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Abstract

Reducing anthropogenic carbon emissions is a challenge all of us need to address. There is need to innovate to reduce carbon emissions effectively. Three innovative ideas are presented in this paper to help the construction industry make progress, at construction site/compound level, towards net zero or even zero carbon emissions. These ideas are: make the construction site/compound a prosumer of renewable energy for use on, and export from, the site/compound; adopt carbon emissions analysis for construction sites/compounds (CEAfCS); and adopt CEAfCS metrics as climate change requirements when using Option X29 of NEC4 Engineering and Construction Contract and/or other forms of contract. These ideas have arisen from an iterative creative thinking process that has considered nature of the construction site/compound; nature of operations on a construction site/compound; renewable energy technologies available and their likely development over the next few years; and units of measuring relevant quantities. These ideas constitute a framework that provides opportunity to manage the journey towards minimising carbon emissions via calculation of key and pinpointed metrics that can be used in planning and/or execution and/or control processes of any construction project.

List of notations

The following symbols are used throughout the paper.

Roman symbols

BCEfEfS	baseline carbon emissions from energy for site/compound in kg CO2e
CEAfCS	carbon emissions analysis for construction sites/compounds
CEfEoS	carbon emissions from energy on site/compound in kg CO2e
CEoREPoS	carbon emissions of renewable energy produced on site/compound in kg CO2e
c_{fossil}	price of fuels in money/litre (or other appropriate units)
c_{grid}	electricity import tariff (adjusted for standing and/or other charges) in money/kWh
CoEoS	cost of energy on site/compound in money
CoMREoS	cost of maximum renewable energy on site/compound in money

$c_{renewable}$	unit cost of renewable energy in money/kWh
e_{fossil}	conversion factor for fossil fuel in kg $CO2e$ per litre (or other appropriate units)
e_{grid}	conversion factor for electricity in kg $CO2e$ per kWh
$e_{renewable}$	conversion factor for renewable energy in kg $CO2e$ per kWh
FFEUoS	fossil fuel energy used on site/compound in kWh
GEItS	grid energy imported to site/compound in kWh
$GEItS_{RPSoS}$	grid energy imported to site/compound when RPSoS is in operation in kWh
kWh	kilowatt hour
p_{carbon}	unit price of carbon emissions in money/kg $CO2e$
REEfS	renewable energy exported from site/compound in kWh
$REEfS_{RPSoS}$	renewable energy exported from site/compound supplied by RPSoS in kWh
REUoS	renewable energy used on site/compound in kWh
$REUoS_{RPSoS}$	renewable energy used on the site/compound supplied by RPSoS in kWh
r_{export}	renewable energy export tariff rate in money/kWh
RfREEfS	revenue from renewable energy exported from site/compound in money
RPSoS	renewable power station on site/compound
SEP	site/compound energy profile in kWh
SEP_{FFEUoS}	SEP component from fossil fuels in kWh
SEP_{GEItS}	SEP component from grid energy imported to site/compound in kWh
SEP_{REEfS}	SEP component from renewable energy exported from site/compound in kWh
SEP_{REUoS}	SEP component from renewable energy used on site/compound in kWh
$SREI_{cefs}$	Site Renewable Energy Index with respect to carbon emissions from site/compound
$SREI_{core}$	Site Renewable Energy Index with respect to cost of renewable energy

$SREIF_{FFEUoS}$ Site Renewable Energy Index with respect to fossil fuels energy used on site/compound

$SREI_{GEItS}$ Site Renewable Energy Index with respect to grid energy imported to site/compound

$SREI_{REEfS}$ Site Renewable Energy Index with respect to renewable energy exported from site/compound

$SREI_{REUoS}$ Site Renewable Energy Index with respect to renewable energy used on site/compound

$SREI_{rfre}$ Site Renewable Energy Index with respect to revenue from renewable energy

Keywords

carbon emissions analysis, **construction**, **contracting**, net zero carbon, option X29, **procurement,** prosumer

1. Introduction

Climate change is a growing concern across the globe and the main driver for this change is emissions of carbon dioxide and other greenhouse gases (IPCC, 2023a). The consequences of climate change such as rising global temperatures are acknowledged by a huge majority of people and organisations worldwide. Indeed such is the concern about climate change that many countries around the globe, as part of the Paris Agreement, have committed to reducing levels of emissions. It has been suggested that to limit global temperature rise to about 1.5 degrees Celsius, about 50% reduction in carbon emissions relative to 2019 levels is required by 2030 followed by net zero carbon emissions by 2050 (IPCC, 2023b). It is widely recognised that climate change can be addressed effectively by moving away from conventional fossil energy sources to non-fossil energy sources. From a technical perspective the main non-fossil energy sources available are renewable sources (solar, wind, water, biomass and geothermal) and nuclear energy (a non-renewable source) (United States Department of Energy, n.d.). On account of renewability and low geopolitical risk, renewable sources of non-fossil energy appear to provide maximum availability to many industries/sectors across the world. Experts have recently indicated that the 1.5 degrees Celsius target appears to have been already breached albeit not on a long term average basis (Bevacqua et al., 2025). Hence, new and innovative ideas about reducing carbon emissions, such as those espoused in this paper cannot come any sooner because their importance continues to grow.

