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RESEARCH ON CARBON ACCOUNTING AND LOW-CARBON CONSTRUCTION PATH FOR A SUPER LARGE CAVERN PROJECT IN HONG KONG

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Abstract: This paper adopts a quantitative methodology based on the Greenhouse Gas(GHG) Emission Factor methodology and refers to the latest version of the ISO 14064 Carbon Emission Standard Evaluation System to conduct a comprehensive carbon accounting about a mega cavern project located in Hong Kong. Based on the characteristics of the project, four categories of carbon emission sources and carbon emission data in the project are analyzed, including direct GHG emissions and removals, indirect GHG emissions from input energy, indirect GHG emissions from transportation and indirect GHG emissions from products used. Finally, the feasibility of low-carbon construction is analyzed for the subsequent construction phase of the project. Using the results of the project's subsequent carbon emissions analysis as a baseline, the design of low-carbon construction proposals is carried out in four aspects: concrete, steel, owned vehicles and construction machinery. Then the low-carbon construction proposals for three cases are discussed. And the final proposal is determined taking into account costs and carbon reduction benefits.

Keywords: Mega cavern project; Carbon accounting; Quantitative methodology; Low-carbon construction

1. INTRODUCTION

According to the United Nations Environment Programme (UNEP), the construction industry accounts for 30% to 40% of global energy consumption (Ramesh et al., 2010). Additionally, data from the International Energy Agency indicates that the construction sector contributes 30% to 50% of total greenhouse gas emissions. Therefore, the construction industry plays a crucial role in energy conservation and emission reduction. In the context of global efforts to promote energy conservation, emission reduction, and green, low-carbon development, the construction industry, being a high-energy-consuming and high-emission sector, has the responsibility and obligation to actively explore sustainable development paths and seek effective solutions for energy conservation, emission reduction, and green, low-carbon practices.

The lifecycle of a building typically consists of four stages: design, construction, operation, and demolition and recycling. During the construction phase, which involves the consumption of building materials, carbon emissions account for 10% to 20% of the building's lifecycle, second only to the operational phase. Therefore, conducting systematic qualitative analysis and reasonable quantitative calculations of carbon emissions during the construction phase is crucial for promoting green buildings and implementing green construction in China, providing both theoretical foundations and practical methods. Additionally, various organizations have established numerous norms and standards to guide enterprises, governments, and the public in achieving the goal of a low-carbon economy through emission reduction and energy conservation. These standards include the Greenhouse

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Gas Protocol, PAS 2050, ISO 14064, and the 2006 IPCC Guidelines for National Greenhouse Gas Inventories, all of which serve as important references for carbon emission assessments.

As research deepens, the construction industry is becoming more professional in calculating carbon emissions and carbon footprint, advancing qualitative analysis to higher levels of quantitative calculation（Wackemagel et al., 1997, Jessica A, 2008, Thomas et al., 2007, Andrew, 2008）. Nicolas H (Nicolas et al.,2012). Researchers consider key variables in the design and construction phases, gather data from material suppliers, and develop tools to estimate the total carbon footprint of construction projects, covering various stages. A. Thomas A (Thomas et al., 2009) proposed a decision-making framework that can analyze the carbon emissions of aggregates used in construction, providing a basis for grading and mixing aggregates. Monahan J (Monahan et al., 2011) uses a lifecycle approach to calculate the consumption of materials and fossil fuels during the building's use phase, comparing the implicit carbon emissions of traditional and modern construction methods. He found that concrete, a key material, accounts for nearly 36% of the total implicit carbon (Hammond et al., 2008). G.P. Hammond created a database of embodied energy and carbon emission factors for building materials, primarily targeting the UK market but widely used in multiple fields and by developers of various carbon and environmental footprint calculation tools.

To address the impact of construction on greenhouse gas emissions, governments and research institutions in several countries have conducted foundational studies. These studies aim to support the auditing of greenhouse gas emissions and promote the evaluation of sustainable buildings. Through these efforts, research teams have compiled a list of building materials and developed a database of carbon emission coefficients, forming a set of tools for assessing the environmental impact of construction. These tools provide crucial support and reference for evaluating the environmental impact of construction projects. Notable examples include the Build Carbon Neutral program in the United States and the UK's Construction Carbon Footprint Calculator, both of which are known for their high data integrity and consistency.

This article, based on a super-large cavern project in Hong Kong, uses the ISO 14064-1:2018 carbon emission evaluation standard system to conduct a carbon inventory during the construction phase and provides a feasibility analysis of low-carbon construction. As the largest cavern project in Hong Kong and even in Asia, the results of this carbon inventory analysis will serve as a reference for the design of low-carbon construction plans for future cavern projects, offering significant engineering guidance.

2. PROJECT OVERVIEW

In December 2017, the Hong Kong Development Bureau issued policy guidelines for the development of caverns to increase land supply. These guidelines included the issuance of the Cavern Master Plan and related planning and technical guidelines. This large-scale cavern project is the first initiative by the Development Bureau to relocate government facilities into caverns, freeing up 28 hectares of land for other public welfare purposes. The project involves site development, main cavern construction, ventilation systems, and ancillary buildings. Construction methods include drilling and blasting, permanent anchor support, OHVD, and other techniques. Additionally, the project includes stone crushing and recycling measures to reduce carbon emissions.

The Hong Kong government has launched the 2035 Resource Recycling Blueprint, with the slogan : Reduce Waste for All, Recycle Resources, and Achieve Zero Landfill. This was followed by the 2025 Hong Kong Climate Blueprint, which aims to achieve an absolute emission reduction of 26%-36%. This project is the largest cave engineering development project currently underway in Hong Kong and Asia. To understand the current greenhouse gas emissions, identify, quantify, and analyze potential emission reduction directions and measures, and to develop relevant management strategies for the construction team in this cave engineering project, the project team has planned this greenhouse gas quantification report.

This GHG quantification report is prepared in accordance with ISO 14064-1:2018, which is established by the International Organization for Standardization (ISO) to provide international uniform specifications and guidelines for quantification of GHG emissions and removals and for this report.

3. PRINCIPLE OF DRILLING AND BLASTING METHOD

3.1. Purpose and process of carbon inventory

To actively respond to local policies and the group's sustainable development plan, this paper analyzes the carbon emissions during the current construction phase of the project, based on its characteristics. It also examines the carbon emissions from different methods of gravel processing and evaluates the effectiveness of current emission reduction measures. Through a carbon inventory, an internal carbon management process is established, and the feasibility of low-carbon construction practices in this project is studied, laying the groundwork for future implementation.

The technical route of carbon inventory and low-carbon construction feasibility analysis in this paper is shown in Figure 1:

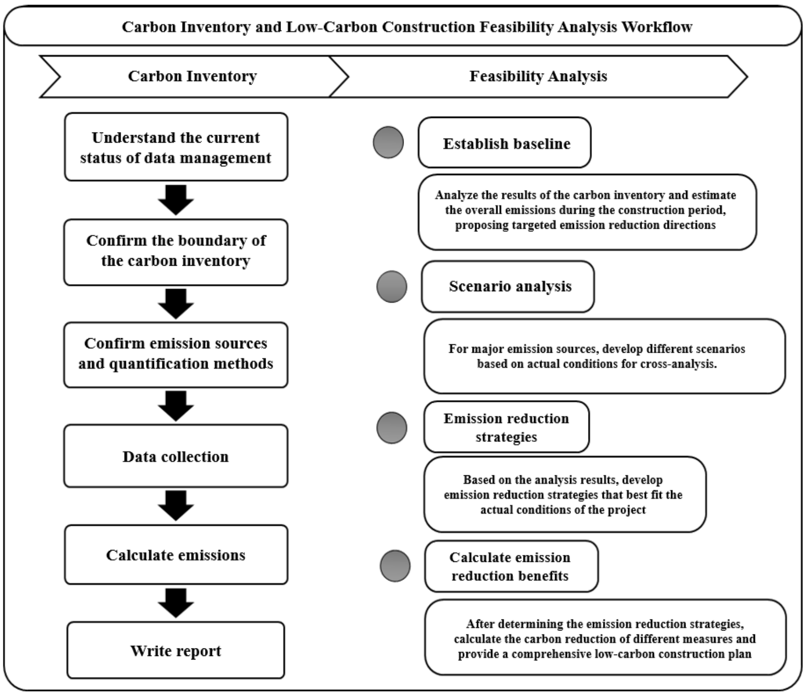

Figure 1. *Carbon Inventory and Low-Carbon Construction Feasibility Analysis Technology Roadmap*.

