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Estimating the greenhouse gas emissions of cold chain infrastructure in China from 2021 to 2060

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ABSTRACT

Cold chain infrastructure is vital in the modern food system, yet the greenhouse gas (GHG) emissions of cold warehouse construction and operation are unclear. This article fills the gap by presenting an environmental modeling study to estimate the future trajectory of GHG emissions of cold warehouses in China from 2021 to 2060. A hybrid analysis is used to estimate the potential GHG emissions over time, using environmental input-output analysis (EIO) for construction and process-based analysis for operation. We analyzed five scenarios: cleaner refrigerants (CR), cleaner electricity sources (CE), higher energy efficiency (HE), cleaner cold warehouses (CCW), and a business as usual (BAU) scenario. The results show the trend of GHG emissions in all scenarios and reveal the effectiveness of these measures, with cleaner electricity sources and higher energy efficiency having stronger impacts than introducing cleaner refrigerants on reducing GHG emissions. Another key finding is that electricity consumption during cold warehouse operation is responsible for over 85% of total emissions in 40 years in all scenarios.

1. Introduction

The United Nations Sustainable Development Goal (SDG) 2 is to “End hunger, achieve food security and improved nutrition and promote sustainable agriculture” (United Nations, 2015). With the improvement of global living standards, the cold chain industry plays a critical role in the global food system. The cold chain is the refrigerated supply chain that prevents spoilage, prolongs the shelf life, and improves the food safety of perishable products (Global cold chain alliance, 2018a; Zhao et al., 2018; Dong et al., 2021b). At the same time, refrigeration is energy-intensive and often employs high global warming potential (GWP) refrigerants, increasing the climate burden of the food supply chain. To quantify this environmental load, this article estimates potential greenhouse gas (GHG) emissions of cold chain infrastructure in China, under a variety of improvement scenarios.

A complete cold chain requires cold warehouses, refrigerated transportation, refrigeration in retail stores, and household refrigeration (Global cold chain alliance, 2018b; Zhao et al., 2018; Dong et al., 2021b). Cold chains are well established in developed countries but refrigeration resources in developing countries are limited (Mercier et al., 2017). Older data published by the USDA estimated that over 90% of perishable food products are transported by refrigerated trucks in developed countries, in contrast to less than 20% in China (USDA, 2008). Unfortunately, recent estimates are not available in the literature. Refrigerated transport in developing countries is expected to expand along with the entire cold chain industry (Heard and Miller, 2016, 2018). From 2014 to 2018, the cold storage capacity in India and China increased by 15% and 36%, respectively (Salin, 2018). However, few studies provide robust quantitative estimates of GHG emissions from cold chain expansion at a national scale. Dong and Miller (2021) estimated that the GHG emissions from cold chain activities are approximately 1–3% of total emissions in China in 2018, which includes perishable food embodied emissions along the supply chain in addition to cold chain infrastructure. Estimating the growth of cold chain infrastructure and associated GHG emissions in China can support the industry to grow sustainably within the country, as well as provide broadly applicable insights to the other nations experiencing rapid cold chain development. This article chooses the context of China due to the size of potential market growth and relative data availability. The study estimates emissions within the period of 2021 to 2060, which is expected to be the period of most rapid cold chain expansion, with the end year aligning with the carbon-neutral target in China (Mallapaty, 2020).

According to Green Cooling Initiative (2020), worldwide GHG emissions from domestic, commercial, industrial, and transport refrigeration

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Nomenclature

Acronyms

BAU	Business as usual
CCW	Cleaner cold warehouses
CE	Cleaner electricity
CR	Cleaner refrigerants
EIO	Environmental input-output
GHG	Greenhouse gas
GWP	Global warming potential
HCFC	Hydrochlorofluorocarbon
HE	Higher energy efficiency
LCA	Life cycle assessment