The UK has been active in the quest to reduce carbon emissions for some time. In 2008, the UK became the first country to pass a binding commitment, in the form of the Climate Change Act 2008, to reducing carbon emissions. In the original Act, the target was to reduce the net carbon account by 80% below 1990 level by 2050. In 2019, the target was tightened to 100% (net zero) and the new target was made legally binding by the Climate Change Act 2008 (2050 Target Amendment) Order 2019. Many organisations in UK have responded to the net zero target and developed (or are developing) visions, missions, strategies, action plans, etc. to help them make their contribution effectively which are underpinned by the recognition for starting and continuing to research and innovate. National governments (such as UK government) and non-governmental institutions (such as UK Green Building Council) have set targets to facilitate changes required to address climate change. It is widely recognised that impact to achieve any targets relating to carbon emissions and limiting temperature rise can be generated at various levels from individual to national. Many individuals, organisations, industries and countries are committed to acting. Research and innovation are required in all domains including technological, organisational, policy and regulatory to support and facilitate appropriate actions.

The work presented in this paper was aimed at introducing three innovative ideas with which the construction industry can reduce use of fossil fuels during the construction phase and contribute to addressing climate change. The first idea is to make the construction site/compound a prosumer of renewable energy for use on, and export from, the site/compound. This term prosumer which was originally coined by Alvin Toffler (Toffler, 1982), merges 'producer' and 'consumer,' to describe individuals or organisations that not only consume but also produce the same goods. The second idea is to adopt a novel method, carbon emissions analysis for construction sites/compounds (CEAfCS), developed by the author and described for the first time herein. CEAfCS comprises of a nomenclature, ten steps and twelve equations all of which were devised by the author. The third idea is to adopt CEAfCS metrics as climate change requirements to be incorporated in the project scope when using Option X29 of NEC4 Engineering and Construction Contract (NEC, 2022) and/or other forms of contract as appropriate. The ideas are based on the unit of analysis of a construction site/compound. The unit of analysis should be something that unifies the concepts of interest. In the context of reducing carbon emissions during the construction phase in the construction industry, the concepts of considered for this paper are space (to enable production and distribution of renewable energy) and participants (who have clear and unambiguous responsibilities to each other that facilitate accountability). The only option in the intersection of space and participants, in this context, is the construction site/compound. Every construction project has a construction site/compound defined as part of the construction contract. The construction site/compound presents unique and untapped potential to respond positively, and in a novel way, to the challenge of reducing use of fossil fuels on the construction site/compound and greening the energy mix through exporting renewable energy to the economy via the national grid or other mechanism. A theoretical approach was adopted in the work. It is hoped that access to this paper will lead to practical application and empirical research which may lead to further development and institutionalisation of the ideas in the construction industry in UK and all over the world.

In addition to section 1, there are six more sections in this paper. In section 2, the first idea is explained and justified. In section 3, the methodology of developing CEAfCS is explained. In sections 4 and 5, the second and third ideas respectively are explained and justified as appropriate. In section 6, two scenarios of application of the ideas are explained. In section 7, conclusions are provided and a call to action is made.

2. Construction site/compound as a prosumer of renewable energy

In this section, the first of three ideas at the centre of this paper is explained. The idea is as follows: we can, and should, redefine construction sites/compounds by making them prosumers of renewable energy. Prosumerisation, in this context, signifies an important departure from traditional energy dynamics and the departure transforms passive energy users into active participants in creation of the energy matrix (Belmar et al., 2023). Transformation of construction sites/compounds from passive users of energy to active producers of energy for own and others' consumption represents a momentous change in the holistic quest for net zero carbon, and zero carbon.

The prosumer model is well-established in the domestic energy sector in many advanced countries and its development provides many learning points about, but not limited to, feasibility, incentivisation, diffusion and institutionalisation. The author was motivated by developments in the prosumerisation of domestic energy and, through this paper, seeks to present ideas on which the construction industry can build to transfer prosumerisation of renewable energy to the construction phase of construction projects. In so doing, the author invites stakeholders to focus on source of energy rather than amount of energy consumed on the construction site/compound.

Construction sites/compounds are currently characterised by energy from one or a combination of fossil-fuels (powering construction machines and generators) and electricity imported from the grid and both these sources produce carbon emissions. The thinking here is that we can reduce the carbon emissions by utilising the potential of the construction site/compound to generate renewable energy for use on the construction site/compound and export to the economy, if possible, via the national electricity grid or other mechanism and this would be a better option at least from a carbon emissions reduction perspective. This idea assumes availability of electric construction machinery and given the pace of technological development in this area, this assumption is considered reasonable at least over the medium to long term. Hence, it is important that this idea is embraced, not as a short term solution for the construction industry but as something that can be included as part of medium to long term development of the construction industry but which can be applied in some projects albeit in a limited way in 2026.