3.2. Organizational boundaries and reporting period

3.2.1. Organization boundary setting

This report defines the organizational boundaries according to the operational control rights law, identifies direct and indirect emission sources of facilities managed or controlled by the construction team in terms of operations, and quantifies the identified greenhouse gas emissions. The greenhouse gas accounting for this construction period will cover the works undertaken by the construction team in the cave project, including site survey and leveling, main cave engineering, earthwork and pile foundation engineering, road channel engineering, interstone engineering, office building construction, public utility engineering, and the daily operation of the site office. The defined organizational boundaries include the tunnels and peripheral works of this cave project, as well as the stone quarry and new and old office buildings.

3.2.2. Reporting period and report description

The time frame of this report covers the construction period from July 1, 2021 to March 31,2023 (hereinafter referred to as "reporting period"). This report takes all greenhouse gases generated or involved by the project within the organizational boundary during the reporting period as the accounting scope and quantifies the expected emission reduction measures.

In order to ensure the accuracy of data quality, the project working group will keep the original data files, such as purchase records, transportation records, measurement records, etc., through internal electronic platforms or reports for future verification and tracking.

3.3. Report boundaries

3.3.1. Report boundary definition

Within the established organizational boundaries, the scope of direct and indirect GHG emissions from the project construction process is referred to as the reporting boundary. Based on the characteristics of the emission activities, the reporting boundary is divided into categories 1 through 6:

Category 1: Direct greenhouse gas emissions and removals, i.e. direct emissions and removals owned or controlled by reporting organizations within the organizational boundary;

Category 2: Indirect greenhouse gas emissions from energy inputs, which include only indirect greenhouse gas emissions from fuel combustion associated with the production of final energy and utilities (excluding upstream emissions associated with fuels);

Category 3: Indirect greenhouse gas emissions from transport, that is, indirect greenhouse gas emissions related to transport outside the organizational boundary, such as material and building materials transportation, waste transportation and business travel;

Category 4: Indirect greenhouse gas emissions from the products used, that is, indirect emissions from the products or services used by the project from outside the organizational boundary, such as the implied carbon of outsourced products and capital goods, waste and water treatment processes;

Category 5: Greenhouse gas emissions related to the use of products, that is, greenhouse gas emissions or removals involved in the life cycle of products produced and sold by the project, such as emissions or removals during the use phase of the product, emissions at the end of the life of the product, emissions associated with investment, etc.;

Category 6: Greenhouse gas emissions from other sources, that is, emissions involved in any project but not included in the above categories, as defined by the reporting agency.

3.3.2. Report boundary setting

This report identifies emission sources across various categories by carefully defining the reporting boundaries, identifying all potential emission sources. Based on interviews with personnel, feedback from data collection lists, data collection, and field visits, the report primarily assesses whether these emission activities are quantified based on the reporting organization's control over these activities within its organizational boundaries and the sources of activity data.

After a thorough investigation of the emission sources of the project during the reporting period, the boundaries for this greenhouse gas accounting report are set from Category 1 to Category 6. However, emissions in Categories 3, 5, and 6 are not currently relevant or applicable to this project. In accordance with the ISO 14064-1:2018 reporting standards and requirements, the emission sources of this super-large cavern project during the reporting period are detailed in Table 1.

Table 1. List of Emission Sources in the Reporting Period of the Mega Cavern Project

Emission categories	Emissions activities	Emission source
Category 1: Direct greenhouse gas emissions and removals	1.1 Fixed source combustion	Mechanical equipment
	1.2 Combustion of mobile sources	Personal vehicles, machinery and equipment
	1.3 Process	Welding process
	1.4 Emissary discharge	Fire extinguishers, refrigerants
	1.5 Explosive blasting discharge	Explosive
Category 2: Indirect greenhouse gas emissions from energy inputs	2.1 Input power	External power purchase
Category 3: Indirect greenhouse gas emissions from transport	3.1 Transportation of building materials, materials and mechanical equipment	Conveyance
	3.2 Waste transportation	Conveyance
	3.3 Commuting	Not applicable
	3.4 Travel of customers and visitors	Not applicable
	3.5 Business travel	Uninvolved
Category 4: Indirect greenhouse gas emissions from products	4.1 Outsourced goods and services	Municipal water (including sewage treatment), crushed stone crushing and screening, paper, steel bars, concrete

used	4.2 Capital goods	ED
Category 5: Greenhouse gas emissions associated with product use		Uninvolved
Category 6: Other indirect greenhouse gas emissions		Uninvolved
Direct greenhouse gas emissions from biomass combustion	B5 biodiesel	Mechanical equipment

The criteria for judging the significance of indirect GHG emissions include: quantification methods, availability of emission factors, significance of emissions, availability and accuracy of data, and quantification costs. The exclusion items and explanations of the boundaries of this report are as follows:

(1) For category 3.3 employee commuting and 3.4 customer and visitor travel, considering the complexity of employee or customer travel patterns during the reporting period, the difficulty of systematic data collection and collation, and the quantified costs, such emissions activities cannot collect accurate data and are relatively insignificant, so they are excluded from the boundary of this report.

(2) For category 3.5 Business travel, the reporting institution is not involved in such emissions as it does not involve any business travel related activities during the reporting period.

(3) For category V, the reporting institution is not involved in such emissions as it did not produce or sell any related products or services during the reporting period.

For category VI, the reporting institution is not involved in any other project-related emissions activities during the reporting period, and therefore the reporting institution is not involved in such emissions.

3.4. Quantification of greenhouse gases

3.4.1. Quantitative criteria

According to the Kyoto Protocol, six greenhouse gases are included: carbon dioxide (CO2), methane (CH4), nitrous oxide (N2O), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulfur hexafluoride (SF6). This report also references ISO 14064-1:2018, which includes nitrogen trifluoride (NF3) as one of the categories for calculating direct greenhouse gas emissions. When original data is sufficient, the most suitable quantification standard at the project site is prioritized for calculation. If original data collection is limited, the actual situation will be considered, and a feasible method will be chosen for calculation. The final result of this greenhouse gas quantification is expressed in carbon dioxide equivalent (CO2e).

The specific information involved in the accounting process, such as quantitative methods, activity data and emission factors, is shown in Table 2.

Table 2. Quantitative methodology and emission factors for GHG

Quantitative approach	The main method is emission coefficient method, and the calculation formula is: Greenhouse gas emissions = activity data x emission coefficient x global warming potential (GWP); Some emissions sources obtain data from other publicly available databases.
Activity data	It is mainly collected by two methods: actual measurement and estimation; Priority is given to actual measurements. Where actual measurement data are not available, the report makes an estimate of emissions from activities based on reasonable assumptions or applicable reference materials.
Emission factor	The emission factors calculated in this carbon inventory are selected according to the following priorities to ensure the accuracy of the calculation results: Existing greenhouse gas quantification standards of national or regional governments; Industry emission factors in specific industry literature; General emission factors issued by international authoritative organizations and government agencies; Enterprises themselves publish greenhouse gas quantification standards to

	select emission factors; Complete the quantification work.