Parameters

$C_{cons,\ t}$	Construction emission adjustment factor for year *t*
$C_{cool,\ t}$	Weighted cooling capacity in year *t* [kg/kW]
$C_{ref,\ t}$	Weighted refrigerant production emission factor in year t [$kgCO_2eq$ per kg refrigerant]
$C_{replace}$	Coefficient of device replacement [%]
$CW_{p,\ t}$	Cold warehouse capacity in province *p* in year *t* [m^3]
$Em_{cons,\ t}$	Emissions due to cold warehouse construction in year *t* [$ktCO_2eq$]
$Em_{ele,\ t}$	Emissions due to cold warehouse electricity consumption in year *t* [$ktCO_2eq$]
$Em_{leak,\ t}$	Emissions due to refrigerant leakage in year *t* [$ktCO_2eq$]
$Em_{ref,\ t}$	Emissions due to refrigerant production for recharge in year *t* [$ktCO_2eq$]
$Em_{replace,\ t}$	Emissions due to device replacement in year *t* [$ktCO_2eq$]
$E_{spc,\ t}$	Specific electricity consumption of cold warehouse in year *t* [kWh/m^3]
$Em_{tot,\ t}$	Total emissions in year *t* [$ktCO_2eq/year$]
$Em_{GWP,t}$	Weighted global warming potential of refrigerants in year *t*
$\dot{Em}_{p,t}$	Electricity emission intensity in province *p* in year *t* [gCO_2eq/kWh]
F	Total emission vector calculated from environmental input-output method
f_p	The sum of elements in total emissions vector ***F*** in province *p* [$ktCO_2eq$]
GWP	Global warming potential
l_{cool}	Cooling load [kW/m^3]
r_{leak}	Annual refrigerant leakage rate [%]

increased by 15% from 2010 to 2020. Industrial refrigeration (e.g., food processing and cold storage in warehouses) accounted for over 20% of total emissions in the refrigeration sector in 2020 (Green Cooling Initiative, 2020). Over 60% of electricity consumed in cold warehouses is used for product refrigeration, leading to more severe GHG emissions than other types of storage facilities.

The GHG emissions of cold warehouses come from direct refrigerant leakage and electricity usage during cold warehouse construction and operation (United Nations Environment Programme, 2018). In its existing cold warehouse facilities, China mainly uses R22[1] and R717 (Ammonia) (Zhang et al., 2019; Booten et al., 2020). R22 is a hydrochlorofluorocarbon (HCFC) that has both high ozone depletion potential and high global warming potential. R717 is a natural refrigerant[2] without global warming potential (Ciconkov, 2018). Following the Montreal Protocol, China has reached the first target of reducing HCFCs in 2015 and will continue to cut the production and consumption of HCFCs. Thus, the usage of R22 in cold warehouses is expected to be replaced by alternate refrigerants in China, reducing the environmental impact associated with leakage (United Nations Treaty Collection, 1987, 2016). Nevertheless, GHG emissions due to electricity usage are generally more significant. In China, in 2018, household, commercial, industrial, and transport refrigeration combined contributed to over 10% of nation-wide electricity consumption (International Energy Agency, 2018; Green Cooling Initiative, 2020). Studies report that over 60% of electricity is used for refrigeration in a cold warehouse and approximately 70% of total GHG emissions of cold storage facilities are due to electricity consumption (Evans et al., 2014; International Institute of Refrigeration, 2015). In China, about 60% of power was produced by coal (International Energy Agency, 2018); thus, significant electricity consumption in cold warehouses leads to large GHG emissions.

Previous cold chain environmental studies often use life cycle assessment (LCA) to investigate the life cycle emissions of perishable products delivered by cold chains (Hoang et al., 2016; Heard et al., 2019; Wu et al., 2019). Usually, those studies are oriented around the food life cycle instead of focusing on the cold chain itself. Agricultural operations represent a much greater proportion of the life cycle emissions of food products compared to cold chain emissions (Hoang et al., 2016; Dong and Miller, 2021), which can obscure the importance of GHG emissions associated with refrigeration. In particular, the lifetime construction and operation emissions for cold warehouses are not well studied. The GHG emissions per unit electricity consumption are anticipated to decrease in the coming decades due to China's carbon neutrality target. Meanwhile, China is also experiencing rapid cold warehouse capacity expansion, increasing by 38% from 2014 to 2018 (Salin, 2018). Given these competing effects, the emission trajectory of the cold chain industry is unclear. Additionally, there is a lack of quantitative studies to examine the effectiveness of the carbon-neutral plan (Mallapaty, 2020) and cleaner refrigeration regulations (National Development and Reform Commission of People's Republic of China, 2019) in China over time. Due to those insufficiencies in previous studies, this article has three main objectives:

- Estimate GHG emissions of cold chain infrastructure specifically (i.e., construction and operation) rather than including it as a component in the life cycle of perishable food.
- Model the trajectory of cold warehouses' GHG emissions in China from 2021 to 2060.
- Examine the effectiveness of the carbon-neutral plan and cleaner refrigeration regulations in China on GHG emissions associated with the cold chain.