Just like prosumerisation of domestic energy is not for every domestic dwelling, some construction projects will be better suited for this prosumer idea than others. Particularly, projects with large compounds such as highway, railway, airport and housebuilding projects would be better suited for this idea. However, it is expected that as technology develops even projects with relatively small sites/compounds may be able to apply this model. It is expected that many of the issues of implementation of prosumerisation of renewable energy in the construction phase would benefit from lessons learnt from prosumerisation of domestic energy and this is why the author feels that issues of feasibility are a matter of willingness of the stakeholders to incentivise, promote or, even, legislate.

When it comes to excess energy produced, prosumerisation of renewable energy in the domestic sector adopts one or a combination of exporting to grid or battery storage. Here, choice can be influenced by costs, revenue, availability of renewable resources, access to grid and other factors. Similar factors are expected to influence construction contractors and clients when they make their choices.

For the construction industry, the prosumer model offers immense potential. Consider construction sites/compounds, traditionally viewed as energy drains, evolving into vibrant energy-producing hubs! These sites/compounds could produce renewable energy and deliver two things, namely, reduce their carbon emissions and supply non-fossil power to the economy and, hence, help the country increase local energy production and reduce carbon emissions (Tantau et al., 2021). In other words, construction sites/compounds could become places to produce infrastructure as well as energy; construction sites/compounds could become decentralised energy production units spread all over the country. While the idea of advancing sustainable energy systems through creating prosumers has been highlighted in extant literature (Brown et al., 2019; Kuznetsova and Anjos, 2021; Sotnyk et al., 2023; Villar et al., 2017), it has, hitherto, not been considered for application on a construction site/compound. This is a call to change this situation.

Construction sites/compounds as power stations bring speed to increasing local energy supply and race to net zero carbon emissions. This is because construction sites/compounds are temporary installations and may not be subject to stringent planning restrictions. Temporary installations such as tower cranes, materials silos, etc, are already acceptable temporary structures on construction sites/compounds. Renewable energy installations such as wind turbines can join this group of temporary structures on many construction sites/compounds without much concern or difficulty as part of new site/compound set up process. For example in UK, this is particularly possible because Part 4 of Schedule 2 of The Town and Country Planning (General Permitted Development) (England) Order 2015 indicates that: " *… provision on land of buildings, moveable structures, works, plant or machinery required temporarily in connection with and for the duration of operations being or to be carried out on, in, under or over that land or on land adjoining that land* …" is permitted development. Furthermore, according to The Town and Country Planning (Environmental Impact Assessment) Regulations 2017, such permitted development is not subject to ecological assessment. It is assumed that other countries have or can have similar provisions in their planning laws.

As a simple illustration, consider one thousand sites/compounds running at any one time with wind turbines generating 100kW each. This would be 100MW of power generated. These sites /compounds can be set up in next to no time at next to negligible cost relative to the cost of the construction projects. When you consider this in relation to how much time would be required to take one 100MW wind farm through planning, engineering, procurement and construction together with associated costs, it becomes clear that construction sites/compounds would deliver sooner and at lower cost. This vision of construction sites/compounds as prosumers of renewable energy aligns with the global sustainability goals. As the world grapples with energy and environmental challenges, the prosumer model provides a vision of interaction with the energy grid (or energy storage technology) to increase energy supply (meet demand), energy decentralization, grid resilience, and sustainability (Lisin et al., 2019).

The idea of the construction site/compound as a prosumer of renewable energy is one the construction industry must embrace. However, it is important to note that:

- not every site/compound will be suitable for the idea;
- some construction sites/compounds will be more suitable for the idea than others;
- some construction sites/compounds will be more suitable for different sources of renewable energy than others; and
- the idea does not have to apply equally to each and every construction site/compound to benefit the construction industry, nation and the world.

In section 4 of this paper, a method developed by the author that can be used in the construction industry to embrace the idea of the construction site/compound as a prosumer of renewable energy is presented. The method is referred to as carbon analysis for construction sites/compounds (CEAfCS). However, before CEAfCS is presented, an explanation of how it was developed is provided in section 3 below.

3. Methodology for developing CEAfCS

CEAfCS was developed by the author to be a method for analysing and evaluating performance of a construction site/compound as a prosumer of renewable energy. CEAfCS was developed using critical analysis of the nature of the construction site/compound, operations on a construction site/compound, sources of energy for construction site/compound and units of measuring relevant quantities. This was achieved using the analytical tool of structured creative thinking involving conceptual exploration (Boden, 2004), iterative model construction (Finlay, 2002; Simon, 1996), reflective thought experiments (Gendler, 2014) and conceptual evaluation (Boden 2004; Rescher, 1991; Thagard, 2001; and Simon, 1996).

Drawing on established ideas about systematic reasoning and conceptual model construction in Thagard (2001), an open-ended conceptual exploration of energy demand and supply on the construction site/compound and associated economic and carbon emissions impacts was conducted. This exploration utilised iterative questioning and abductive interpretation (Boden, 2004). As a result of this exploration, key terms of CEAfCS were devised.