For category five, which pertains to indirect greenhouse gas emissions related to product use, this project does not currently address such emissions. Similarly, for category six, which involves indirect greenhouse gas emissions from other sources, this project also does not address these emissions. Therefore, this article will focus on greenhouse gas emissions related to categories one through four.

3.4.2. Category 1: Direct GHG emissions and removals

(1) Fixed source combustion

According to the statistical records from the reporting period, the fixed-source machinery and equipment used by the reporting institution include generators, fans, and vibration clamps. Given the significant difficulty and labor intensity of record segmentation, the project's equipment, including both owned and leased by contractors, is combined for calculation. The machinery and equipment used in the project were utilized from July 2021 to March 2022, during the first and second phases of the project. The usage frequency and power consumption of the machinery and equipment were nearly equal between the two phases, so the fixed-source greenhouse gas emissions from the use of machinery and equipment are allocated equally between the first and second phases. The fuel used for the machinery and equipment includes B5 biodiesel, and the greenhouse gas emission coefficient for fuel combustion is detailed in Appendix I. The CO2 emissions from the combustion of the biomass portion of B5 biodiesel will be separately calculated and reported under the category' Direct greenhouse gas emissions from biomass combustion' in Section 3.4.6, and will not be included in the total emissions.

Direct emissions from mechanical equipment (fixed sources):

$$\text{Emissions}(CO_2) = \sum \text{Fuel consumption} \times CO_2\text{Emission coefficient} \qquad (1)$$

$$\text{Emission}\left(\frac{CH_4}{N_2O}\right) = \sum \text{Fuel consumption} \times \text{Emission coefficient}\left(\frac{CH_4}{N_2O}\right) \times GWP \qquad (2)$$

In formulas (1) and (2), the calculation is based on the emission coefficient of different fuels; fuel consumption is measured in litres (L).

(2) Mobile source combustion

During the reporting period, a total of 24 private cars, 9 light trucks, 4 medium and heavy trucks, 2 minibuses, and 1 traffic signal vehicle were held. The private cars, light trucks, medium and heavy trucks, and minibuses were used for personnel transportation, while the traffic signal vehicle was used for site traffic management. The non-road mobile sources used in the project included excavators, pile foundations, large cranes, concrete spraying trucks, dump trucks, loaders, aerial work platforms, tunnel drilling machines, earth compactors, concrete tankers, sand-carrying barges, tugboats, and flat barges. The transportation vehicles used in the project participated in the first and second phases of the project from July 2021 to March 2022. The usage frequency and power consumption ratio of the vehicles in both phases were nearly 1:1, so the greenhouse gas emissions from the use of transportation vehicles were allocated equally between the first and second phases. Private cars run on gasoline, light trucks, medium and heavy trucks, and traffic signal vehicles run on diesel, and minibuses run on liquefied petroleum gas. The fuel for non-road mobile source equipment is B5 biodiesel and fuel oil (ship use). The emission factors for the fuels used in the selected own vehicles and non-road mobile sources are detailed in Appendix I.

Direct emission reference formula (1) and (2) for self-owned vehicles and mechanical equipment (non-road mobile sources). Emission is based on the corresponding emission coefficient of vehicle type and fuel used by mechanical equipment; fuel consumption L count.

(3) Welding process

During the construction process, this project uses acetylene to protect the carbon dioxide shielding gas, which is directly released into the air. To address the greenhouse gas emissions from the combustion of acetylene during welding, this project quantified the emissions using Hong et al. (Hong et al., 2015) academic paper, selecting a value of 3.39 kgCO2e/kg for the greenhouse gas emissions from acetylene welding.

The direct emission of the welding process (process) by the institution is referenced to formula (1), and the consumption of acetylene is measured in kg.

(4) Escape discharge

During the reporting period, institutions purchased and used fire extinguishers and air conditioners, leading to greenhouse gas emissions during storage and use. To quantify these emissions, this study references the IPC (Agarwal et al., 2005) report on refrigerants, which provides annual emission rates for different types of air conditioners. Based on the institutional data on the purchase quantities of fire extinguishers and air conditioners, their pre-filling amounts, and their global warming potential (GWP) coefficients, the study calculates the greenhouse gas emissions from these emissions. The annual emission rate for window and split-type air conditioners is assumed to be 1%, while for ceiling-mounted air conditioners, it is assumed to be 3%. For some air conditioners, the pre-filling amount of refrigerant was not provided, so the report estimates it based on the specifications of the air conditioners. The fire extinguishing system used in the project was shared between the first and second phases of the project from July 2021 to March 2022, so the emissions from the fire extinguishing system are allocated equally between the two phases.

Direct emission of fire extinguishers and refrigerants:

$$\text{Emission}(CO_2e) = \sum \frac{\text{Fire extinguishers}}{\text{Fefrigerant purchase amount}} \times \text{Anual emission rate} \times \text{Global warming potential coefficient} \quad (3)$$

In formula (3), the pre-filled amount of greenhouse gas in the fire extinguisher/refrigerant is measured in kg.

(5) Ejection of explosives

During the project's reporting period, blasting operations were conducted using explosives, and the carbon dioxide produced during the blasting process was directly released into the air. To quantify the greenhouse gas emissions from the combustion of explosives during blasting, the emission factors were calculated using the chemical metering method based on the components that would produce greenhouse gases when burned. The emission factors for various types of explosives are detailed in Appendix I.

The direct discharge reference formula for explosives is (1), and the consumption of explosives is measured in kg, nos. (nos.) and m according to different types.

3.4.3. Category 2: Indirect greenhouse gas emissions from purchased energy

During the reporting period, the project's power system operated normally, and the power usage of both the new and old office buildings and the site was combined for calculation. The project is located in the New Territories and is supplied by CLP Power Limited. This project quantified the greenhouse gas emissions from purchased electricity using the emission factors published in CLP Power Limited's 2021-2022 Sustainability Report. The electricity purchased by the project was used jointly by the first and second phases from July 2021 to March 2022, so the indirect greenhouse gas emissions from the purchased electricity were allocated equally between the first and second phases. For more details on the greenhouse gas emission factors for the purchased electricity, see Appendix I.

Indirect emissions from purchased electricity:

$$\text{Emissions}(CO_2e) = \text{Electricity purchased} \times \text{Emission coefficient} \quad (4)$$

In formula (4), the purchased electricity is measured in kilowatt-hours (kWh).

3.4.4. Category 3: Indirect greenhouse gas emissions from transport

This report calculates the greenhouse gas emissions from the transportation of building materials, supplies, and machinery to construction sites, as well as the transportation of waste generated at these sites to landfills. Due to the lack of information on transportation distances and types of transport for building materials, supplies, machinery, and general waste, only the manufacturer/supplier, warehouse location, and waste disposal points are provided. Therefore, this report estimates and assumes the transportation distances from the starting point of building materials, supplies, and machinery to the construction site, and from the construction site to the disposal points (including overseas, cross-border, and domestic transportation if applicable) using Google Maps' general transportation distances. The transport vehicles are assumed based on the weight of the transported items. For the greenhouse gas emission factors for these transportation processes, please refer to Appendix I.

Indirect emissions from transport:

$$\text{Emissions}(CO_2e) = \text{Transport weight} \times \text{Distance} \times \text{Emission coefficient} \quad (5)$$

In formula (5), the transport weight and transport distance are measured in tons (t) and kilometers (km) respectively.

