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Carbon reduction performance and economic analysis in building construction - a pilot trial of low-carbon construction in the O•PARK2 construction phase

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ABSTRACT

With the wide application of green building standards to reduce the carbon emissions from the operation phase, the carbon emissions during the construction phase are becoming more and more significant. Carbon footprint management is necessary and low-carbon measures, including low-carbon construction materials, construction site electrification, on-site renewable energy systems, and low-carbon alternative fuels should be considered. Taking a real case of a Design-Build-Operate project, O•PARK2, as a pilot trial, this study investigates the carbon reduction efficiency and cost increment of various low-carbon measures, and introduces the Green Premium Index to explore the tradeoff between carbon reduction and carbon offsetting by credit purchasing. Low-carbon measures adopted in O•PARK2 were proved to be carbon reduction efficient, achieving 4,612 tonnes of CO_2e emission reduction. Early development of decarbonisation strategy enables further emission reduction and lower cost increments during the construction phase, in which low-carbon construction material should be prioritised, followed by construction site electrification, and the use of solar panels and B5 biodiesel. With low-carbon construction materials locally manufactured, construction decarbonisation progress in Hong Kong will be significantly enhanced. Low-carbon construction should see carbon reduction as the main direction, and carbon offsetting as supplemental.

KEYWORDS Low-carbon construction material; construction site electrification; on-site renewable energy system; low-carbon alternative fuels; green premium index; carbon offsetting

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1. Introduction

The Hong Kong Government announced Hong Kong's Climate Action Plan 2050 in 2021, striving to reduce carbon emissions by 50% before 2035 and achieve carbon neutrality before 2050. The reduction of carbon emissions from the building sector is a major task in Hong Kong because the built environment (New Buildings and Existing Buildings) accounts for 71% of Hong Kong's territorial carbon emissions (CIC, 2020). A study from the United Nations Environment Programme indicated that operational emissions account for 72% of total carbon emissions from the built environment, while construction-embodied emissions account for 28% (UNEIEA, 2017). Hence, most of the current studies and practices focus on the reduction of carbon emissions from the operation phase. However, the construction industry is a vital sector that contributes to a city's economic growth and long-term development, which will consume notable resources, such as construction materials, fuels, and electricity for various construction machinery and transportation equipment, etc., and emit a significant amount of greenhouse gases in a short period due to the consumption of these resources (Chong et al.,2013). With the wide application of green building standards to reduce the carbon emissions from the operation phase, the carbon emissions during the construction phase are becoming more and more significant (Shi et al., 2021). Hence, decarbonisation during the construction phase has attracted more and more concern in recent years.

As the major carbon emission source is the embodied carbon of construction materials, the adoption of low-carbon construction materials is the key to construction decarbonisation. Concrete and rebar are two critical materials for all building construction, which contribute more than 80% of the total carbon emissions during the construction phase. Therefore, studies and applications of low-carbon construction materials mainly focus on cement in concrete and rebar. During the last few decades, the construction sector has been looking for an alternative for Ordinary Portland Cement (OPC), the production of which causes a high carbon footprint and air pollution. In recent research, the three most remarkable types of low-carbon binders, including alkali-activated or geopolymer, carbonate, and belite-ye'elimite-based binders, have been developed rapidly in the concrete production industry to replace OPC. Among all the low-carbon binders, alkali-activated binder is currently adopted in some countries, while the other two materials are still not commercialised (Shi et al., 2019). So far, two types of binders are generally used as OPC substitutes in concrete production. Pulverised fuel ash (PFA), known as fly ash, can partially replace OPC (20% PFA and 40% PFA) to produce cost-efficient and less carbon-intensive concrete (Lai et al., 2022). Ground Granulated Blast furnace Slag (GGBS), a by-product of the steel industry, is also widely used as a partial replacement for OPC (from 0 to more than 55%) in concrete production due to its low-energy and low-carbon intensive feature (Saranya et al., 2018). Carbon capture, utilisation and storage (CCUS) applied in concrete/brick production is another cutting-edge decarbonisation approach which is adopted globally, which is estimated to save 0.1-1.4 gigatonnes of CO_2 by 2050 (Ravikumar et al., 2021). In addition, the embodied carbon of steel reinforcement bars (rebar) can be significantly reduced by switching the manufacturing process from blast furnace-basic oxygen furnaces (BF-BOFs) to electric arc furnaces (EAFs) since up to 100% of steel scrap can be fed as raw material in the EAF process (Fan and Friedmann, 2021). It is estimated that rebar made with 100% recycled content instead of iron ore can save two thirds of energy consumption in steelmaking in the United Kingdom (Sustainable Concrete UK, 2020).

In order to reduce the carbon emissions generated from on-site activities, construction site electrification, on-site renewable energy, and low-carbon alternative fuels are also encouraged. According to the research completed by the University of Queensland, there are several fossil fuel-free options for the construction phase, e.g., electricity, hydrogen, biodiesel, and renewable diesel (Heywood, 2022). Photovoltaic power generation panels (PVs) are the most popular and are being increasingly adopted in the construction phase, which could provide a substitute for electricity generated from fossil fuel for sustainable construction activities usage. Battery energy storage systems (BESSs) are commonly used in electricity grids, solar power installation, etc. and are further being introduced in the construction phase due to their competitively low carbon emissions and operating cost compared to diesel generators, less downtime in the power generating period and less noise (CLP Power Hong Kong Ltd., 2021). The combination of PVs and BESSs can shift the peak production from PVs during the nighttime, which is considered as the alternative for diesel generators in construction sites to reduce carbon emissions (Yoo et al., 2020). Other than PVs and BESSs, it is predicted that about 40% of fossil fuel-driven construction machinery can be replaced by electricity-driven ones by 2030. Another fossil fuel-free energy is hydrogen, which causes zero carbon emissions and could significantly enhance air quality on site. However, the lack of hydrogen-powered construction machinery and the availability of green hydrogen limit its application in the short and medium term (Heywood, 2022). And to further reduce carbon emissions, B5 biodiesel (5% biodiesel + 95% petroleum diesel) derived from vegetable oils or animal fats can be applied to most construction equipment (e.g., cranes, boom lifts, etc.). Nevertheless, biodiesel usage in construction sites is only limited up to B20 blends due to machinery and equipment limitations (Heywood, 2022).