Conceptual exploration was followed by iterative model development. Tentative equations were devised and revised iteratively as they were subjected to checks to ensure clarity, completeness and coherence (Thagard, 2001). Any inconsistencies identified led to revision in line with principles of reflective reasoning (Finlay, 2002) and artificial systems modelling (Simon, 1996).

Robustness of emerging ideas and equations were tested through thought experiments generated by the author. Thought experiments are established and effective tools for assessing coherence and implications of theoretical proposals (Gendler, 2014). Thought experiments enabled the author to identify and address any contradictions or weaknesses in the ideas and equations.

Throughout the process of designing CEAfCS, ideas and equations were tested with four criteria: coherence, explanatory power, generative potential and parsimony. Drawing on coherence-based accounts of reasoning (Thagard, 2001), coherence was tested by considering whether the ideas and equations avoided internal contradictions. Explanatory power of the ideas and equations was tested by evaluating the extent to which they broadened and deepened our understanding of sources and impacts of energy on construction sites/compounds in line with ideas in Rescher (1991). Generative potential of the ideas and equations was tested by evaluating the extent to which they opened up new lines of research in line with Boden (2004). Drawing on Simon (1996), parsimony was tested by evaluating the extent to which the ideas remained simple whilst retaining adequacy.

4. Carbon emissions analysis for construction sites/compounds (CEAfCS)

In this section, the second of three ideas at the centre of this paper is explained. This idea entails adoption of CEAfCS, a method developed following the methodology described in section 3. CEAfCS considers consumption of energy (regardless of source) within the physical boundaries of the construction site/compound and outside of the site/compound for purposes of disposal of construction waste only. CEAfCS also considers renewable energy produced within the physical boundaries of the construction site/compound but some of this renewable energy may be exported via charging electric vehicles on the site/compound which may be used to transport people from the site/compound. CEAfCS does not include energy consumption for delivering plant, materials, supplies or people to the construction site/compound.

Thirty-seven terms (see list of notations) to operationalise the CEAfCS have been defined incorporating a nomenclature devised by the author for the terms using a simple approach to acronyms involving first letters of all the words in the term with upper case letters for major words and lower case letters for minor words. CEAfCS method is comprised of ten steps and involves twelve equations. The equations are numbered for clear association of each equation with its respective step for consistent reference. Table 1 provides a summary of CEAfCS to enhance understanding of its details which are provided in the subsections 4.1 – 4.10. Column 5 of Table 1 provides guidance to stakeholders as to what they should be aiming for at respective steps of CEAfCS. The purpose of Table 1 is to provide a simple overview to enhance understanding of CEAfCS and its application.

Table 1 Outline of carbon emissions analysis for construction sites/compounds (CEAfCS)

CEAfCS Step	**CEAfCS Description**	**CEAfCS Equation Number**	**CEAfCS Equation/Method**	**Objective Function**
1	Determining amount of energy available on a construction site/compound	1	$SEP = \sum SEP_{GEItS} + \sum SEP_{REUoS} + \sum SEP_{REEfS} + \sum SEP_{FFEUoS}$	Maximise SEP
2	Determining amount of carbon emissions of energy on a construction site/compound	2	$CEfEoS = \sum (e_{grid} \times SEP_{GEItS}) + \sum (e_{renewable} \times SEP_{REUoS}) + \sum (e_{renewable} \times SEP_{REEfS}) + \sum (e_{fossil} \times SEP_{FFEUoS})$	Minimise CEfEoS
3	Determining cost of energy on a construction site/compound	3	$CoEoS = \sum(c_{grid} \times SEP_{GEItS}) + \sum(c_{renewable} \times SEP_{REUoS}) + \sum(c_{renewable} \times SEP_{REEfS}) + \sum(c_{fossil} \times SEP_{FFEUoS}) + p_{carbon} \times (CEfEoS – BCEfEfS)$	Minimise CoEoS
4	Determining revenue from renewable energy exported from a construction site/compound	4	$RfREEfS = \sum (r_{export} \times SEP_{REEfS})$	Maximise RfREEfS
5	Determining maximum amount of renewable energy that can be produced on a construction site/compound	-	Design and construct RPSoS	Maximise $REUoS_{RPSoS}$ Maximise $REEfS_{RPSoS}$ Minimise $GEItS_{RPSoS}$
			Measure $REUoS_{RPSoS}$, $REEfS_{RPSoS}$ and $GEItS_{RPSoS}$	-
6	Determining cost of producing maximum renewable energy on a construction site/compound	-	Estimate CoMREoS	-
7	Determining carbon emissions from producing maximum renewable energy on a construction site/compound	-	Estimate CEoREPoS	-
8	Determining revenue from maximum renewable energy produced on a construction site/compound	8	$RfREEfS_{RPSoS} = \sum(r_{export} \times REEfS_{RPSoS})$	Maximise $RfREEfS_{RPSoS}$
9	Constructing RPSoS	-	Implement approved construction programme for RPSoS	-
10	Evaluating carbon emissions performance of a construction site/compound			
10.1	Evaluating carbon emissions performance of a construction site/compound with source of energy metrics	10.1.1	$SREI_{REUoS} = \sum SEP_{REUoS} \div SEP$; $0 \le SREI_{REUoS} \le 1$	Maximise $SREI_{REUoS}$
		10.1.2	$SREI_{REEfS} = \sum SEP_{REEfS} \div SEP$; $0 \le SREI_{REEfS} \le 1$	Maximise $SREI_{REEfS}$