3.4.5. Category 4: Indirect greenhouse gas emissions from products used

(1) Outsourced goods and services

Municipal water (including sewage treatment) is supplied to the office building and site by the Water Supplies Department. The municipal water and sewage treatment used in the project were shared between the first and second phases of the project from July 2021 to March 2022. Therefore, the indirect greenhouse gas emissions from municipal water and sewage treatment are allocated in a 1:1 ratio to the first and second phases of the project for calculation purposes. As of the date of this report's release, the Water Supplies Department has not published the 2021/2022 annual report. Thus, this quantification reference is based on the greenhouse gas emission factor for electricity use in water treatment published in the 2020/2021 annual report. For more details on the greenhouse gas emission factor, see Appendix I.

Indirect emissions from the use of electricity by the Water Supplies Department to treat drinking water:

$$\text{Emissions}(CO_2e) = \text{Fresh water consumption} \times \text{Emission coefficient} \quad (6)$$

In formula (6), water consumption is measured in cubic meters (m3).

Wastewater discharge from office buildings. This item combines the domestic wastewater from office buildings and mobile toilets with the wastewater from mobile toilets on the site for calculation. It quantifies the average greenhouse gas emissions per unit volume of domestic wastewater treated by the Drainage Department. All wastewater from office buildings is discharged through sewage pipes into the Drainage Department's sewage wells, while the wastewater from mobile toilets on the site is collected by a contracted company and sent to the Drainage Department's wastewater treatment facilities. The volume of domestic wastewater from office buildings is estimated based on the specifications of mobile toilets and the collection records of the contracted company's suction trucks. The collection frequency of the contracted company is recorded by the institution, with mobile toilets having a capacity of 0.5m³ and suction trucks having a capacity of 12m³. This item references the greenhouse gas emission factors for electricity used in wastewater treatment, as published in the Drainage Department's 2020/2021 and 2021/2022 Sustainability Reports, with detailed reference information provided in Appendix I.

Indirect discharge from the treatment of sewage by the Water Supplies Department

$$\text{Emissions}(CO_2e) = \text{Sewage discharge} \times \text{Emission coefficient} \quad (7)$$

In formula (7), the sewage discharge is measured in m3.

Crushed stone crushing and screening. Within the organizational boundary, the project purchased crushed stone crushing and screening services from sub-contractors during the reporting period. The machinery and equipment used for crushing and screening involved B5 biodiesel, which indirectly generated greenhouse gas emissions. Refer to Table 5 for the emission factors of B5 biodiesel.

The indirect emission of machinery and equipment (fixed source) in outsourcing services is referenced to formula (1) and (2).

Paper, steel bars, and concrete. Within the project's organizational boundaries, the project mainly purchased and used materials such as paper, I-beams, angle irons, and concrete during the reporting period. Since the recycling ratio of all materials used could not be provided, they were all assumed to be produced from pig iron. The paper purchased was used jointly by the first and second phases of the project from July 2021 to March 2022. Therefore, the greenhouse gas emissions from the paper used during this period were allocated equally between the first and second phases. For more details on the carbon emission coefficients of the main materials and building materials used during the reporting period, see Appendix One.

Indirect emissions from the use of materials and building materials (material implied carbon)

$$\text{Emissions}(CO_2e) = \sum \text{Material purchase} \times \text{Emission coefficient} \quad (8)$$

In formula (8), different material types are calculated according to the corresponding weight or volume units, including t, kg and m3; the emission coefficient of some building materials such as concrete and steel is estimated by referring to academic articles, databases and combining the actual production mode and ratio of materials.

(2) Capital goods

During the reporting period, the project purchased copiers, computer hosts, etc.

The indirect emissions caused by capital goods such as laptops and printers are calculated as follows, and the corresponding emission factors are recorded in the table below.

The indirect emission reference formula (8) for capital goods is based on different material types according to the corresponding units; it involves the integration of emission coefficients and unit conversion.

The emission coefficient of concrete will vary depending on the proportion of fly ash (PFA) regenerated components contained in it. The emission coefficient of concrete used in this project is calculated according to the proportion of fly ash regenerated components used. For example, the emission coefficient of concrete 20/20D+PFA with 3% regenerated components can be calculated as:

$$262 \times (1\text{-}3\%)+3\% \times 12 = 254.50 \text{ kgCO2e/kg}$$

3.4.6. Direct greenhouse gas emissions from biomass combustion

The direct greenhouse gas emissions from biomass combustion include the carbon dioxide released by the combustion of biomass components in B100 biodiesel and B5 biodiesel, that is, the amount of carbon dioxide absorbed by the fuel source itself during its growth stage. See Table 12 for the emission coefficient used in the calculation.

The reference for direct emission of biomass combustion is formula (1), and the fuel consumption is measured in L.

3.5. Summary of greenhouse gas emission quantification results

From July 1, 2021, to March 31,2023, the total greenhouse gas emissions from this super-large cavern project were 18,383.46 tCO2e, with Category I emissions at 4,007.39 tCO2e, Category II emissions at 2,025.73 tCO2e, Category III emissions at 3,157.57 tCO2e, and Category IV emissions at 9,192.77 tCO2e. There were no emissions from Category V or Category VI. The total direct greenhouse gas emissions and indirect greenhouse gas emissions were 4,007.39 tCO2e and 14,376.06 tCO2e, respectively. Appendix II: The quantified results of greenhouse gas emissions summarize the various sources and data of greenhouse gas emissions from this super-large cavern project.

The percentages of greenhouse gas emissions by each emission category are as follows: Category One accounts for 21.80%, Category Two for 11.02%, Category Three for 17.18%, Category Four for 50.01%, and Categories Five and Six together account for 0% (no sources or data for these emissions). Ranked by the source of emissions, the use of concrete is the primary source of greenhouse gas emissions, with a total of 5,604.80 tCO2e, accounting for 30.49% of the project's total emissions. The second largest contributor is the embodied carbon from purchased steel, at 3,185.38 tCO2e (17.33%), followed by waste transportation, at 3,101.11 tCO2e (16.87%). The remaining emissions account for 35.32% of the project's total.

3.6. Greenhouse gas strategy

Unlike the carbon reduction during the operation phase, which primarily focuses on direct greenhouse gas emissions from fixed and mobile sources, as well as indirect emissions from purchased electricity, the carbon footprint of building materials accounts for over 80% of construction period emissions. Therefore, emission reduction measures downstream in the value chain are essential for reducing construction period emissions. However, achieving this requires the collaborative efforts of the construction industry value chain, meeting the design requirements of developers and architects while working with suppliers to find suitable low-carbon building materials. The specific carbon reduction measures implemented on the site are listed in Table 3.

Table 3. Carbon reduction measures

Carbon reduction measures	**Domain**	**Office**
Direct greenhouse gas emissions	Use biodiesel to operate site machinery and equipment.	Low-carbon travel, promote electric vehicles.
Other indirect greenhouse gas emissions	Supply chain management, using low carbon building materials such as PFA concrete.	Increase the application rate of smart construction sites on new sites.

By March 31,2023, the project had implemented various carbon reduction measures, including replacing conventional diesel with B5 biodiesel and substituting ordinary concrete with PFA (fly ash) concrete that contains recycled materials. The effectiveness of these measures has been documented. During the reporting period, these measures collectively reduced carbon emissions by 412.60 tCO2e. For details on the effectiveness of each measure, see Table 4.

