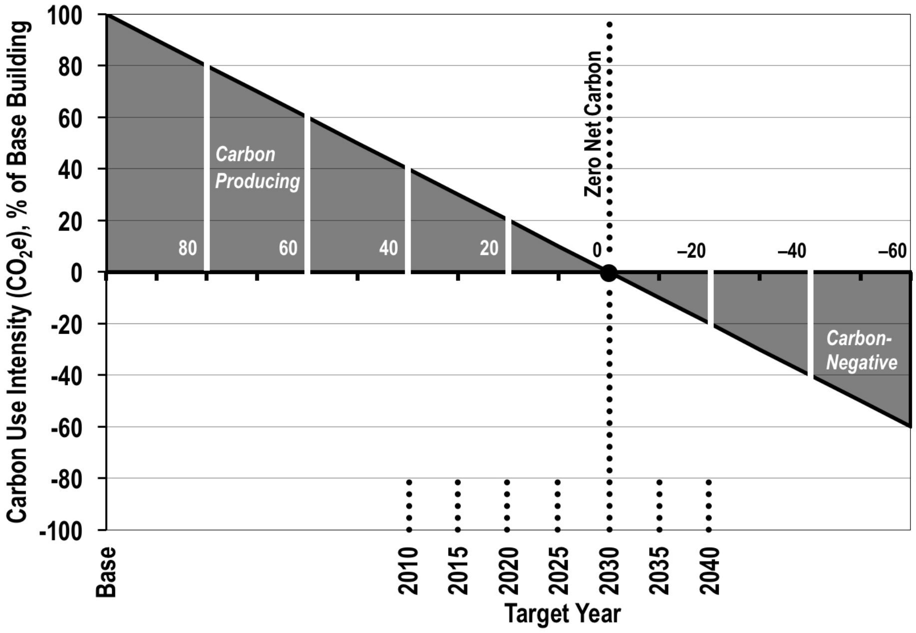

FIGURE 5. Carbon Balance Index (CBI) Targets

have to make an assumption that the zero (ZNC) value includes the 20% allowable off-site renewable energy. While EUI values are commonly published for various base buildings, the CUI is rarely available and must be calculated as described above using the fuel mix and country or regional emissions rates. So, CBI = 100 is *not universal*; rather it is calibrated to local energy supply infrastructure performance, climate, and end use energy mix. With this as a given assumption, we can establish relative reductions in CBI aligned to the targets of Architecture 2030 (80% less fossil fuels in 2020, carbon-neutral in 2030, etc.). The *SWL Tools* spreadsheet workbook (DeKay, 2016) helps to calculate a building's CUI, CBI, and to compare these against various targets. An excerpt is shown in Fig. 6.

From the 2010 target onward, the targets become a linear progression, with negative CBI targets (carbon-consuming or carbon-offsetting) after 2030. In this manner, CBI = 0 is both "carbon-neutral" in the 2030 Targets schema and "zero net-carbon" in the NBI, et al, definition of ZNC. However, the reader and user of CBI should be clear that, in buildings with a positive CBI (left of zero), depending on the mix of fossil fuel types, the level of energy design for conservation and passive design, and the degree and mix of on-site and off-site renewables, a building meeting the 2030 Targets for a given year, say 2020, may or may not meet the CBI targets shown in Fig. 5. Said another way, a building with a given energy use can produce more or less carbon than a building with the same energy use and a different mix of fossil fuel types and renewable energy types.

CARBON USE INTENSITY TARGETS

Target % Emissions Reduced from Typical Bldg.	Target CUI CO_2e lbs/ ft^2, yr	Targets Achieved?	
Typical Building	14.5	NA	
25%	10.9	NA	
50%	7.3	YES	
60%	5.8	YES	
70%	4.4	YES!	GOOD WORK!
80%	2.9	YES!!	CLIMATE STEWARD!
90%	1.5	YES!!	NEAR CARBON NEUTRAL BUILDING
Carbon Neutral	0.0	YES!!!	CARBON CONSUMING BUILDING!