		10.1.3	$SREI_{GEItS} = \sum SEP_{GEItS} \div SEP$; $0 \le SREI_{GEItS} \le 1$	Minimise $SREI_{GEItS}$
		10.1.4	$SREI_{FFEUoS} = \sum SEP_{FFEUoS} \div SEP$; $0 \le SREI_{FFEUoS} \le 1$	Minimise $SREI_{FFEUoS}$
10.2	Evaluating carbon emissions performance of a construction site/compound with cost metrics	10.2.1	$SREI_{core} = (\sum(c_{renewable} \times SEP_{REUoS}) + \sum(c_{renewable} \times SEP_{REEfS})) \div CoEoS$; $0 \le SREI_{core} \le 1$	Minimise $SREI_{core}$
10.3	Evaluating carbon emissions performance of a construction site/compound with carbon emissions metrics	10.3.1	$SREI_{cefs} = (\sum (e_{renewable} \times SEP_{REUoS}) + \sum (e_{renewable} \times SEP_{REEfS})) \div CEfEoS$; $0 \le SREI_{cefs} \le 1$	Minimise $SREI_{cefs}$
10.4	Evaluating carbon emissions performance of a construction site/compound with revenue from renewable energy metrics	10.4.1	$SREI_{rfre} = RfREEfS \div CoEoS$; $0 \le SREI_{rfre} \le \infty$	Maximise $SREI_{rfre}$

4.1 CEAfCS Step 1: Determining amount of energy available on a construction site/compound

Energy available on a construction site/compound is the sum of grid energy imported to site/compound (GEItS), renewable energy used on site/compound (REUoS), renewable energy exported from site/compound (REEfS) and fossil fuel energy used on site/compound (FFEUoS). To determine GEItS, collect data relating to electricity imported from the grid in kWh from respective electricity meters. To determine REUoS, collect data relating to renewable electricity used on the site/compound in kWh from respective electricity meters or other appropriate sources. To determine REEfS, collect data relating to renewable energy exported from site/compound in kWh from respective electricity meters or other appropriate sources. To determine FFEUoS, collect construction and other plant data (such as type, number, model, technical efficiency, hours of operation, amount of fuel used where applicable); compute energy in kWh using appropriate equations and standard conversion factors from reliable sources such as UK's Department of Energy Security and Net Zero or international equivalents. Depending on granularity of the data or with appropriate assumptions, produce a site/compound energy profile (SEP) for site/compound. There will be a SEP component from grid electricity imported to site/compound (SEP_{GEItS}), SEP component from renewable energy used on site/compound (SEP_{REUoS}), SEP component from renewable energy exported from site/compound (SEP_{REEfS}) and SEP component from fossil fuels on site/compound (SEP_{FFEUoS}). Hence, obtain SEP for the construction site/compound from Equation 1.

$$\mathrm{SEP} = \sum \mathrm{SEP_{GEItS}} + \sum \mathrm{SEP_{REUoS}} + \sum \mathrm{SEP_{REEfS}} + \sum \mathrm{SEP_{FFEUoS}} \qquad \text{Equation 1}$$

4.2 CEAfCS Step 2: Determining amount of carbon emissions of energy on a construction site/compound

Carbon emissions of energy on a construction site/compound is given by the sum of carbon emissions from electricity imported from the grid to site/compound, carbon emissions of renewable energy on site/compound and carbon emissions of fossil fuels used on site/compound. To determine carbon emissions of energy, identify appropriate conversion factors for electricity, $e_{grid,}$ in kg CO_2e per kWh, renewable energy, $e_{renewable,}$ in kg CO_2e per kWh and fossil fuels, e_{fossil} in kg CO_2e per litre (or other appropriate units) from prevailing standard conversion factor tables from reliable sources such as UK's Department of Energy Security and Net Zero or international equivalents. With these parameters, obtain the carbon emissions from energy on site/compound (CEfEoS) in kg CO_2e from Equation 2.

$$\mathrm{CEfEoS} = \sum(\mathrm{e_{grid}} \times \mathrm{SEP_{GEItS}}) + \sum(\mathrm{e_{renewable}} \times \mathrm{SEP_{REUoS}}) + \sum(\mathrm{e_{renewable}} \times \mathrm{SEP_{REEfS}}) + \sum(\mathrm{e_{fossil}} \times \mathrm{SEP_{FFEUoS}}) \quad \text{Equation 2}$$