Table 4. *Effectiveness of carbon reduction measures*

Carbon reduction measures	**Carbon footprint reduction (tCO2e)**	**Office carbon reduction (tCO2e)**	**Overall carbon reduction (tCO2e)**
Scope 1 carbon reduction measures			
1.1 Use of B5 biodiesel (as opposed to regular diesel)	179.16	-	179.16

Scope 3 carbon reduction measures			
3.1 PFA concrete (as compared to concrete without recycled components)	233.44	-	233.44
Total (tCO2e)			412.60

4. FEASIBILITY ANALYSIS OF LOW-CARBON CONSTRUCTION

4.1. Baseline and scenario setting

This article analyzes the carbon emissions of the project over a 46-month period from April 2023 to February 2027, based on the construction plan. The analysis results are used as a baseline to design low-carbon construction solutions for four areas: concrete, steel, company-owned vehicles, and construction machinery. Three scenarios are established. In each scenario, the selection of low-carbon building materials is guided by local and international standards, the product catalogs of local suppliers, and recommendations from relevant institutions. The number of electric vehicle replacements is determined based on the data and types planned by the procurement department. Construction machinery replacements prioritize the types needed for future projects. The implementation scenarios combine emission reduction measures under different conditions, considering factors such as feasibility, practicality, economic costs, and carbon reduction benefits.

Table 5. Low-carbon construction proposals for a baseline and three cases

Emission reduction measures	**Baseline scenario setting**	**Scenario 1 is set**	**Scenario 2 is set**	**Scenario 3 is set**	**Implement scenario setting**
Concrete	Based on the actual concrete mix ratio provided	All replaced with 35% PFA (fly ash)	All replaced with 45% GGBS (fly ash)	All replaced with 75% GGBS	All replaced with 45% GGBS
Steel Products	0% RC BF-BOF (Oxygen furnace smelting)	50% RC EAF (Arc furnace smelting)	75% RC EAF	100% RC EAF	100% RC EAF
Private vehicles	Eight fuel private cars Two natural gas minibuses Nine fuel-powered pickup trucks	Eight electric private cars Two natural gas minibuses Nine fuel-powered pickup trucks	Eight electric private cars Two electric minibuses	Eight electric private cars Two electric minibuses Nine electric pickup trucks	Eight electric private cars Two natural gas minibuses Nine fuel-powered pickup trucks
Construction machinery	Diesel machinery and equipment	Replacement of electrical and mechanical equipment, including: Other mechanical equipment: air compressor, dump truck, forklift, aerial work platform, concrete tank truck, crane	Replacement of electrical and mechanical equipment, including: Other mechanical equipment: air compressor, dump truck, forklift, aerial work platform, concrete tank truck, crane excavator	Replacement of electrical and mechanical equipment, including: Other mechanical equipment: air compressor, dump truck, forklift, aerial work platform, concrete tank truck, crane Excavators,	Replacement of electrical and mechanical equipment, including: Other mechanical equipment: air compressor, dump truck, forklift, aerial work platform, concrete tank truck, crane

				loaders	

4.2. Quantitative methodology--prediction method and prediction results

The carbon emission analysis of section 4.1 baseline and three scenarios is carried out by using the quantitative methodology in Section 3.4. The greenhouse gas emission sources and emissions of the project are based on past carbon emission data per unit time and future construction period or related unit estimates.

The emission results under the baseline scenario are shown in Figure 2. It is evident that the primary sources of emissions during the project's 46-month construction period are concrete, steel embodied carbon, the use of machinery and equipment, and waste transportation. Under the baseline scenario, the total greenhouse gas emissions for the project over the 46-month construction period are 155,018.93 tCO2e. The largest source of greenhouse gas emissions is concrete, with an emission of 105,844.38 tCO2e; followed by steel embodied carbon, with an emission of 27,500.57 tCO2e; machinery and equipment emissions amount to 7,337.87 tCO2e, and waste transportation emissions amount to 5,536.75 tCO2e.

The percentages of future construction period emissions and reductions under each scenario are shown in Table 6. Compared to the baseline scenario, the total greenhouse gas emissions for Scenarios 1, 2, and 3 are 119,375.50 tCO2e,105,019.55 tCO2e, and 67,794.73 tCO2e, respectively, with carbon reduction percentages of 22.99%,32.25%, and 56.27%. The total greenhouse gas emissions for the implementation scenarios are 105,025.49 tCO2e, with a total carbon reduction of 9,993.44 tCO2e, representing a carbon reduction percentage of 32.25%.

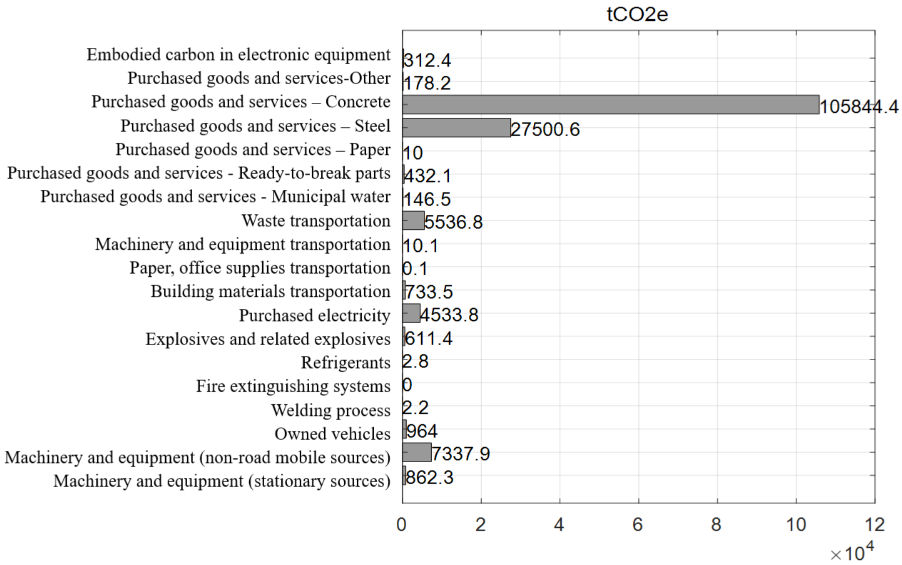

Figure 2. GHG emission results for the baseline during the next 46 months of the construction period

Table 6. Results of GHG emissions of three cases for the future construction period

Emission categories	**Emission source**	**Scenario 1 Future emissions (tCO2e)**	**Scenario 2 Future emissions (tCO2e)**	**Scenario 3 Future emissions (tCO2e)**	**Implement scenario future emissions (tCO2e)**
Category 1: Direct	MECHANICAL EQUIPMENT	858.07	858.07	858.07	858.07

greenhouse gas emissions and removals	(FIXED SOURCES)				
	Mechanical equipment (non-road mobile sources)	5,964.73	2,015.52	1,495.68	2,015.52
	Personal vehicles	824.01	818.07	698.40	824.01
	Process engineering	2.16	2.16	2.16	2.16
	Fire-extinguishing system	0.00	0.00	0.00	0.00
	Cryogen	2.76	2.76	2.76	2.76
	Explosives and related blasting supplies	611.39	611.39	611.39	611.39
	Direct greenhouse gas emissions	8,263.13	4,307.97	3,668.46	4,313.91
Category 2: Indirect greenhouse gas emissions from energy inputs	External power purchase	5,560.42	8,504.07	8,891.54	8,504.07
Category 3: Indirect greenhouse gas emissions from transport	Building materials transportation	733.51	733.51	733.51	733.51
	Paper and office supplies transportation	0.11	0.11	0.11	0.11
	Mechanical and electrical equipment transportation	10.14	10.14	10.14	10.14
	Waste transport	5,536.75	5,536.75	5,536.75	5,536.75
Category 4: Indirect greenhouse gas emissions from products used	Outsourced goods and services-municipal water	146.48	146.48	146.48	146.48
	Sourced goods and services-crushed stone crushing and screening	432.13	432.13	432.13	432.13
	Sourcing of goods and services-paper	10.01	10.01	10.01	10.01
	External goods and services-steel	13,764.11	10,253.68	6,743.25	10,253.68
	Outsourced goods and services-concrete	84,428.14	74,594.13	41,131.78	74,594.13