To summarize, this article estimates the total GHG emissions of the entire cold warehouse capacity in China over a 40-year period. By providing robust, quantitative analysis, this study characterizes an overlooked, yet important, contribution to China's overall climate footprint. Although long-term projections are inherently uncertain, the present study is essential to determine whether planned interventions will achieve climate targets. Another added value of the present article is a comprehensive scenario analysis that demonstrates the effectiveness of various interventions to guide decision-makers in the cold chain and related industries, in China and elsewhere throughout the world.

[1] R22 is a typical hydrochlorofluorocarbon (HCFC) refrigerant as a substitution to R12. R12 is a chlorofluorocarbon (CFC) refrigerant which has severe ozone depletion effects. CFCs have been phased out according to the Montreal Protocol (United Nations Treaty Collection, 1987). HFCs are in the process of phase-out: developed countries and developing countries will completely phase out HCFCs in 2030 and 2040, respectively.

[2] Natural refrigerants are considered to be alternatives to synthetic refrigerants due to their low global warming potential and ozone depletion potential (Ciconkov, 2018). Natural refrigerants mainly include R717 (Ammonia), R744 (CO_2), and hydrocarbons (Ciconkov, 2018).

2. Literature review

With its sizable energy demand and increased anticipated growth, it is critical to understand the sustainability of the cold chain industry. From the perspective of environmental impacts, this section comprehensively reviews cold chain studies, environmental modeling methods, and the application of those methods.

James and James (2010) is one of the early studies that provide a comprehensive review of the environmental impacts of the food cold chain. This article emphasized the importance of using cold chain logistics to address the food losses issue in developing countries and discussed the environmental burden of refrigeration facilities. The tradeoff of preventing food losses while adding the environmental burdens associated with refrigerant and electricity use is a core sustainability issue for cold chain growth in developing countries (Hu et al., 2019; Wu et al., 2019). Even though developing countries are expecting to have a rapid growth of the cold chain industry, Patidar et al. (2021) found that few articles studied the challenges of the cold chain in developing countries. Certain literature (Zhao et al., 2018; Dong et al., 2021b) discuss the drivers and status of the cold chain in China and found economic growth promotes the cold chain development. Dong et al. (2021b) additionally investigated the methods of evaluating the cold chain's environmental impacts and concluded that studies could focus on the life cycle of perishable food along the cold chain or focus on the life cycle of cold chain facilities. In addition, Gao et al. (2021) reviewed the application status of cleaner refrigerants in China, indicating that although traditional HCFCs are still largely used, the increased application of natural refrigerants is inevitable.

To quantify the cold chain influence on the environment, life cycle assessment (LCA) is a standard framework to evaluate the lifetime environmental impacts of industrial activities or products (Pennington et al., 2004; Rebitzer et al., 2004). The LCA method has been used in a variety of contexts including waste management (Khandelwal et al., 2019), renewable energy technologies (Ludin et al., 2018), and chemical conversion processes (Artz et al., 2018). Regarding the cold chain, LCA has been used to track the lifetime of perishable food in a specific cold chain network (Hoang et al., 2016; Wu et al., 2019; Dong and Miller, 2021). Dong and Miller (2021) studied perishable food products delivered by the cold chain in China, finding that the embodied emissions of food losses and wastes can reach over 60% in meat cold chains. Wu et al. (2019) studied an orange cold chain from South Africa to Switzerland and package design was proven to have strong impacts on the environmental tradeoff. Hoang et al. (2016) investigated a salmon cold chain from Norway to other European countries and they found the production stage contributes to nearly 40% of total lifetime emissions.

Although the cold chain is usually included in most LCA of food products, detailed life cycle impacts of cold chain facilities themselves are rarely discussed, including identification of interventions that can most effectively reduce its impacts. Some studies have investigated the lifetime GHG emissions of refrigerated transportation. Li (2017) compared the life cycle climate performance of R404A and R452A refrigerants in different operation conditions. Wu et al. (2013) studied refrigerated transportation using R404A, R744 (CO_2), and R410A and found that using the R744 refrigeration system does not always have the lowest lifetime emissions due to high energy consumption in the R744 systems. Rai and Tassou (2017) examined using cryogenic fluids (i.e. liquid N_2 and CO_2) in refrigerated vehicles and found cryogenic fluids refrigeration systems can result in significant GHG emissions owing to large liquid N_2 and CO_2 demand. These articles have advanced the understanding of the environmental impacts of refrigerated vehicles; however, the life cycle emissions of cold warehouses remain relatively understudied. Hence, one focus of the present article is to fill the gap and better characterize the lifetime environmental impacts of cold warehouses.