4.3 CEAfCS Step 3: Determining cost of energy on a construction site/compound

Cost of energy on a construction site/compound is the sum of cost of electricity imported from the grid, cost of renewable energy, cost of fossil fuels used and cost of carbon emissions produced. To determine cost of electricity imported from the grid, collect relevant data of the electricity import tariff (adjusted for standing and/or other charges), c_{grid}, in units of money/kWh. To determine cost of renewable energy, collect relevant data of the unit cost of renewable energy, $c_{renewable}$, in units of money/kWh. To determine cost of fossil fuels used, collect appropriate data of the price of fuels, c_{fossil}, in money/litre (or other appropriate units). To determine cost of carbon emissions produced, collect relevant data of the price of carbon emissions, p_{carbon}, in money/kg CO_2e and identify/determine baseline carbon emissions from energy for site/compound, BCEfEfS, in units of kg CO_2e. With appropriate data, obtain cost of energy on site/compound (CoEoS) from Equation 3.

$$\mathrm{CoEoS} = \sum(\mathrm{c_{grid}} \times \mathrm{SEP_{GEItS}}) + \sum(\mathrm{c_{renewable}} \times \mathrm{SEP_{REUoS}}) + \sum(\mathrm{c_{renewable}} \times \mathrm{SEP_{REEfS}}) + \sum(\mathrm{c_{fossil}} \times \mathrm{SEP_{FFEUoS}}) + \mathrm{p_{carbon}} \times (\mathrm{CEfEoS} - \mathrm{BCEfEfS}) \quad \text{Equation 3}$$

4.4 CEAfCS Step 4: Determining revenue from renewable energy exported from a construction site/compound

Revenue from renewable energy exported from site/compound (RfREEfS) is the product of the renewable energy export tariff rate (in units of money/kWh), r_{export} and SEP_{REEfS}. Hence, RfREEfS can be obtained from Equation 4.

$\mathrm{RfREEfS} = \sum(\mathrm{r_{export}} \times \mathrm{SEP_{REEfS}})$ Equation 4

4.5 CEAfCS Step 5: Determining maximum amount of renewable energy that can be produced on a construction site/compound

To determine maximum amount of renewable energy that can be produced on a construction site/compound:

1. collect data about the site/compound (e.g. location, area, opening date and closing date) and associated topographic data (altitude) and meteorological data (e.g. solar irradiance, wind speed and wind direction);
2. conduct physical surveys of the site/compound and interviews with neighbouring landowners to determine how much more land can be acquired (and associated cost) to maximise the area of the construction site/compound;
3. collect data about technical specifications of available renewable energy sources (e.g. about turbines and solar panels from manufacturers and installers) and statutory provisions pertaining to installation of renewable energy infrastructure as temporary structures from planning authorities;
4. collect data from respective distribution network operator for the electricity grid to help determine requirements for connecting the construction site/compound to the electricity grid; and
5. use all data collected in steps 1, 2, 3 and 4, together with other relevant data and appropriate codes of design to design and document a renewable power station on site/compound (RPSoS) for maximum renewable energy production for the construction site/compound ensuring that RPSoS is designed for reuse i.e. aim for a demountable RPSoS and includes appropriate instrumentation to measure, among others, renewable energy used on the site/compound supplied by RPSoS ($REUoS_{RPSoS}$), renewable energy exported from site/compound supplied by RPSoS ($REEfS_{RPSoS}$) as well as grid energy imported to site/compound when RPSoS is in operation ($GEItS_{RPSoS}$).

4.6 CEAfCS Step 6: Determining cost of producing maximum renewable energy on a construction site/compound

To determine cost of producing maximum renewable energy on a construction site/compound, take the design information of the RPSoS and use the price data from the latest public data and/or market data (from multiple quotes from manufacturers, suppliers, installers, maintenance service providers, etc.) to develop a comprehensive cost estimate for the RPSoS covering the duration of construction phase of the construction project, including maintenance (routine and periodic), demounting and removal of the RPSoS. The relevant costs should be adjusted appropriately for the expected number of reinstallations. The sum of all relevant costs is the cost of maximum renewable energy on site/compound (CoMREoS).

4.7 CEAfCS Step 7: Determining carbon emissions from producing maximum renewable energy on a construction site/compound

To determine carbon emissions from producing maximum renewable energy on a construction site/compound, take the design information of the RPSoS and use carbon data from appropriate databases (such as UK's CESMM4 Carbon and Price Book or its international equivalents) and produce a comprehensive carbon estimate for the RPSoS over the duration of construction phase of the construction project, including maintenance (routine and periodic), demounting and removal of RPSoS. The sum of all the relevant quantities is the carbon emissions of renewable energy produced on site/compound (CEoREPoS) in units of kg CO_2e.