With the application of low-carbon construction approaches, it is impossible to realise carbon neutrality during the construction phase due to the consumption of construction materials. PAS 2060 carbon-neutrality standard (BSI, PAS 2060:2014), the first internationally recognised standard for carbon neutrality, suggests that carbon neutrality can be achieved via four key stages: measure, reduce, offset, document, and validate. It requires the entity to implement the carbon footprint management plan and achieve a certain amount of reduction before offsetting the residual emissions. Kerry Properties Ltd. started to seek opportunities for decarbonisation and purchased Renewable Energy Certification (REC) for the first time for multiple investment properties in 2021. However, carbon offsetting sometimes plays a tricky role in reducing carbon emissions as it may lead to greenwashing when organisations do not prioritise in-house emissions reduction or double-count carbon credits. The feasibility and meaning of carbon neutrality during the construction phase should be extensively evaluated.

In view of the current applicable technologies for construction decarbonisation and the status of carbon neutrality strategies in the construction industry, this study focuses on the O•PARK2 project as a pilot trial to apply various decarbonisation approaches in civil, structural, and architectural construction for the discussion of relevant issues. Carbon reduction efficiencies of different decarbonisation approaches are evaluated accordingly. Furthermore, economic evaluation of the decarbonisation approaches is conducted. Finally, the tradeoff between carbon reduction and carbon offsetting by credit purchase is tentatively explored.

2. Methodologies applied in O•PARK2

2.1. Introduction of O•PARK2

O•PARK2 is a Design-Build-Operation (DBO) project of the Environmental Protection Department in Hong Kong, located at Sha Ling, North District of the New Territories. O•PARK2 is the second organic resources recovery centre that adopts anaerobic digestion technology in Hong Kong to convert food waste into biogas for electricity generation and fertiliser as a by-product for landscaping or agricultural applications. Based on the results from the feasibility study in early 2021, the project team has adopted different carbon reduction measures since July 2021 to reduce the emissions of the remaining period of the construction phase, including low-carbon construction materials, construction site electrification, application of renewable energy, and application of B5 biodiesel. This study focuses on the construction phase of the O•PARK2 construction site, which will be indicated as “the Project”.

2.2. Methodology for carbon accounting

2.2.1. Classification of emission sources

Emission sources from on-site activities, embodied carbon of major construction materials (i.e., cradle to gate) and office supplies during the construction phase have been identified and categorised into Category 1 to 6 in accordance with ISO 14064 (Table 1).

Table 1. Greenhouse Gas (GHG) Inventory of O•PARK2 during the construction phase in accordance with ISO 14064.

Emission category	Emission activity	Emission source
Category 1: Direct GHG emissions and removals	1.1 Personnel transportation	Owned vehicles
	1.2 Machinery and equipment operations	Construction machinery
	1.3 Welding	Welding equipment
	1.4 Fugitive emissions	Air-conditioning; fire extinguishing system
	1.5 Fuel consumption	Cooking stoves
Category 2: Indirect GHG emissions from imported energy	2.1 Imported electricity	Purchased electricity
Category 3: Indirect GHG emissions from transportation	3.1 Transportation of construction materials, supplies, and machinery	Transportation vehicles
	3.2 Waste transportation	Transportation vehicles
Category 4: Indirect GHG emissions from products used by the organisation	4.1 Purchased goods and services	Municipal water (including sewage treatment), paper, rebar, structural steel, concrete, mortar/ cement, and other construction materials
	4.2 Capital goods	Printing equipment
Category 5: GHG emissions associated with the use of products from the organisation	Not applicable*	
Category 6: Indirect GHG emissions from other sources	Not applicable**	

* O•PARK2 did not produce or sell any related products or services during the construction phase.
** No activities associated with carbon emissions from other sources have been identified.

2.2.2. The classification of carbon reduction measures and relevant baseline

In order to reasonably reflect and evaluate the carbon reduction as well as the cost-effectiveness of various measures during the construction phase, the carbon reduction of each measure is calculated based on comparing the emissions of the baseline (on-site practices before implementation of carbon reduction measures) with that of the actual situation. The details of each reduction measure and its baseline are summarised in Table 2. For easy comparison, the evaluation period for carbon emissions is from January 2021 to June 2022, while that for carbon reduction approaches are applied step by step from July 2021 to June 2022 in this study.

Table 2. Information of carbon reduction measures and relevant baseline.

Carbon reduction measure		Baseline	Start of implementation
Category 1:			
Construction Site Electrification	Battery Energy Storage System (BESS)	1 Traditional diesel generator	2021.10
	Electric vehicle (EV)	3 Petrol vehicle	2022.06
Application of B5 biodiesel	B5 biodiesel (B5)	Ultra-low-sulphur diesel (ULSD)	2022.01
Category 2			
On-site renewable energy application	Solar panels	-	2021.12
Category 4:			
Low-carbon Construction Material	100% recycled content (RC) rebar[a]	Rebar with 31%[d] RC (EAF)	2021.08
	GGBS concrete (vs. PFA)[b]	C20/20D (OPC); C45/20D (30% PFA)	2021.11
	GGBS concrete (vs. OPC)[c]	C20/20D (OPC); C45/20D (OPC)[e]	-
	CO_2 mineralisation curing concrete brick based on CCUS technology (CCUS bricks)	Local brick	2022.03

a. Rebar with 100% RC (EAF)
b. C20/20D (40% GGBS); C45/20D (60% GGBS)
c. C20/20D (40% GGBS); C45/20D (60% GGBS)
d. Average percentage of the recycled content in rebar purchased before August 2021.
e. The comparison of C45/20D (60% GGBS) with C45/20 (OPC) is further established for analysis purposes. C45/20D (30% PFA) was used in actual situations before the implementation of GGBS concrete.