CARBON BALANCE INDEX: YOUR DESIGN $CBI = (EUI_{des} \div EUI_{typ}) \times 100\%$

[Net] Your Design CUI CO_2e lbs/ ft^2/ yr	Base Bldg. Typ. CUI CO_2e lbs/ ft^2/ yr	Carbon Balance Index (CBI)
(5.7)	14.5	-39.5%

FIGURE 6. Carbon Use Intensity (CUI) and Carbon Balance Index calculated in *SWL Tools* (DeKay, 2016)

EBI and CBI Compared

Building on earlier work of Dekay & Giddings (2016) on the *Energy Balance Index* (EBI), the CBI and EBI targets, curves and zero points are compared in Fig. 7. The EBI is indexed to the same base building performance in EUI units and a zero value is a site net-zero energy building, meaning that it produces as much energy on-site annually as it consumes. EBI values are negative when the building is a net energy consumer and positive when it is a *plus-energy* building that exports net annual energy. Carbon, on the other hand, is produced by the building's use of fossil fuels and, therefore, has a logically positive value (CBI > 0) to the left of zero when it burns source fossil fuels, while a building is "carbon-negative" (CBI < 0) when it no longer uses fossil fuels for operation and produces renewable energy for export.

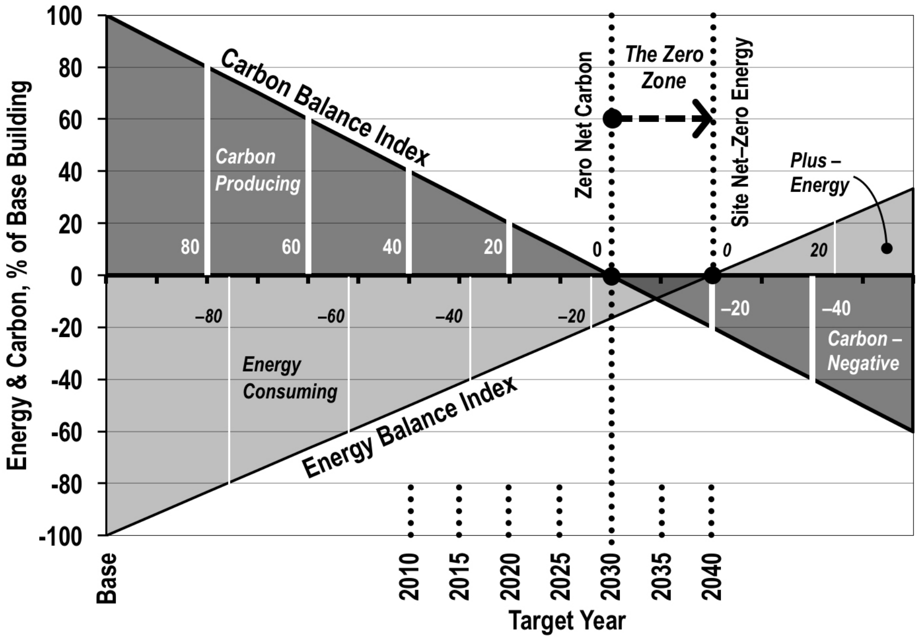

FIGURE 7. Carbon Balance Index (CBI) and Energy Balance Index (EBI) Targets compared

Therefore, one can see that Figure 7 shows two building performance indices with different definitions of zero. When EBI and CBI are overlaid, an ambiguous "Zero Zone" appears. The difference is in the system boundary. We could set the EBI zero at the CBI zero point, but critics argue that one could simply purchase one's way to zero energy, rather than design and engineer the performance. The distinction of *site net-zero* seems to remain useful, if not necessarily for all buildings. We could similarly move the CBI zero point to align with EBI, with critics arguing for the efficacy of a focus on fossil fuels, rather than where the renewables are sourced. The good news is that if every building operated in the Zero Zone, the climate crisis would be solved by design. Buildings in the Zero Zone would all be high-performance buildings. It is useful to note that if a ZNC building uses no on-site renewables and imported renewables are maxed out at the 20% set by the 2030 Challenge, the only way to further improve CBI and become carbon-negative is to add on-site production.

Findings

With the Carbon Balance Index, carbon-neutral buildings (as defined by the 2030 Challenge) have CBI = 0. Positive CBI means some fossil fuels are used and carbon is produced, while negative CBI projects "consume" carbon by exporting excess energy and offsetting fossil grid energy. Depending on the rate of imported renewable energy, 'carbon neutral' can have a range on the Energy Balance Index (EBI) from 0 to –20.

The paper provides a method to quantify and index CO_2e performance relative to the ZNC definition (and beyond) and relative to the 2030 Target of "carbon-neutral," by using carbon reduction targets in the five-year increment promoted by Architecture 2030 for fossil fuel reduction. The value of the CBI is that it honors and builds on the work of NBI and Architecture 2030 as important driving forces in solving the climate crisis by design, while also giving credit and value to the more impactful emissions offset power of on-site renewables. The CBI, being based in the carbon use intensity (CUI) methodology outlined, also helps with the critical distinction between fossil fuel types on the way to ZNC, and provides a way to fairly assess progress toward and beyond ZNC.

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