4.8 CEAfCS Step 8: Determining revenue from maximum renewable energy produced on a construction site/compound

To determine revenue from renewable energy exported from site/compound with RPSoS ($RfREEfS_{RPSoS}$), compute the sum of the product of the renewable energy export tariff rate (in units of money/kWh), r_{export}, and renewable energy exported from RPSoS, $REEfS_{RPSoS}$. Hence, $RfREEfS_{RPSoS}$ can be obtained from Equation 8.

$$RfREEfS_{RPSoS} = \sum(r_{export} \times REEfS_{RPSoS}) \qquad \text{Equation 8}$$

4.9 CEAfCS Step 9: Constructing RPSoS

This step involves mobilisation of resources (materials, plant/equipment and labour) to construct RPSoS as part of the construction site/compound set up process. Step 9 can arise from internal motivation of a construction organisation that seeks to pursue reduction of carbon emissions on its own volition. Step 9 can also arise from external motivation, invoked by the client in the construction contract via clear and unequivocal requirement to produce renewable energy during the construction phase. Step 9 can also arise from appropriate legal and regulatory provisions designed to promote active reduction of carbon emissions, for example, via planning permission protocols. The ultimate consequence of Step 9 is realisation of a construction site/compound designed to maximise the potential to be a prosumer of renewable energy.

4.10 CEAfCS Step 10: Evaluating carbon emissions performance of a construction site/compound

Evaluate carbon emissions performance of a construction site/compound with respect to energy, cost, carbon emissions and revenue from renewable energy using various metrics provided in sections 4.10.1 – 4.10.4.

4.10.1 Evaluating carbon emissions performance of a construction site/compound with source of energy metrics

Compute the Site Renewable Energy Index with respect to renewable energy used on site/compound ($SREI_{REUoS}$), renewable energy exported from site/compound ($SREI_{REEfS}$), grid energy imported to site/compound ($SREI_{GEItS}$), and fossil fuels energy used on site/compound ($SREI_{FFEUoS}$) from:

$SREI_{REUoS} = \sum SEP_{REUoS} \div SEP;$ $0 \le SREI_{REUoS} \le 1$ Equation 10.1.1

$SREI_{REEfS} = \sum SEP_{REEfS} \div SEP;$ $0 \le SREI_{REEfS} \le 1$ Equation 10.1.2

$SREI_{GEItS} = \sum SEP_{GEItS} \div SEP;$ $0 \le SREI_{GEItS} \le 1$ Equation 10.1.3

$SREI_{FFEUoS} = \sum SEP_{FFEUoS} \div SEP;$ $0 \le SREI_{FFEUoS} \le 1$ Equation 10.1.4

4.10.2 Evaluating carbon emissions performance of a construction site/compound with cost metrics

Compute the Site Renewable Energy Index with respect to cost of renewable energy, $SREI_{core}$ from:

$SREI_{core} = (\sum(c_{renewable} \times SEP_{REUoS}) + \sum(c_{renewable} \times SEP_{REEfS})) \div CoEoS;$ $0 \le SREI_{core} \le 1$ Equation 10.2.1

4.10.3 Evaluating carbon emissions performance of a construction site/compound with carbon emissions metrics

Compute the Site Renewable Energy Index with respect to carbon emissions from site/compound, $SREI_{cefs}$ from:

$SREI_{cefs} = (\sum(e_{renewable} \times SEP_{REUoS}) + \sum(e_{renewable} \times SEP_{REEfS})) \div CEfEoS;$ $0 \le SREI_{cefs} \le 1$ Equation 10.3.1

4.10.4 Evaluating carbon emissions performance of a construction site/compound with revenue from renewable energy metrics

Compute the Site Renewable Energy Index with respect to revenue from renewable energy, $SREI_{rfre}$ from:

$$SREI_{rfre} = RfREEfS \div CoEoS; \qquad 0 \leq SREI_{rfre} \leq \infty \qquad \text{Equation 10.4.1}$$

5. CEAfCS metrics as climate change requirements in project scope

In this section 5, the third of three ideas at the centre of this paper is explained. The idea entails adopting one or more of the seven CEAfCS metrics in section 4.10 as climate change requirements in construction contracts using the standard NEC4 Engineering and Construction Contract (NEC4 ECC). Option X29 which was recently introduced for NEC4 ECC (NEC, 2022) is a major step in management of carbon emissions on a construction site/compound. Option X29 enables main parties (client and contractor) in NEC4 ECC to identify and agree climate change requirements as part of the project scope. As such, the contractor has to provide or comply with the stated climate change requirements in order to provide the works in accordance with the scope. Failure to comply with the climate change requirements will be a breach of the contractor's obligation. This means that option X29 can be used to promote achievement of desired climate change requirements at the level of an individual construction project. As highlighted in Mahmoud et al. (2023), this provides opportunity to clients to really drive the construction industry's progress towards addressing climate change if appropriate climate change requirements are identified and applied.