2.2.3. Carbon emission and reduction calculation

The total carbon emissions of the Project during the construction phase can be calculated as follows:

$$E_T = E_1 + E_2 + E_3 + E_4 \,, \quad (1)$$

where E_T represents the total carbon emissions of the Project during the construction phase (tCO2e), and E_1., E_2, E_3 and E_4 are carbon emissions from category 1, 2, 3, and 4 as defined in Table 1.

2.2.3.1. Category 1: Direct GHG emissions and removals

The below formula shows the calculation of the emissions due to on-site construction activities:

$$E_1 = \sum_{k=1}^{K} \sum_{b=1}^{B} C_{k,b} EF_{k,b} + \sum_{x}^{X} FU_x \times A_x \times GWP_x \,, \quad (2)$$

where $C_{k,b}$ is the consumption of fuel by equipment b; $EF_{k,b}$ is the emission factor of fuel; FU_x is the charge amount of the refrigerant or fire suppressant x; A_x is the annual leakage rate; and GWP_x is the global warming potential of the refrigerant or fire suppressant *x*.

To reduce emissions generated from on-site activities, construction site electrification measures have been implemented. The diesel generator was replaced by the BESS to supply power to a tower crane while on-site petrol vehicles have been replaced by electric vehicles (EVs). To calculate the corresponding carbon reduction, the fuel consumption in the baseline is estimated based on the recorded electricity consumption in consideration of the specifications and efficiencies of the BESS and EVs.

B5 biodiesel has been applied to replace ultra-low-sulphur diesel (ULSD) for other on-site construction equipment, and the carbon reduction from the application of B5 biodiesel is calculated based on the difference in emission factors of fuels. The emission factor used for the calculation of emissions due to on-site activities is shown in regard to local standards or publications. Table 3 summarises the emission factors used for direct energy consumption.

Table 3. Emission factors for direct and indirect energy consumption.

Energy source/activity	Emission factor/ annual leakage rate	Unit	References
Electricity-CLP	0.50 (2019)	$kgCO_2e/kWh$	CLP, 2019
	0.37 (2020)		
	0.39 (2021)		
Petrol (Passenger car)	2.66	$kgCO_2e/L$	HKEPD & HKEMSD, 2010
Diesel (Stationary source)	2.62		
Diesel (Public light bus)	2.75		
Diesel (non-road mobile source)	2.62		
Acetylene	3.38	$kgCO_2e/kg$	Hong J.K. et al., 2015
LPG	3.02	$kgCO_2e/kg$	HKEPD & HKEMSD, 2010
B5 Biodiesel (Stationary source)	2.61	$kgCO_2e/L$	EPA, US, 2021
B5 Biodiesel (Non-road mobile source)	2.61		
Freshwater processing-WSD	0.42* (2020)	$kgCO_2e/m_3$	WSD, 2019-2020
Sewage treatment-DSD	0.21 (2021)		DSD, 2019-2021
Refrigerant (R-410A)	1%	\	IPCC, 2006
Fire suppressant (FM200)	2%	\	
*The published value is 0.417 kgCO2e/m3.			

2.2.3.2. *Category 2: Indirect GHG emissions from imported energy*

The formula below is used to calculate the GHG emissions from imported energy: electricity:

$$E_2 = \sum_{i=1}^{I} Q_{Elec}\, EF_{Elect}\,, \tag{3}$$

where $Q_{k,b}$ is the consumption of electricity and EF_{Elect} is the emission factor of electricity.

On-site renewable energy application is recommended to reduce Category 2 emissions. The installation of PV panels directly reduces the electricity consumption supplied by CLP Group (CLP); thus, the carbon reduction from the application of PV panels can be quantified based on the emission factor of electricity supplied by CLP. The emission factors used for imported energy are shown in Table 3.

2.2.3.3. *Category 3: Indirect GHG emissions from transportation*

The calculation of emissions from transportation includes construction materials (supplier to site), supplies and rental equipment for construction works (supplier to the site) and on-site construction waste (site to facility). In the case of limitations in obtaining the distance, estimation is conducted. The emissions from transportation can be calculated as follows:

$$E_3 = \sum_{m=1}^{M} \sum_{n=1}^{N} Q_m D_{m,n} EF_n\,, \tag{4}$$

where Q_m is the weight of cargo *m* (t); $D_{m,n}$ is the distance of transportation for cargo *M* (km); and EF_n refers to the emission factor for transport mean *n* ($kgCO_2e/tkm$). Table 4 summarises the emission factors used for transportation in this study.

Table 4. Emission factors for transportation.

Means of transport	Emission factor ($kgCO_2e/tkm$)	References
Light duty petrol truck (2t)	0.334	GBT 51366-2019
Light duty diesel truck (2t)	0.286	
Medium duty diesel truck (8t)	0.179	
Heavy duty diesel truck (18t)	0.129	
Heavy duty diesel truck (48t)	0.057	
Bulk carrier (avg.)	0.00* (2021-2022)	DBEI, UK, 2019-2022
Cargo flight (international)	1.02 (2021)	
	1.02 (2022)	
* The published value is 0.003539 $kgCO_2e/tkm$.		