		178.17	178.17	178.17	178.17
	Electronic devices have hidden carbon	312.40	312.40	312.40	312.40
	Indirect greenhouse gas emissions	111,112.37	100,711.58	64,126.27	100,711.58
	Total greenhouse gas emissions	119,375.50	105,019.55	67,794.73	105,025.49
	Total carbon reduction	35,643.43	49,999.38	87,224.20	49,993.44
	Percentage of carbon reduction	22.99%	32.25%	56.27%	32.25%

4.2.1. Replace ordinary concrete with low carbon concrete

In order to facilitate the analysis, the following assumptions are made: The implied carbon emission of concrete in the baseline scenario is estimated according to the actual concrete type and mix ratio. It is assumed that the concrete purchased in the future construction period can be replaced by low-carbon concrete, and the total amount of concrete purchased in the future construction period is estimated by subtracting the measured amount at the time of bidding from the already ordered amount.

When analyzing, it is important to consider the impact of concrete with different recycled components on the construction period, contract restrictions, and the testing required for using higher recycled component content. Moreover, the actual availability of concrete (with varying recycled component levels) largely depends on the supplier, and further communication with the supplier is necessary to determine the availability of low-carbon concrete. The changes in the implied carbon emissions of concrete under three scenarios are shown in Figure 3. When 35% PFA (fly ash), 45% GGBS (gypsum blast furnace slag), and 75% GGBS are used, the implied carbon emissions of concrete in future construction projects are reduced by 20.23%, 29.52%, and 61.14% compared to the baseline scenario, respectively. Adding fly ash negatively affects the strength of concrete, particularly its early strength[29,30]. Considering that a high proportion of GGBS replacement may not meet the engineering requirements for concrete strength, the implementation scenario selects a GGBS replacement ratio of 45%.

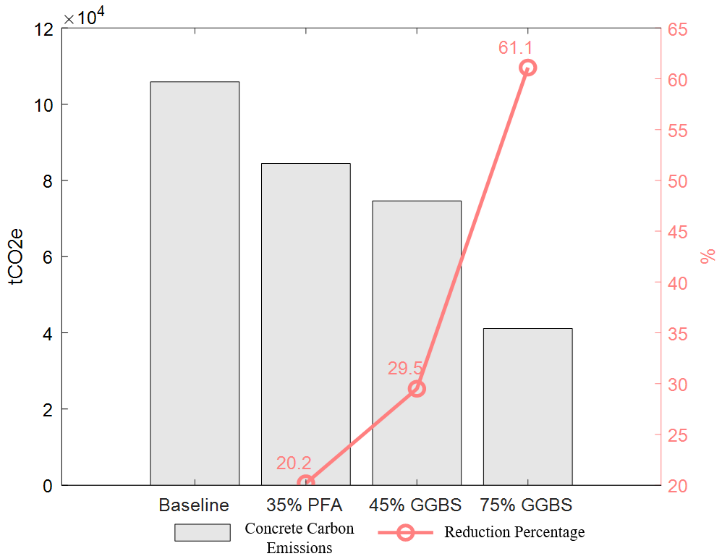

Figure 3. Variations of implied carbon emissions from concrete for three cases

4.2.2. Replace ordinary steel with low carbon steel

Under the baseline scenario, the types and quantities of steel for future construction periods are detailed in Table 17. For ease of analysis, this paper makes the following assumptions: the implicit carbon emissions from steel in the baseline scenario are estimated based on future actual procurement types. It is assumed that all steel

purchased during the future construction period can be replaced with low-carbon steel. Additionally, it is assumed that all steel purchased under the baseline scenario is produced using the BF-BOF (blast furnace) method (without any recycled components). The total amount of steel expected to be purchased during the future construction period will be updated at any time. Currently, the latest measurement (as of the end of July) is used, minus the data received by the end of March 2023.
When conducting actual analysis, it is important to note that the availability of low-carbon steel (with varying degrees of recycled content) largely depends on the supplier. Further communication with the supplier is necessary to ensure the availability of low-carbon steel. The three scenarios involve replacing 50%, 75%, and 100% of the recycled content in the steel. The changes in the implicit carbon emissions of the steel are shown in Figure 4. Compared to the baseline scenario, the implicit carbon emissions of the steel used in future construction projects are reduced by 49.95%, 62.71%, and 75.48%, respectively. In the implementation scenario, the steel is replaced with 100% recycled content steel.

Table 7. Types and amount of steel for the baseline case in the future construction period

Order number	**Type of steel**	**Unit**	**The total amount of work to be purchased is estimated**
1	Steel	/t	121.16
2	Steel pipe	/t	215.56
3	Other section steel	/t	43.70
4	Concrete iron Rebar	/t	9090.77
Total		/t	9471.19

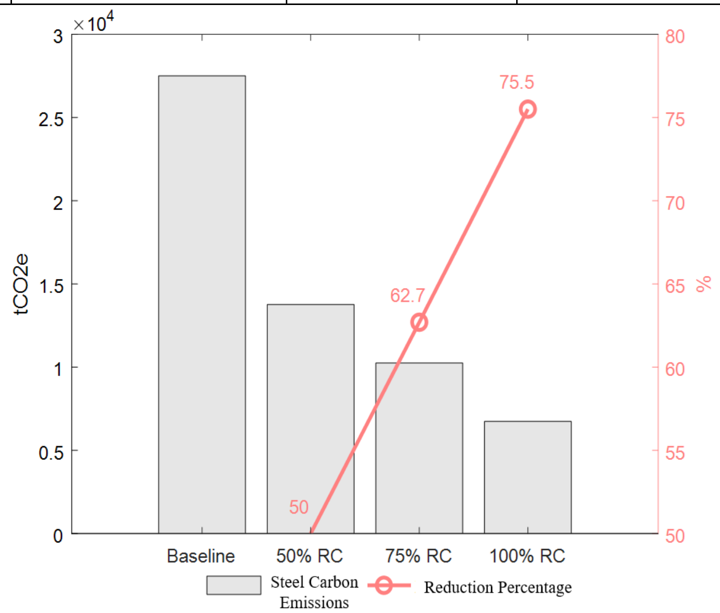

Figure 4. Variations of implied carbon emissions from steel for three case

4.2.3. Replace the self-owned fuel vehicle with electric vehicle

Under the baseline scenario, fuel consumption is calculated based on the average monthly fuel consumption of existing vehicles and their future operational duration, and the carbon emissions from gasoline and diesel combustion are estimated. To facilitate the calculations, the following assumptions are made: 8 private cars, 2 small buses, and 9 pickup trucks will be replaced; some existing vehicles have been scrapped, and electric vehicles will be replaced 12 months after the start of the project; the energy consumption per kilometer for electric vehicles is estimated based on the battery capacity and maximum range provided by the supplier.

The carbon emissions of electric and fuel vehicles are calculated under three scenarios, as shown in Figure 5. Compared to the baseline, the carbon emission reduction ratios for future construction period vehicles are 14.52%, 15.14%, and 27.55%, respectively. To ensure the project's vehicle needs while considering both costs and carbon reduction benefits, all eight fuel-powered private cars will be replaced with electric private cars.