CEAfCS Equations 10.1.1, 10.1.2, 10.1.3, 10.1.4, 10.2.1, 10.3.1 and 10.4.1 provide quantitative and objective metrics that can be used as climate change requirements. The metrics can be set at pre-contract stage, monitored throughout the construction stage and verified at post-construction stage. They provide a basis from which carbon reduction on construction sites/compounds can be pursued and incentivised at project, organisational and industry levels. CEAfCS equations provide a novel and straightforward way of institutionalising the quest for net zero carbon emissions on construction sites/compounds. CEAfCS equations have potential to facilitate further innovation of construction sites/compounds operations and practices.

While the specific example of using Option X29 of NEC4 is highlighted in this section, it is important to note that other standard forms of contract such as FIDIC or even bespoke forms of contract can be adapted to accommodate CEAfCS. In section 6 below, two scenarios of application of CEAfCS are explained.

6. CEAfCS method in practice

CEAfCS method described in section 4 can be applied in practice in one of two scenarios as described herein. It is expected that scenario 1 will become less common and scenario 2 will take hold as the industry matches to net-zero and zero carbon construction site/compound and scenario 2 will become the norm in the not-too-distant future. Analysis and interpretation shall be undertaken with reference to the journey towards net zero carbon emissions from the perspectives of all internal and external stakeholders in construction projects. Both scenarios 1 and 2 may facilitate understanding of construction site/compound performance relative to peers or benchmarks and/or determination of improvements that can be implemented on the current and/or future projects.

6.1 Scenario 1: Steps 1, 2, 3, 4, 10

In scenario 1, steps 1, 2, 3 and 4 are implemented for any site/compound in the pre-construction stage (with estimated figures), during the construction stage (with actual figures 'to date' as construction progresses or as revised estimates for the whole project taking into account actual figures 'to–date' and estimates for remaining project duration) or post-construction (with final figures). Steps 1, 2, 3 and 4 are followed by step 10, at any stage to provide required evaluation of the carbon performance of the construction site/compound.

6.2 Scenario 2: steps 5, 6, 7, 8, 9, 1, 2, 3, 4, 10

In Scenario 2, steps 5, 6, 7, 8 and 9 are implemented first followed by steps 1,2, 3 ,4 and 10 respectively. In this scenario, the attributes of the renewable power station on the site/compound (RPSoS) including $REUoS_{RPSoS}$, $GEItSR_{PSoS}$, $REEfS_{RPSoS}$, CoMREoS, CEoREPoS and $RfREEfS_{RPSoS}$ are included as part of SEP_{REUoS}, SEP_{GEItS}, SEP_{REEfS}, CoEoS, CEfEoS and RfREEfS respectively and as appropriate in steps 1, 2, 3 and 4. The scenario enables step 10 to be implemented at any time during construction and post-construction to provide an evaluation of the carbon performance of the construction site/compound.

7. Conclusions

As of early 2025, almost every person, organisation and nation knows about the need to act in all activities to reduce anthropogenic carbon emissions (IPCC, 2023a; IPCC 2023b). The question that remains, and will persist for some time, is 'what are we doing to bring about the desired reduction in carbon emissions?'

In this paper, a novel quantitative method to facilitate effective action at the level of the construction phase of a construction project referred to as CEAfCS is offered. CEAfCS is predicated upon the idea of changing construction sites/compounds from conventional workplaces at which things are built to workplaces at which things are built and renewable energy is generated for use on the site/compound and elsewhere.

CEAfCS encourages and enables the main parties to a construction contract (the client and contractor) to incorporate net zero or even zero carbon at the basic unit of analysis of the construction industry. This is particularly made easy in NEC4 ECC by the recent introduction of Option X29. This is because specific CEAfCS metrics (derived from Equations 10.1.1, 10.1.2, 10.1.3, 10.1.4, 10.2.1, 10.3.1 and 10.4.1) can be set by the client as climate change requirements as part of the project scope and, therefore, be part of the contractual obligations of the contractor. This allows the contractor to take the climate change requirements into account at tendering stage and provide resources for net zero (or zero) carbon objectives properly and get compensated/rewarded for it. However, construction projects are delivered using different forms of contract and not just NEC4 ECC. The idea of climate change requirements incorporated in the construction contract as part of the obligations of the contractor can be implemented in many and diverse ways. In each of these ways, the aforementioned CEAfCS metrics provide a simple approach to quantifying, monitoring and evaluating climate change performance on the construction site/compound.

From a practical perspective, CEAfCS is simple and beautiful as it provides for consideration of carbon emissions at the simplest and most important unit of analysis of the construction industry which is the construction site/compound. The two scenarios outlined for application of CEAfCS allow for progressive calculation of key and pinpointed metrics that can be used in planning and/or execution and/or control processes of any construction project. I call upon everyone to consider, apply and promote CEAfCS in construction management research and practice. Moreover, CEAfCS has potential to be developed further. I hope that some of us will dedicate time in months and years to come to test, refine and validate CEAfCS. If you, the reader of this article, rise up and respond to this call for action, we will leverage effort of researchers and practitioners from anywhere in the world and bring this idea and method to the mainstream of construction management research and practice and realise its benefits sooner.

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