2.2.3.4. *Category 4: Indirect GHG emissions from products used by the organisation*

The embodied carbon of building materials and supplies includes the emissions due to energy consumption in the resource extraction and production processes which can be calculated as follows:

$$E_4 = \sum_{i=1}^{I} Q_i\, EF_i + (W \times EF_w + S \times EF_s)\,, \tag{5}$$

where Q_i represents the quantity of building materials or office supply *i* in the unit of kg or m^3; refers to the carbon emission factor ($kgCO_2e/kg$ or $kgCO_2e/m^3$); *W* and *S* are

Table 5. Emission factors for construction materials and supplies.

Construction materials/ supplies	Description	Emission factor	Unit	References
Rebar (EAF)	100% recycled	0.55	$kgCO_2e/kg$	Calculated based on the percentage of recycled content[a]
	31% recycled	1.34		
	0% recycled	1.70		
Rebar (BF-BOF)	13% recycled	2.07		
Structural Steel (EAF)	0% recycled	1.70		
Structural Steel (BF-BOF)	0% recycled	2.3		
Concrete	20/20D 75mm	262	$kgCO_2e/m^3$	Gan et al., 2015
	30/20D 75mm	295		
	20/20D 100mm (40% GGBS)	168	$kgCO_2e/m^3$	Estimated based on the percentage of PFA or GGBS content[b]
	45/10D 150mm (25% PFA)	251		
	45/20D 150mm (30% PFA)	235		
	45/20D 150mm (60% GGBS)	156		
	50/20D 200mm (26% PFA)	269		
	Foam concrete	164	$kgCO_2e/m^3$	Estimated based on concrete mix provided from supplier
	Shotcrete	409		
	Cement mortar	409		
	Screed	259		
Local brick	-	95.7	$kgCO_2e/m^3$	Zhang et al. 2022
CCUS brick		34.7	$kgCO_2e/m^3$	
Ordinary Portland Cement		0.735	$kgCO_2e/kg$	GBT 51366-2019
Water		0.417	$kgCO_2e/m^3$	HKWSD, 2020
PFA		0.008	$kgCO_2e/kg$	CICGPC CFP Quantification Tool
GGBS		0.083	$kgCO_2e/kg$	
Sheet piling		1.55	$kgCO_2e/kg$	ICE V3.0, Bath U.
Sand		0.00*	-	Yan et al., 2010
Paint		6.83	-	ABRI, TW, 2019
Plastic Liner		2.35 (2021)	-	DBEI, UK, 2019-2022
		2.35 (2022)	-	
20mm aggregates		2.18	-	GBT 51366-2019
Paper		0.74 (2021)	$kgCO_2e/kg$	DBEI, UK, 2019-2022
		0.74 (2022)		
Printer	TASKalfa 5053ci	1455	$kgCO_2e/unit$	Product Environmental Aspect Declaration, Eco Leaf Japan, 2019
	TASKalfa 6053ci	1596		
	TASKalfa 3253ci	907		
	HP Color LaserJet Enterprise M553dn	24.87	$kgCO_2e/kg$	DBEI, UK, 2021
	HP Color LaserJet Enterprise 700 M712dn	24.87		

a. Carbon emissions of rebar and steel are calculated based on the production processes (EAF or BF-BOF) and the percentage of recycled content (scrap), with reference to the emission factors provided by Gan et al. (2017) and WSA (2011):

- Direct-reduced iron (EAF): 1.54 $kgCO_2e/kg$
- 100% scrap (EAF): 0.39 $kgCO_2e/kg$
- Pig iron (BF-BOF): 2.09 $kgCO_2e/kg$
- Carbon reduction from scrap (BF-BOF): 1.405 $kgCO_2e/kg$
- Rebar finishing: 0.16 $kgCO_2e/kg$
- Structural steel finishing: 0.21 $kgCO_2e/kg$

Thus, for the EAF process rebar with 31% recycled content, the carbon emission factor can be calculated as: 1.54×(1-31%)+0.39×31%+0.16=1.34 $kgCO_2e/kg$. For BF-BOF process structural steel with 13% recycled content, the carbon emission factor can be calculated according to the reduction from scrap: 2.09-1.405×13%+0.16= 2.07 $kgCO_2e/kg$.

b. The calculation of carbon emission factors for different types of concrete is based on the concrete mix provided by manufacturers, and emission factors for each ingredient are extracted from various publications as shown above.

*The published value is 0.0074 $kgCO_2e/kg$.

the amount of water consumed and sewage discharged; and EF_w and EF_s are the corresponding emission factors for the processing of freshwater and wastewater respectively.

For the implementation of low-carbon construction materials which includes rebar with 100% recycled content, GGBS concrete and CCUS brick, the carbon reduction for each measure is calculated based on the quantity of materials procured and the change in emission factors of materials in the baseline and reduction scenarios. The emission factor used for the calculation of embodied carbon of construction materials and supplies is shown in Table 5.

2.3. Methodology for economic analysis

Carbon reduction potential and cost increment analysis are conducted to evaluate the actual performance of each low-carbon measure adopted in O•PARK2 during the studied period, while Green Premium Index analysis is conducted to evaluate the long-term performance of low-carbon measures covering 48 months of implementation.

2.3.1. Carbon reduction potential

Carbon reduction potential evaluates the emission reduction efficiency of low-carbon measures. The low-carbon measures, baseline measures, and implementation time refer to Table 2. The carbon reduction potential of each low-carbon measure can be calculated as follows:

$$R_P = 1 - \frac{E_r}{E_b}\,, \tag{6}$$

where R_P represents the carbon reduction potential of the measure (%); E_r represents the carbon emission of the carbon reduction measure; and E_b represents the emission of the baseline measure.

2.3.2. Cost increment percentage

Cost increment percentage evaluates the investment of each low-carbon measure, consisting of capital cost and operation cost. In this analysis, the lease cost of the BESS was not included (BESS-w/o lease) as the BESS on site is a trial module supported by CLP. Other low-carbon measures, baseline measures and implementation time are listed in Table 2. The cost increment percentage of each low-carbon measure can be calculated as follows:

$$I_P = \frac{C_r}{C_b} - 1\,, \tag{7}$$

where I_P represents the cost increment percentage of the measure (%), C_r represents the cost of the carbon reduction measure, and C_b represents the cost of the baseline measure.