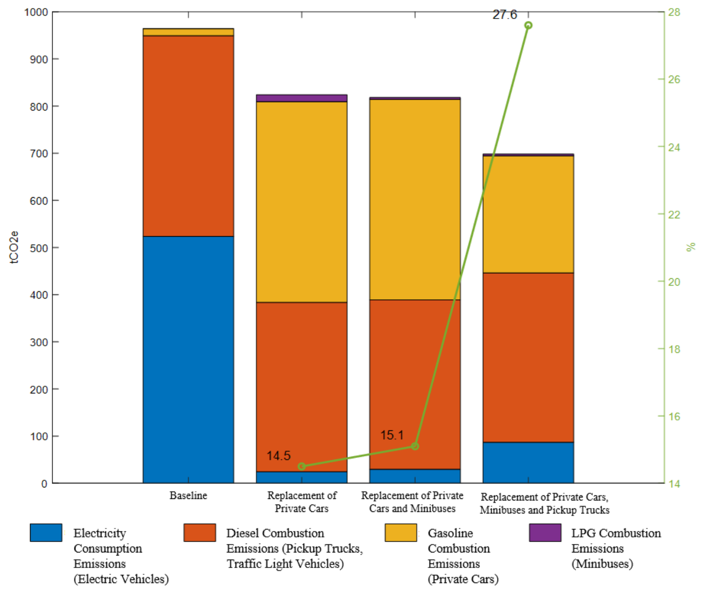

Figure 5. GHG emission results for electric and fuel vehicles for three cases

4.2.4. Replace diesel machinery with pure electric machinery

Under the baseline scenario, diesel consumption is calculated based on the average monthly fuel consumption of diesel machinery and the expected operating duration in the future, to estimate the carbon emissions from diesel combustion. For ease of calculation, the following assumptions are made: only replacement of newly added or currently rented machinery (purchased or existing machinery is not considered for replacement) is taken into account; it is assumed that electric equipment will replace diesel equipment on a 1-for-1 basis (based on working weight), starting from the beginning of the future construction period; according to research findings, the typical engine conversion efficiency is approximately 46%; the charging and discharging efficiency of the power battery is approximately 95%.

In the three scenarios, the calculation results of carbon reduction benefits of replacing diesel machinery with pure electric machinery are shown in Figure 6. The percentage of carbon reduction is 4.77%, 18.46% and 20.26% respectively. The diesel machinery mainly replaced in the implementation scenario is air compressor, dump truck, forklift, aerial work platform, concrete tank truck, crane truck, etc.

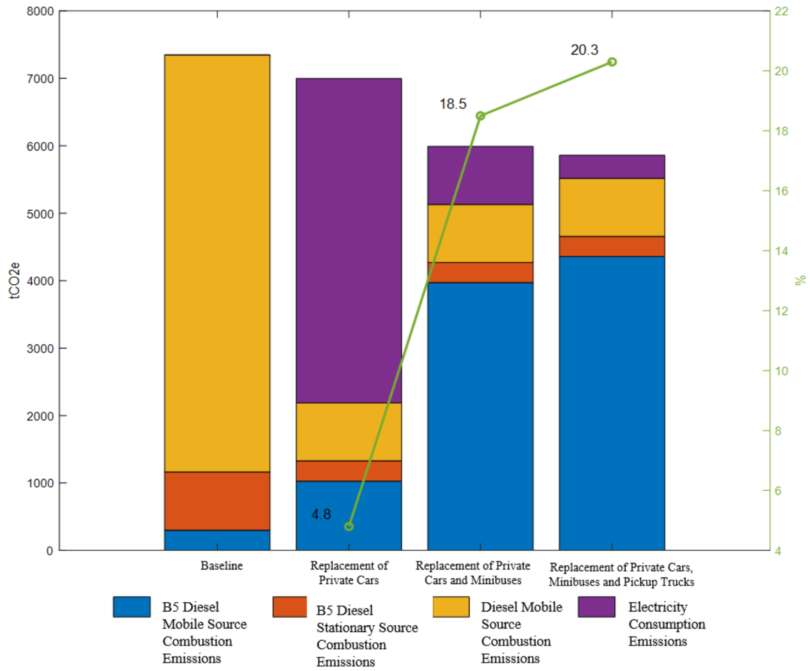

Figure 6. *Results of carbon reduction benefits of pure electric machinery for three cases*

5. CONCLUSION

This article focuses on the construction phase of a super-large cavern project in Hong Kong, from July 1, 2021, to March 31,2023. It employs a quantification method based on greenhouse gas emission factors to calculate the project's greenhouse gas emissions during this period. Based on the sources of greenhouse gas emissions, the project's emissions can be categorized into four main types: direct greenhouse gas emissions and removals, indirect emissions from energy inputs, indirect emissions from transportation, and indirect emissions from the products used. The article then forecasts the carbon emissions for the remaining construction phase of the project, sets three scenarios for carbon reduction measures, and selects the final implementation plan by considering the feasibility, economic cost, and carbon reduction benefits of each option. The main conclusions of this article are as follows:

(1) During the reporting period from July 1, 2021 to March 31,2023, the total greenhouse gas emissions of this super large cavern project were 18,383.46 tCO2e. The percentage of greenhouse gas emissions in four categories accounted for 21.80%,11.02%,17.18% and 50.01% of the total, respectively.

(2) The primary sources of greenhouse gas emissions are the carbon footprint of concrete and steel, as well as waste transportation. Concrete use is the main source of greenhouse gas emissions for the project, accounting for 5,604.80 tCO2e, or 30.49% of the total emissions. Steel has a carbon footprint of 3,185.38 tCO2e, or 17.33%, waste transportation contributes 3,101.11 tCO2e, or 16.87%, and other factors account for 35.32% of the total emissions.

(3) Under the baseline scenario, the total greenhouse gas emissions of the project in the next 46 months are 155,018.93 tCO2e, among which the largest source of greenhouse gas emissions is concrete, followed by steel implied carbon, machinery and equipment and waste transportation.

Compared to the baseline scenario, the future greenhouse gas emission reductions for scenarios 1, 2, and 3 are 22.99%, 32.25%, and 56.27%, respectively. The total greenhouse gas emissions from the final implementation scenario are 105,025.49 tCO2e, with a total reduction of 49,993.44 tCO2e, representing a 32.25% reduction. The implementation scenario involves replacing all concrete with 45% GGBS (fly ash), switching to 100% RC EAF (electric arc furnace) for steel, and using 8 electric private cars, 2 natural gas minibuses, and 9 fuel-powered pickup trucks for mechanical vehicles. Additionally, electric machinery and equipment, including air compressors, dump trucks, forklifts, aerial work platforms, concrete mixer trucks, and cranes, will be replaced.

(5) Implementation of carbon management and emission reduction measures. During the process of carbon inventory and feasibility analysis, the granularity of data significantly impacts the accuracy of the results. For instance, breaking down the fuel consumption of vehicles or machinery can provide insights into the emission status of individual vehicles or machines. Currently, the feasibility analysis is based on numerous assumptions. In the future, it is necessary to monitor the implementation of each measure and collect actual data for more accurate comparisons. For example, the carbon reduction performance of a single machine can be assessed by monitoring emissions over a period and comparing them with the historical emissions of the replaced model.

This article, set against the backdrop of a super-large cavern project in Hong Kong, conducts a comprehensive carbon footprint assessment for certain construction phases and completes a feasibility analysis for low-carbon construction in subsequent stages. It serves as a comprehensive reference for carbon footprint assessments during other construction phases and provides valuable guidance for future low-carbon construction feasibility analyses and carbon reduction plan designs.