There are two major categories of LCA: process-based LCA and economic input-output LCA (EIO-LCA). Process-based LCA uses a bottom-up approach, itemizing each of the inputs and outputs of a given product or process, using an inventory of materials and energy inputs at each phase of the life cycle. One disadvantage of using process-based LCA is that the system boundary is often truncated based on available information, which can increase modeling errors (Ji and Chen, 2016; Pomponi and Lenzen, 2018). EIO-LCA employs a top-down approach that bases its inventory on the interrelated economic flows among industrial sectors in an economy (Hong et al., 2016; Tao et al., 2018). By compiling the emissions data of each sector, the EIO method can trace the carbon emissions associated with major industry sectors within an economy (Hong et al., 2016; Ji and Chen, 2016; Lin et al., 2019). The EIO-LCA approach does not have system boundary truncation issues associated with process-based LCA, but often is not able to provide detailed information since inventory knowledge is aggregated by sector (Suh and Huppes, 2005; Ji and Chen, 2016). EIO-LCA lends itself to analysis of broad economic sectors. For example, Hong et al. (2016) used multi-regional input-analysis to study the embodied energy in China's construction industry and Ji and Chen (2016) used environmental input-output analysis to calculate the carbon footprint of a wind farm in China.

To help overcome the weaknesses of each approach, hybrid EIO and process-based LCA methods have been developed and applied to a variety of industries (Wan Omar, 2018; Liao et al., 2020). The hybrid approach combines the broad, economy-wide perspective of EIO-LCA with more detailed process-based data in order to develop a sufficiently large system boundary with higher resolution data to model a particular process or product within a broader industry sector. Liao et al. (2020) used a hybrid method to estimate the GHG emissions of an urban wastewater treatment system where the EIO method is used to quantify the chemical usage and labors input and the process-based LCA is used in the sludge treatment stage. Wan Omar (2018) used hybrid LCA to study embodied emissions of building systems, which is similar to the task of the present article. In Wan Omar (2018), the EIO method is used to calculate the emissions of upstream materials and the results of EIO are the input for the downstream production stages. Although there are controversies about whether the hybrid LCA yields more accurate than the process-based LCA (Yang et al., 2017; Pomponi and Lenzen, 2018; Perkins and Suh, 2019), the hybrid analysis is still an effective approach to connect process-based analysis for the use and disposal phase and the EIO for the upstream construction or manufacturing phase (Suh and Huppes, 2005). In this article, we follow the methodology outlined in Suh and Huppes (2005) and use the Tiered hybrid analysis to quantitatively estimate the GHG emissions of cold warehouses in China from 2021 to 2060.

3. Methods

3.1. System boundary

The system boundary is displayed in Fig. 1 and the functional unit is defined as cold warehouse volume, with inventory data reported as ton CO_2 equivalent [tCO_2eq/m^3]. The computation of each Chinese province follows the system boundary in Fig. 1. We first estimate the cold warehouse capacity of each province in each year between 2021 and 2060, and use the hybrid method (Suh and Huppes, 2005) to calculate the provincial GHG emissions, using the EIO method to calculate construction phase emissions and the process-based method to calculate operation phase emissions. The results at the provincial or national scale are presented in aggregate [$ktCO_2eq$]. As shown in Fig. 1, the construction phase includes emissions from building construction, refrigerant and insulation materials manufacturing, machinery and metal products production, and other materials and services. The operation phase consists of emissions from electricity consumption, refrigerant leakage and production, and refrigeration unit replacement. It should be noted that the replacement of refrigeration units contains both the end-of-life of old devices and the manufacturing of new devices.

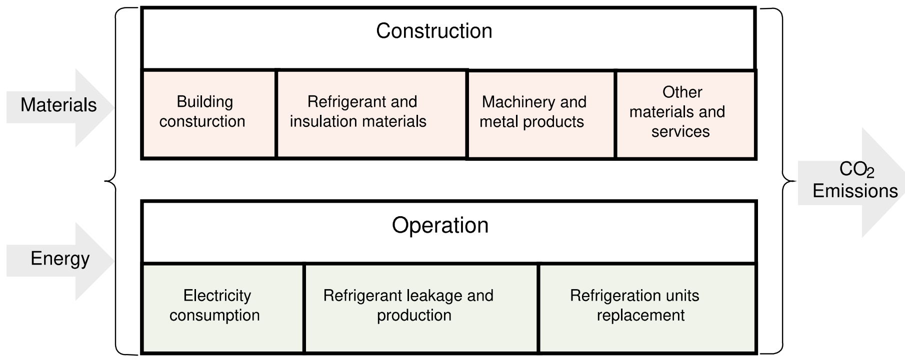

Fig. 1. The system boundary of calculating the cold warehouse emissions in China. The calculation of each province is based on this figure and the emissions in China are aggregated from each province.