2.3.3. Green premium index (GPI)

In order to evaluate the cost-effectiveness of the low-carbon measures, GPI is introduced for comparison. Green premium refers to the total cost increment per unit of carbon emission reduction of the low-carbon measures, then normalised by the specific green premium of carbon credit of voluntary emission reduction projects as GPI. The GPI analysis is based on 48-month implementation of low-carbon measures. The GPI can be calculated as below:

$$G = I/R/C\,, \tag{8}$$

where G is the GPI calculated for the low-carbon measures; I is the total cost increment including operation cost and capital cost; R is the carbon reduction calculated for the measure; and C is a specific carbon credit price.

3. Results and discussion

3.1. Carbon emission and reduction

Construction works on O•PARK2 were in full swing during the studied period from January 2021 to June 2022, and the relevant carbon emissions were closely monitored. The implementation of low-carbon measures gradually commenced from August 2021 as shown in Figure 1, including low-carbon rebar and concrete for Category 4, construction site electrification and B5 biodiesel for Category 1, and renewable energy for Category 2. Low-carbon construction materials are prioritised in the decarbonisation strategy which can significantly reduce carbon emissions of Category 4. The project team applied the first lot of rebar with 100% recycled content in August 2021. Comparing the carbon emissions from Category 3 and Category 4 in August 2021 and June 2021, the rebar consumption amount in August 2021 was more than twice that in June 2021, but the responsible carbon emission in August 2021 was significantly less than that in June 2021. More rebars with 100% recycled content were purchased according to the construction progress in the following months. PFA concrete was used for the construction of the superstructures of two main buildings, while GGBS concrete was put in place for ancillary buildings from November 2021 and CCUS bricks were also introduced to build internal block walls in March 2022. The application of GGBS concrete and CCUS bricks leads to further decreased carbon emission of Category 4. The construction site electrification approaches applied in the Project are BESS and EVs. The first generation of BESS provided by CLP began to run from October 2021, while the electric vehicles were ready in place in June 2022. Although the construction activities varied every month, carbon reduction of Category 1 is still observable due to the implementation of the BESS, EVs, and B5 biodiesel on site from October 2021. Regarding renewable energy, a solar panel system was installed on the roof of the site office to supplement the electricity consumed by the site office from December 2021 and supporting EV charging from January 2022, contributing to the carbon reduction of Category 2. However, the total carbon emissions in Category 2 slightly increased due to the site electrification measures. In general, the carbon reduction potentials from different decarbonisation measures cannot be revealed well in Figure 1, because the carbon emissions from each month vary and can hardly be compared under different construction activities. Therefore, the carbon emission proportions of four categories from January 2021 to June 2021 (6 months without low-carbon measures) and July 2021 to June 2022 (12 months with step-by-step applied low-carbon measures) were further compared to analyse the overall effects of low-carbon measures.

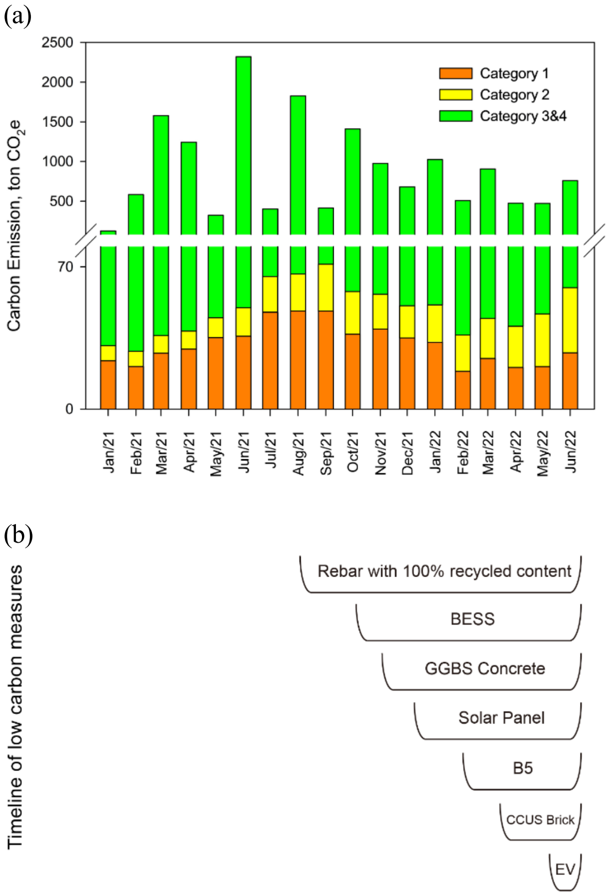


Figure 1. Monthly carbon emissions of O•PARK2 construction and low-carbon measures implementation timeline.

Figure 2 shows the carbon emission proportions before (Figure 2(a)) and after (Figure 2(b)) implementation of low-carbon measures. After adoption of low-carbon measures, the carbon emissions of Category 4 decreased from 90.39% to 86.89%, among which the carbon emission portion of rebar significantly declined from 63.75% to 34.43%. Although the carbon emission portion of concrete nearly doubled from 26.36% to 49.19% after site decarbonisation, its ratio to the carbon emissions from other materials consumption in Category 4 decreased from 97.6 to 15.0. On the contrary, the carbon emissions from the construction material transportation (Category 3) increased from 5.90% to 6.54%, because some low-carbon construction materials cannot be easily obtained locally. With the wide application of low-carbon construction materials and the development of green supply chains, the carbon emissions from Category 3 may be significantly reduced. Besides, the carbon emission proportion of Category 2 rocketed to 2.51%, mainly due to the execution of construction site electrification resulting in the carbon emission shifting from Category 1 to Category 2. Without the application of solar panels, the carbon emissions proportion of Category 2 would be even larger.