6. ACKNOWLEDGMENTS

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8. Appendix I: Carbon emission coefficient

Table 1. *Emission factor table for machinery and vehicle fuel combustion*

type	Fuel category	CO2 Emission factor （kg/L）	CH4 Emission factor （g/L）	N2O Emission factor （g/L）	Reference sources
MECHANICAL EQUIPMENT (FIXED SOURCES)	Diesel oil	2.614	0.024	0.007	Environmental protection agency And the Electrical and Mechanical Engineering Department, 2010
	B100 biodiesel	2.496	0.037	0.003	U.S. Environmental Protection Agency, 2020-2023
	B5 biodiesel	2.483	0.025	0.007	The calculation is based on the mixing ratio and the above emission coefficient
Private car	Clear gasoline	2.360	0.253	1.105	Environmental protection agency And the Electrical and Mechanical Engineering Department, 2010
Light trucks, medium and heavy trucks, traffic signal vehicles	Diesel oil	2.614	0.145	0.072	Environmental protection agency And the Electrical and Mechanical Engineering Department, 2010
Microbus	Liquefied petroleum gas	1.679	1.679	1.679	Environmental protection agency And the Electrical and Mechanical Engineering Department, 2010
Mechanical equipment (non-road mobile sources)	Fuel oil (shipboard)	2.645	0.146	1.095	Environmental protection agency And the Electrical and Mechanical Engineering Department, 2010
biomass fuel	B100 biodiesel	2.496	0.037	0.003	U.S. Environmental Protection Agency, 2020-2023
	B5 Biodiesel (excluded from the statistical scope)	0.125	-	-	The calculation is based on the mixing ratio and the above emission coefficient

Table 2. *Emission coefficients for various types of explosives*

Type of explosive	CO2 Emission factor	unit	Component reference product
Bulk emulsion explosive （Cartridge）	0.013	kgCO2e/kg	EMULSION HIGH EXPLOSIVE (CARTRIDGED)
Emulsion explosive （Bulk Emulsion）	0.164	kgCO2e/kg	No.1 Rock Emulsion Explosive-Aoxin Technology
Initiator (Booster)	0.887	kgCO2e/kg	Relay detonator-Aoxin Technology
In-hole delay detonator (IHD)	0.000300	kgCO2e/nos.	Austin SHOCK*STAR MS
Electronic detonators （Electric Detonator）	0.000476	kgCO2e/nos.	Electric detonator-Xi 'an Qinghua Civil explosive Equipment Co., LTD
Bundle connectors （Bunch Connector）	0.0000501	kgCO2e/nos.	Austin SHOCK*STAR Surface
Detonating cord （CordtexTM 5G）	0.002	kgCO2e/m	CordtexTM5G
Detonating cord （CordtexTM 40G）	0.017	kgCO2e/m	CordtexTM40G

Table 3. *Greenhouse gas emission factor table for outsourced electricity*

Year	Emission factor	Unit	Reference sources
2021	0.39	kgCO2e/kWh	China Power Limited 2021,2022 Sustainability Report
2022	0.39		

Table 4. *Greenhouse gas emission factors for modes of transport involved*

Type of shipping	Emission factor	Unit	Reference sources
Light petrol truck transport (2t load)	0.334	kgCO2e/t • km	Ministry of Housing and Urban-Rural Development, China, 2019
Medium diesel truck transport (8t load)	0.179		
Heavy duty diesel truck transport (18t)	0.129		
Heavy duty diesel truck transport (30t)	0.078		
Heavy duty diesel truck transport (46t)	0.057		
Dry bulk ship transportation (2500t deadweight)	0.015		
Container ship transport (200TEU deadweight)	0.012		

Table 5. *Greenhouse gas emission factor table for municipal water use*

Year	Emission factor	Unit	Reference sources
2020/2021	0.428	kgCO2e/m3	Hong Kong Government Water Supplies Department 2020/2021

			Annual Report

Table 6. *Greenhouse gas emission factor of sewage treatment*

Year	Emission factor	Unit	Reference sources
2020-2021	0.21	kgCO2e/m3	Hong Kong Government Water Supplies Department 2020-2021 Sustainable Development Report
2021-2022	0.22	kgCO2e/m3	Hong Kong Government Water Supplies Department 2021-2022 Sustainability Report

Table 7. *Carbon emission factors for the use of capital goods and materials involved*

Product name	Emission factor	Unit	Reference sources
Paper			
Paper, 2021	919.40	kgCO2e/t	Department of Energy Security and Net Zero, Department for Environment, Food and Rural Affairs
Paper, 2022	919.40		
Paper, 2023	910.48		
Capital goods			
Computer mainframe	24865.48	kgCO2e/t	Department of Energy Security and Net Zero, Department for Environment, Food and Rural Affairs
Display screen			
Computer interface equipment			
Storage system			
Printer			
Network switches			
Server			
Camera **Gas testing machine** **Scanner** **Measuring apparatus** **Electric vehicle charging equipment**	5647.95	kgCO2e/t	Department of Energy Security and Net Zero, Department for Environment, Food and Rural Affairs
Noise monitoring station	3267.00	kgCO2e/t	Department of Energy Security and Net Zero, Department for Environment, Food and Rural Affairs
Electronic scale bridge			
Source	6308.00	kgCO2e/t	Department of Energy Security and Net Zero, Department for Environment, Food and Rural Affairs
iPhone 13 128GB	64.00	kgCO2e per unit	Apple, US, 2021
iPhone14 128GB	61.00	kgCO2e per unit	Apple, US, 2021
iPad Pro 128GB	118.00	kgCO2e per unit	Apple, US, 2021
iPad Pro 256GB	129.00	kgCO2e per unit	Apple, US, 2021
GALAXY S21 ULTRA	22.90	kgCO2e per unit	Samsung, 2023
SAMSUNG GALAXY TabS7 + (5G)(8GB RAM +256GB) (Mystic Navy)	48.20	kgCO2e per unit	Samsung, 2023
Concrete			
Portland cement **Ordinary Portland Cement**	2,315.25	kgCO2e/m3	Emission factors are referenced to GBT 51366-2019
Fly ash	12.00	kgCO2e/m3	CICGPC CFP Quantification Tool - Ready-mixed Concrete
Concrete C20*	262.00	kgCO2e/m3	* Since there is a linear relationship between the minimum cement-based binder content and strength grade, the emission coefficient of C20 can be inferred from the emission coefficient of C30 and C40
Concrete C30	295.00	kgCO2e/m3	Refer to Gan et al. (Gan et al., 2017)
Concrete C40	335.00	kgCO2e/m3	Refer to Gan et al. (Gan et al., 2017)
Concrete C45*	349.00	kgCO2e/m3	* Since there is a linear relationship between the minimum cement-based binder content and strength grade, the emission coefficient of C45 can be inferred from the emission coefficient of C30 and C40
Concrete 20/20D + PFA	254.50	kgCO2e/m3	Concrete containing recycled components is calculated by the method below this table
Concrete 30/10 FV600MM PFACSF plain shotcrete	283.68	kgCO2e/m3	
Concrete 30/20D+PFA	283.68	kgCO2e/m3	
Concrete 40/20D+PFA	318.85	kgCO2e/m3	
Concrete 45/20D+PFA	332.15	kgCO2e/m3	
Concrete 45/10 FV600MM PFA	335.52	kgCO2e/m3	
Concrete iron			
Steel plate	2.25	kgCO2e/kg	The emission coefficient is estimated based on the research data in Gan et al. (Gan et al., 2019) and the actual situation, assuming that the steel is produced by blast furnace-converter method and does not contain scrap steel recycling components.
Merchant steel	2.30		
Steel pipe	2.34		
Concrete iron	2.25		