3.2. Cold warehouse capacity modeling

We estimate the anticipated cold warehouse capacity of each province during the study time period. The estimate is based on the gap between the level of cold warehouse development in China and developed countries. We use the capacity in m^3 per capita to indicate the cold warehouse development. In developed countries, the cold warehouse development index is in the range of 0.2–0.28 m^3 per capita (Salin, 2018). In contrast, Chinese cold warehouse capacity is below 0.1 m^3 per capita in 2018 (Salin, 2018). We assume 0.25 m^3 per capita as the final target in China. We use the provincial cold warehouse capacity data (50yc.com, 2019) divided by the 2018 population data (National Bureau of Statistics, 2020) to compute the capacity per capita in each province. Then, we follow the capacity increase trend between 2014 and 2018 and assume a 13% capacity increase rate (The Forward Economist, 2018). The cold warehouse capacity in province p in year t after 2018 ($CW_{p,\ t}$) is calculated from the capacity in the previous year and the increase rate. Then, the obtained capacity data from 2021 to 2060 are used in later estimations. The base year cold warehouse capacity and the population are shown in Table S1 in the supplementary materials.

3.3. Hybrid LCA analysis

Once the capacity of each province is obtained, we conduct the hybrid LCA for each province as described in 3.3.1 and 3.3.2. The GHG emissions are compiled in [$ktCO_2eq/m^3$] and aggregated to each province and then for China.

3.3.1. Environmental input-output life cycle assessment (EIO-LCA)

EIO-LCA is used for the construction activities shown in Fig. 1. The emissions of the whole value chain of industrial activities can be calculated by Eq. (1), where $\boldsymbol{F}$ [$ktCO_2eq$] is the total emissions driven by the demand $\boldsymbol{Y}$ [USD], $\boldsymbol{A}$ is the coefficient matrix of the input-output table, $\boldsymbol{I}$ is the identity matrix, $\boldsymbol{E}$ [$ktCO_2eq$/USD] is the emission intensity. Complete formulas for the EIO analysis are included in the supplementary materials.

$$\boldsymbol{F} = (\boldsymbol{I} - \boldsymbol{A})^{-1}\boldsymbol{Y} \times \boldsymbol{E} \tag{1}$$

For this work, we use the multi-regional input-output (MRIO) table for 42 industrial sectors located in 31 out of 34 provinces in China (excluding Hong Kong, Macau, and Taiwan due to inconsistent data) because the economic activities (National Bureau of Statistics, 2020) and electricity sources (Li et al., 2017) are different in each Chinese province. Fig. S1 in the supplementary materials displays the structure of an MRIO table. The computation principle of MRIO is the same as the single region EIO, and essentially, the MRIO table merely integrates the intermediate table, final demand, and value-added of multiple regions (Liu et al., 2019). The 2017 MRIO table is used, as it is the most recent available (National Bureau of Statistics of China, 2020; Zheng et al., 2020). The list of industrial sectors in China is provided in Table S2 in the supplementary materials. In addition, the emission data of industrial sectors was taken from the Chinese Environmentally Extended Input-output dataset (Tian et al., 2021).

To perform the computation, we use a 10,000 t cold warehouse as a reference (National Development and Reform Commission of People's Republic of China, 2019). We assume the construction activities of cold warehouses are similar across all provinces, and we use the same demand vector in all provinces. Table S3 in the supplementary materials shows the matching between expenditures of building the cold warehouse and the data of the demand vector from National Development and Reform Commission of People's Republic of China (2019). The $\boldsymbol{F}$ computed in each province by Eq. (1) represent the $ktCO_2eq$ for building the 10,000 t reference cold warehouse. According to Salin (2018), the 10,000 t capacity corresponds to 43,000 m^3 in volume. Hence, we additionally compile the per-unit construction emission [tCO_2eq/m^3] by $\frac{f_p}{43,000}$, where f_p is the sum of each element in emission vector $\boldsymbol{F}$ in the province p.