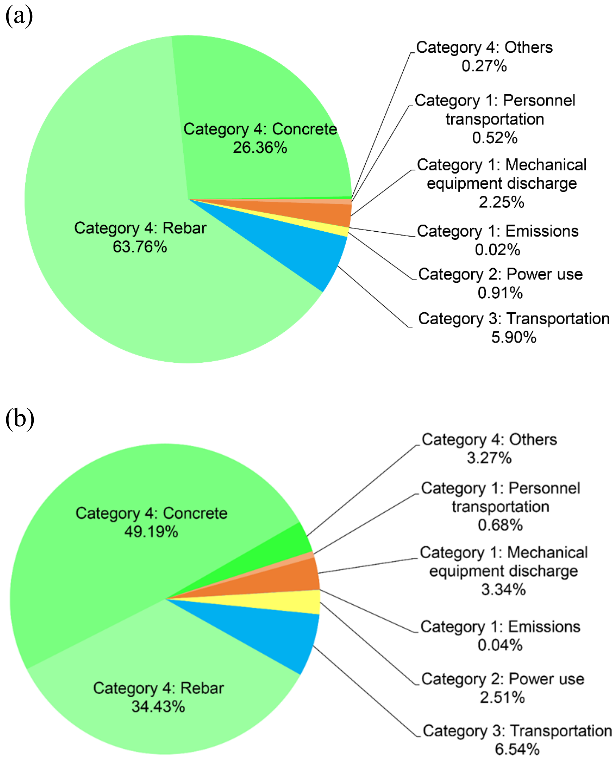


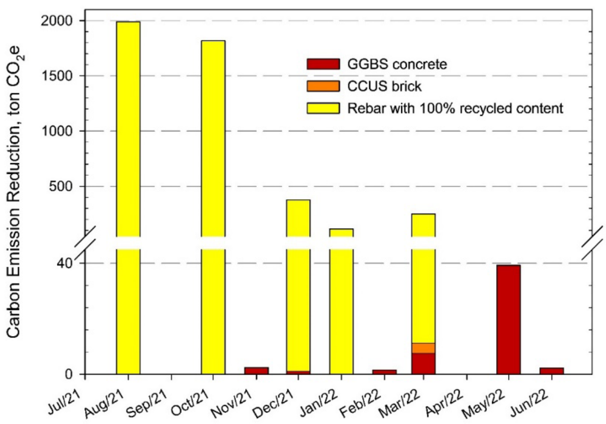
Figure 2. The proportions of carbon emission from different categories (a) before implementation of low-carbon measures (January 2021-June 2021); and (b) after implementation of low-carbon measures (July 2021 to June 2022).

The detailed carbon emission reduction performance of each low-carbon measure is shown in Figure 3. The carbon emission reduction from the application of 100% recycled rebar was significant in August 2021 and October 2021, which approached 2,000 tonnes of CO_2e in each month (Figure 3(a)). Moreover, the carbon emission reduction due to the implementation of 100% recycled rebar in 21 December, 22 January and 22 March exceeded 200 tonnes of CO_2e. The 100% recycled rebar application accounted for 47% of total rebar usage in the Project, contributing an overall 4,272 tonnes of CO_2e of carbon emission reduction. Due to the limited sources of GGBS concrete and CCUS bricks, the total carbon emission reduction from these two measures was 58 tonnes of CO_2e. In the near future, the localised GGBS source may be replaced by the municipal solid waste incineration residual from I•PARK1. For CCUS bricks, the localised technology development and the establishment of the standards in Hong Kong are key issues for wide application.

Since October 2021, the BESS exhibited stable performance with more than 1.6 tonnes of CO_2e per month of carbon emission reduction (Figure 3(b)), which was the greatest carbon reduction effect compared to other approaches for Categories 1 and 2. Solar panel ranked second to the BESS and its performance displayed apparent seasonal fluctuations. In six and a half months of application, the solar system generated 24,608 kWh, equivalent to an emission reduction of 9.6 tonnes of CO_2e (Figure 3(b)), covering 36% of total electricity consumed by the site office. The highest compensation rate was as high as 45% in March 2022. Although EV application was late and only one month's result is presented in Figure 3(b), it is expected to achieve a reduction of at least 0.6 tonnes of CO_2e emission per month with EVs in the future. As the only low-carbon alternative fuel, B5 biodiesel was used for other Powered Mechanical Equipment (PME) on site, but its contribution to carbon emission reduction was limited at less than 50 kg of CO_2e per month.

The monthly summary for carbon emission reduction cannot give an accurate picture of the performance of each low-carbon measure, so the carbon reduction potential, contribution to overall carbon reduction, and its economic analysis were further conducted.

(a)



(b)

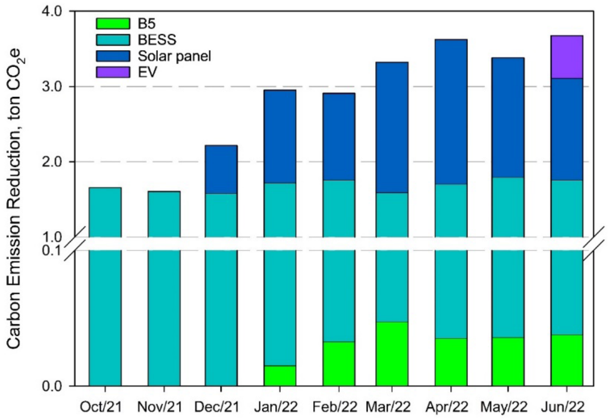


Figure 3. Monthly carbon reduction of O•PARK2 due to the implementation of (a) low-carbon construction materials; (b) BESS, electric vehicles, solar panels, and B5 biodiesel.

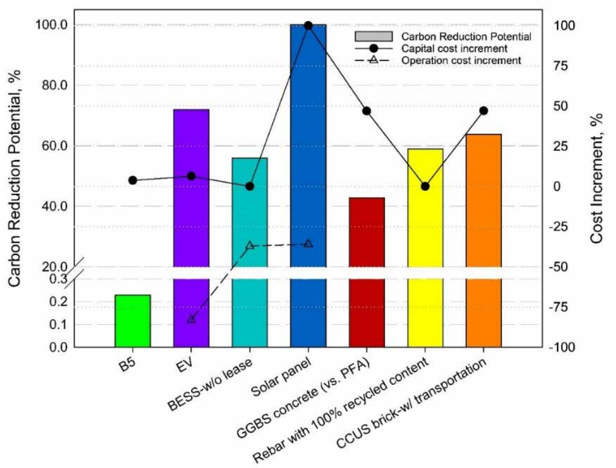
3.2. Carbon reduction efficiency and economic analysis of low-carbon measures

As aforementioned, seven low-carbon measures are adopted in O•PARK2, achieving 4,612 tonnes of CO_2e emission reduction from July 2021 to June 2022. As the feasibility of these measures has been verified in O•PARK2, their carbon reduction potential and the relevant investment are also reviewed in Figure 4. Figure 4(a) indicates the comparison between each low-carbon measure and the relevant baseline, while Figure 4(b) gives the carbon emission reduction and economic contributions from each low-carbon measure.

As shown in Figure 4(a), most of the low-carbon measures applied in the Project have a carbon reduction potential higher than 40% compared to the baseline approaches, while the cost increment varied over a large range. The EVs, BESS, and solar panels enabled a reduction of operation costs, indicating that long-term application can generate better economic benefits. The price premiums for B5 and 100% recycled rebar can be ignored, but the price premiums for GGBS concrete and CCUS bricks are approaching 50%. As aforementioned, the localised application of GGBS concrete and CCUS bricks should be seriously considered to reduce the price premium in the future.

In terms of the contribution to the overall carbon reduction performance and investment in Figure 4(b), 100% recycled rebar gives the best performance, contributing 98% of carbon reduction in this project without the price premium. On the contrary, GGBS application only led to 1.2% of total carbon reduction but consumed around 30% of the total investment for carbon reduction in this project. The investment in solar panels was the highest and contributed nearly 70% of the total investment for decarbonisation. Therefore, the solar panels will be considered to be applied in O•PARK2's operation period, to increase the decarbonisation and economic benefits.

(a)



(b)

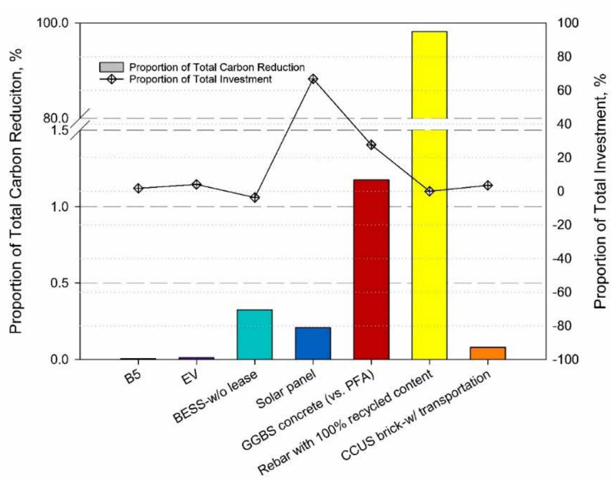


Figure 4. Economic analysis including (a) carbon reduction potential and cost increment percentage of low-carbon measures compared to the baseline approaches; and (b) the proportion of total investment for carbon reduction and contribution to total carbon reduction in O•PARK2 tests from July 2021 to June 2022 from each low-carbon measure.

3.2.1. Low-carbon construction materials

As construction materials are responsible for over 90% of carbon emissions during the construction period (Figure 2(a)), the adoption of construction materials with low embodied carbon should be prioritised. CCUS brick is introduced in Hong Kong for the first time, which can achieve 5.5% (carbon dioxide utilisation to brick weight percentage) carbon fixation efficiency during the curing process (Zhang et al., 2022). The embodied carbon of CCUS bricks is 64% lower than for local eco-bricks (Figure 4(a)). Adopting the average recycled content of rebar in this project before July 2021 as the baseline at 31%, rebar with 100% recycled content achieved a 59% emission reduction. GGBS concrete used in this project, including C45 concrete with 60% GGBS and C20 with 40% GGBS, contributed an average carbon emission reduction of 43%. If compared with C45 OPC concrete, C45 concrete with 60% GGBS can reduce carbon emissions by up to 53% (not shown in Figure 4(a)).

3.2.2. Construction site electrification

Due to the involvement of both capital and operation costs, early application of EVs, BESSs, and solar panels for construction sites is necessary. EVs and BESSs can achieve 72% and 56% carbon reduction respectively (Figure 4(a)), which will be further enhanced with the cleaner electricity system of CLP. Although the overall carbon reduction from construction site electrification was not as significant as that due to low-carbon construction materials, it is expected to perform better in the long run considering that construction site electrification also benefits noise reduction and improves air quality. In terms of operation cost, EVs can save 83% compared to petrol vehicles, while a BESS can save 37% compared to traditional diesel generators (Figure 4(a)). However, if the lease cost is considered, a BESS requires additional cost compared to traditional generators. With the rapid development of batteries, the competitive of BESSs will be enhance with lower cost.