Finally, Eq. (2) is used to compute the total construction emissions in $ktCO_2eq$ given any added capacity value in China from year $(t-1)$ to year t. In Eq. (2), $CW_{p,\ t}$ is the total cold warehouse capacity in province p in year t, $C_{cons,\ t}$ is the construction emission adjustment factor for year t, and the summation operation accumulates construction emissions from each province. Note that the MRIO table represents the year 2017, and it is not appropriate to estimate emissions that occur in future years. Ideally, an input-output table for each year until 2060 is needed. To solve this issue, a construction emission adjustment factor, $C_{cons,t}$, is used to estimate construction emissions occurring after the base year. The construction emissions in 2060 are set to be 20% greater or smaller than that in the base year and the emission changes between 2021 and 2060 are evenly distributed to each year by $C_{cons,\ t}$. Refer to the supplementary materials for more details of computing $C_{cons,\ t}$.

$$Em_{cons,t} = C_{cons,t} \times \sum_p \left(\frac{f_p}{43,000} \times (CW_{p,t} - CW_{p,t-1}) \right) \tag{2}$$

3.3.2. Process-based analysis

The process-based approach is used to estimate GHG emissions for electricity consumption, refrigerant leakage and production, and device replacement for each year from 2021 to 2060. The definition and description of all key parameters are listed in nomenclature.

We calculate emissions from the cold warehouses' electricity consumption in [$ktCO_2eq$] in year t by Eq. (3), where $E_{spc,\ t}$ [kWh/m^3 per year], $\dot{E}m_{p,t}$ [g/kWh], and $\sum_p CW_{p,t}$ [m^3] are specific electricity consumption of cold warehouses, electricity emission intensity, and total cold warehouse capacity in year t, respectively. Note that $E_{spc,\ t}$ and $\dot{E}m_{p,t}$ are the adjustment parameters for implementing higher energy efficiency (HE) and cleaner electricity (CE) scenarios. More details are in Section 3.4. To find the specific electricity consumption, we follow Evans et al. (2014) and also use the cold storage capacity [m^3] to predict the electricity consumption. Commercial cold warehouse electricity consumption data for China is found in Table S5 of the supplementary materials (cclcn.com, 2012). We use the ordinary least square to fit a model between cold warehouse capacity and electricity consumption to find the electricity consumption at other given capacities. The specific electricity consumption measured in [kWh/m^3 per year] obtained by our linear model falls in the range of electricity consumption in Evans et al. (2014). In addition, $\dot{Em}_{p,t}$ is identified for each province p, and it is calculated from the electricity emission intensity of each power source in China (Li et al., 2017) and the share of different power sources in every province (Ding et al., 2017). Table S4 in the supplementary materials records the electricity emissions intensity. Based on the data in Ding et al. (2017) we create Figs. S2 and S3 in the supplementary materials to visualize the electricity sources in each province in China.

$$Em_{ele,t} = E_{spc,t} \times \sum_{p} \left(CW_{p,t} \times \dot{Em}_{p,t} \right) \quad (3)$$

Emissions from refrigerant leakage in year t are estimated by Eq. (4), where l_{cool} is the cooling load [kW/m^3], $C_{cool,\ t}$ is the weighted refrigerant cooling capacity in year t [kg/kW], r_{leak} refers to the annual leakage rate, and $\dot{Em}_{GWP,t}$ is the weighted global warming potential to indicate the emission property based on the GWP of R22 and R717. We first calculate the annual leakage quantity via $\left(l_{cool} \times C_{cool,t} \times r_{leak} \times \sum_{p} CW_{p,t} \right)$ and multiply it with the $\dot{Em}_{GWP,t}$ of the refrigerant. Similarly, we use Eq. (5) to calculate the emissions of leaked refrigerant for recharge purposes in year t, where $C_{ref,\ t}$ [kgCO_2eq per kg refrigerant] is the weighted refrigerant production emission factor. In this article, we assume only R22 and R717 are used in cold warehouses in China (Zhang et al., 2019; Booten et al., 2020). The ratio between R22 and R717 changes over time because of the cleaner refrigerant plan (Zhang et al., 2019). Essentially, it affects $C_{cool,\ t}$, $\dot{Em}_{GWP,t}$, and $C_{ref,\ t}$, and the changes of those three parameters are reflected in the cleaner refrigerant (CR) scenario (Section 3.4).