3.2.3. On-site renewable energy application

Theoretically, a solar panel has a carbon reduction potential approaching 100% and is the most feasible renewable energy. It is estimated that 72% of electricity consumed by site offices can be supplemented if solar panels are installed on the whole roof of a site office. Standardised MiC offices equipped with solar panels could be a good option for the construction of site offices for engineering projects in rural areas. As the capital investment in solar panels is high, reusing all these MiC site offices with solar panels several times is suggested.

3.2.4. Application of B5 biodiesel

The wider use of biodiesel in lieu of fossil fuels is encouraged in Hong Kong, though B5 biodiesel has limited carbon reduction potential (Figure 4(a)). B5 has a slight cost increment, but the price fluctuates a lot depending on supply. The other low-carbon alternative fuel is hydrogen. Diesel-hydrogen hybrid engines will be a solution for PME in the near future, achieving up to a 85.9% reduction of carbon emissions with 13.3% higher efficiency than conventional diesel combustion (Liu et al., 2022).

3.3. GPI analysis

To comprehensively analyse their carbon reduction potential, operation cost and capital cost increment, the GPI of the aforementioned low-carbon measures in long-term implementation (48 months) is calculated and shown in Figure 5. The GPI of CLP green electricity is also introduced for comparison. Because the fuel adjustment cost of CLP electricity kept increasing in 2022, both the lowest one in January at 38.6 cents and the highest one at 57.3 cents in December are listed for comprehensive comparison.

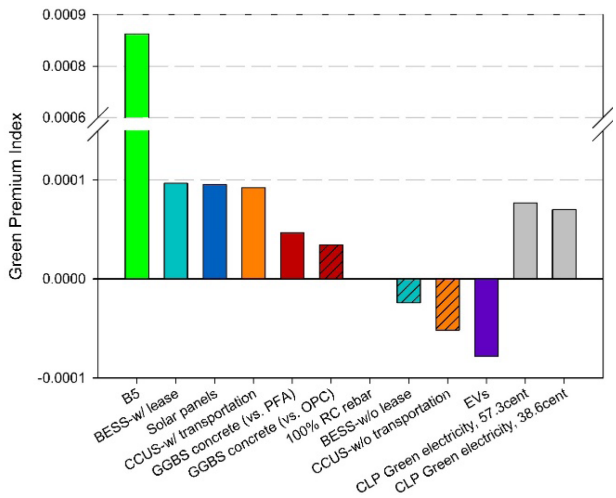


Figure 5. Greem Premium Index (GPI) of low-carbon measures in 48-month implementation.

EVs are the best choice and worth being promoted to all construction sites, which also aligns with the Hong Kong Roadmap on Popularisation of EVs. Comparing the CCUS bricks with and without transportation, CCUS bricks have high potential for being an efficient measure if localised manufacturing is realised. BESSs will become more competitive when the technology matures and the manufacturing cost is further reduced. Rebar with 100% recycled content is the most easy to accept and quick to use without cost increment, but additional cost may be incurred due to the rent of storage plant. Similarly, GGBS concrete is easy to accept and quick to use with considerable increase of cost. Due to the gradual phasing down of coal in Hong Kong, the local supply of PFA will reduce, and then incineration residual from I•PARK1 will be preferred to replace cement in ready-mix concrete. The expanding demand and local availability of GGBS concrete may reduce the GPI. Different from other measures, solar panels require large investment in the early stage. The sensitivity analysis shows that, if a solar panel operates for more than 4.8 years, a solar panel performs better than purchasing CLP green electricity; if operated for more than 6.5 years, it performs even better than purchasing CLP general electricity (not shown in the Figure). Amongst these measures, B5 is the least efficient but is the only low-carbon alternative fuel for PME at this moment.

Although the green premium of most low-carbon measures is competitive compared with CLP green electricity, it is still higher than the carbon credit price. O•PARK2 focuses on the implementation of various low-carbon measures, supplemented by the use of green finance. After striving to reduce carbon emissions by 4,612 tonnes of CO_2e, O•PARK2 purchased carbon credits from the Verified Carbon Standard Program of the Verra to offset the residual carbon emissions from September 2019 to June 2022. The retired verified carbon unit is 24,389.00 tonnes of CO_2e, as certified by a third-party verification body.

4. Conclusion

This study analyses the feasibility of various low-carbon measures, including low-carbon construction materials, construction site electrification, on-site renewable energy application, and B5 biodiesel, during the construction phase of O•PARK2 in Hong Kong. Based on 12-month implementation of low-carbon measures in O•PARK2, carbon reduction efficiency and cost increment were evaluated. In addition, 48-month implementation of low-carbon measures are projected to compare the GPI in a normal construction period in Hong Kong. The following major conclusions can be drawn.

- As the embodied carbon of construction material accounts for over 90% of total emissions, low-carbon construction materials should be prioritised in construction decarbonisation strategies. Rebar with 100% recycled content is the most effective approach, while GGBS concrete and CCUS bricks have great potential, which requires localisation planning.
- Construction site electrification is necessary in low-carbon construction and worth promoting to all construction sites. EVs not only reduce carbon emissions but also save cost, while BESSs will be more competitive with a reasonable lease cost.
- On-site renewable energy systems have the highest carbon reduction potential but require large capital investment in the early stage, which is more suitable for a project with a longer contract period where they can be reused. Standardised MiC site offices equipped with solar panel systems with multiple uses will be a good option.
- With the implementation of various low-carbon measures, considerable carbon emission reduction can be achieved. O•PARK2 has achieved 4,612 tonnes of CO_2e emission reduction in one year, and has the chance to further reduce carbon emissions.

In general, it is suggested to follow the four key stages – measure, reduce, offset, document, and validate – to achieve carbon neutrality in the construction phase, which is comprehensively proved in the O•PARK2 construction period.

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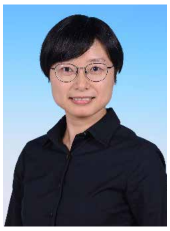

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