In the base year, R717 accounts for 70% of total cold warehouse refrigerant usage (China Cold Chain Logistics Alliance, 2016). According to Brunel University (2008), we consider a typical cooling capacity for R22 to be 3.5 kg/kW and that for R717 is 0.15 kg/kW. Besides, we refer to the ecoinvent database (The ecoinvent Database, 2020) for refrigerant production factors, using 74 kgCO_2eq and 2.4 kgCO_2eq for producing 1 kg of R22 and R717, respectively. The GWP for R22 and R717 are 1810 and 0 (Ciconkov, 2018; United Nations Environment Programme, 2018). Moreover, we assume the annual leakage (r_{leak}) of cold warehouses is constant at 8% (United Nations Environment Programme, 2018). Cooling load (l_{cool}) can vary depending on specific cold warehouse conditions (e.g., dimensions, air infiltration, products respiration). We use an estimated l_{cool} that is measured in [kW/m^3] compiled from Sari and Pratami (2018).

$$Em_{leak,t} = \left(l_{cool} \times C_{cool,t} \times r_{leak} \times \sum_{p} CW_{p,t} \right) \times \dot{Em}_{GWP,t} \quad (4)$$

$$Em_{ref,t} = \left(l_{cool} \times C_{cool,t} \times r_{leak} \times \sum_{p} CW_{p,t} \right) \times C_{ref,t} \quad (5)$$

Computing the emissions from the replacement of refrigeration units is challenging due to the variety of devices used in cold warehouses and the uncertain nature of replacement. Cascini et al. (2016) studied the lifetime emissions of a walk-in refrigeration system and they found that the device replacement emissions contribute to 4–8% of the entire lifetime emissions. Thus, we refer to Cascini et al. (2016) and consider the replacement emissions as a proportion of total emissions in year t. We use $C_{replace}$ to be the coefficient of device replacement and use Eq. (6) to calculate the device replacement emissions.

$$Em_{rep,t} = C_{replace} \times \left(Em_{cons,t} + Em_{ele,t} + Em_{leak,t} + Em_{ref,t} \right) \quad (6)$$

3.4. Scenario analysis

We construct four scenarios to assess the effectiveness of various anticipated policies on controlling the cold warehouse emissions in China from 2021 to 2060, including cleaner refrigerant (CR), higher energy efficiency (HE), cleaner electricity sources (CE), and cleaner cold warehouses (CCW). These are compared to the business as usual (BAU) scenario, which represents an expected worst-case scenario where none of the anticipated policies are adopted. The CCW scenario represents the scenario where all policies are fully implemented as designed. We compute the total emissions in the year t ($Em_{tot,\ t}$) by Eq. (7) which is the summation of Eq. (2) to Eq. (6). When modeling cold warehouse emissions over time, we adjust terms in Eq. (7) to implement different scenarios.

$$Em_{tot,t} = Em_{cons,t} + Em_{ele,t} + Em_{leak,t} + Em_{ref,t} + Em_{rep,t} \quad (7)$$

Business as usual (BAU) scenario: The BAU scenario is the baseline in this study. We model the GHG emissions based on the increase of cold warehouse capacity using the current parameters associated with energy consumption, electricity grid emissions, and existing refrigerants. In this scenario, GHG emissions change only with respect to the capacity in m^3 in each province ($CW_{p,\ t}$). Therefore, the BAU scenario represents a worst-case scenario that reflects a future where the demand for cold warehouses increases but there are no efforts adopted to reduce environmental impacts. To implement the BAU scenario, we simply use Eq. (7) and do not modify any parameters except for the cold warehouse capacity.

Cleaner refrigerant (CR) scenario: The CR scenario is designed based on the Montreal Protocol (United Nations Treaty Collection, 1987) that both developed and developing countries need to phase out HCFC refrigerants. Particularly, China has achieved the first stage goal of reducing HCFC and aims to phase out HCFC in 2030 (Zhang et al., 2019; Dong et al., 2021b). At the moment, R717 and R22 are widely used in cold warehouses, and R717 is expected to replace R22 (China Cold Chain Logistics Alliance, 2016; Booten et al., 2020). To implement the CR scenario, we modify the $Em_{leak,\ t}$ and $Em_{ref,\ t}$ in Eq. (7). In 2021, we consider that R22 and R717 account for 30% and 70%, respectively. In 2030, R22 will be completely substituted by R717. Hence, the ratio of R717 is 0.7 in 2021 and it increases to 1 in 2030. The change in weight affects $C_{cool,\ t}$, $\dot{Em}_{GWP,t}$, and $C_{ref,\ t}$ in Eq. (4) and Eq. (5), and consequently alter $Em_{leak,\ t}$ and $Em_{ref,\ t}$. Note that we assume a constant linear change in the weight between R22 and R717 between 2021 and 2030. Refer to the supplementary materials for the computation of $C_{cool,\ t}$, $\dot{Em}_{GWP,t}$, and $C_{ref,\ t}$.

Cleaner electricity (CE) scenario: We introduce the CE scenario based on China's target of being carbon-neutral in 2060 (Mallapaty, 2020). To achieve carbon-neutral, it is widely agreed that China needs to cut coal power generation, and nuclear, wind, hydro, and solar power are expected to contribute to more share in 2060 (Mallapaty, 2020). The expected overall electricity portfolio in China in 2060 varies across a range of studies (Chen et al., 2020; Mallapaty, 2020; The Oxford Institute for Energy Studies, 2020). We assume the power source mix in China in 2060 will be 16% thermal sources, 17% hydro, 17% solar, 25% nuclear, and 25% wind, which falls within the range of estimates (Chen et al., 2020; Mallapaty, 2020; The Oxford Institute for Energy

Studies, 2020). The $Em_{ele,\ t}$ in Eq. (7) is affected when implementing the CE scenario. Particularly, we adjust the electricity emission intensity factor ($\dot{Em}_{p,t}$) in Eq. (3) to represent the emission reduction of the national grid due to the penetration of renewable electricity. Particularly, we computed the mean targeted electricity emission intensity in China in 2060. We reduce the emission intensity at a constant rate until the emission intensity reaches the targeted value. It is worth mentioning that we do not specify the power source mix for each province in 2060 due to lack of information but merely use the national average. The calculation of $\dot{Em}_{p,t}$ is presented in the supplementary materials.

Higher energy efficiency (**HE**) **scenario**: We develop the HE scenario according to the government's green and high-efficiency cooling and refrigeration plan (National Development and Reform Commission of People's Republic of China, 2019). One main target of the plan is to improve the energy efficiency of refrigeration facilities by 25% in 2030 in China. The HE scenario is designed based on this 25% target. Because only new cold warehouses can have significantly higher efficiency, we implement the efficiency improvement on the new cold warehouse. Similar to the CE scenario, we also alter the $Em_{ele,\ t}$ in Eq. (7) to implement the HE scenario. However, unlike the CE scenario where $\dot{Em}_{p,t}$ in Eq. (3) is changed, the HE scenario affects $E_{spc,\ t}$ in Eq. (3) to represent the changes in $Em_{ele,\ t}$. Based on National Development and Reform Commission of People's Republic of China (2019), we consider the $E_{spc,\ t}$ to reduce by 15% by 2030 and the change rate is constant between 2021 and 2030. More computation details regarding $E_{spc,\ t}$ are in the supplementation materials.

Cleaner cold warehouses (**CCW**) **scenario**: The CW scenario includes the combined effects of cleaner refrigerant, higher energy efficiency, and cleaner electricity sources. In the modeling, modification of Eq. (7) mentioned in the CR, CE, and HE scenarios are all applied to implement the CCW scenario. Therefore, the CCW scenario is expected to have the strongest influence on the lifetime emissions of cold warehouses in China.

4. Results and discussion

The estimated cold warehouse capacity in each province in 2060 is shown in Fig. 2, including the existing capacity in 2021 along with the total suppressed capacity that is expected to be built over time. Fig. S4 in the supplementary materials shows the estimated capacity of all provinces in each future year. Per-year capacity data is further used to estimate the emission trajectory. Provinces with larger populations will require greater cold storage. Hence, Guangdong, Shandong, and Henan provinces are expected to have the greatest total cold warehouse capacity given that they have the largest populations. Meanwhile, Liaoning, Chongqing, Beijing, and Tianjin already have adequate cold warehouses and are not expected to build additional capacity after 2021. Thus, the total estimated emissions of cold warehouses in those regions are entirely from the operation phase between 2021 and 2060. In contrast, regions that are relatively underdeveloped (e.g., Gansu, Xinjiang, Ningxia, Qinghai, and Tibet) have lower cold warehouse capacity in the base year and greater potential to build more in the future. This observation aligns with prior studies that indicate unevenly distributed cold chain resources in China, with more cold warehouses in more developed regions (Dong et al., 2021b). Moreover, the emissions of cold warehouse construction obtained by EIO analysis [tCO_2eq/m^3] are shown in Fig. S5 in the supplementary materials, and these intermediate results are also used for emission trajectory estimation.

Fig. 3 shows the emission changes associated with cold warehouse development in China across the five scenarios from 2021 to 2060.

The BAU baseline curve shows that the GHG emissions increase gradually before flattening after 2040, which reflects the change in expected cold warehouse capacity over time, with 22 out of 31 provinces reaching the cold warehouse construction target in 2040 or earlier. Emissions stabilize after 2040 because the majority of emissions are

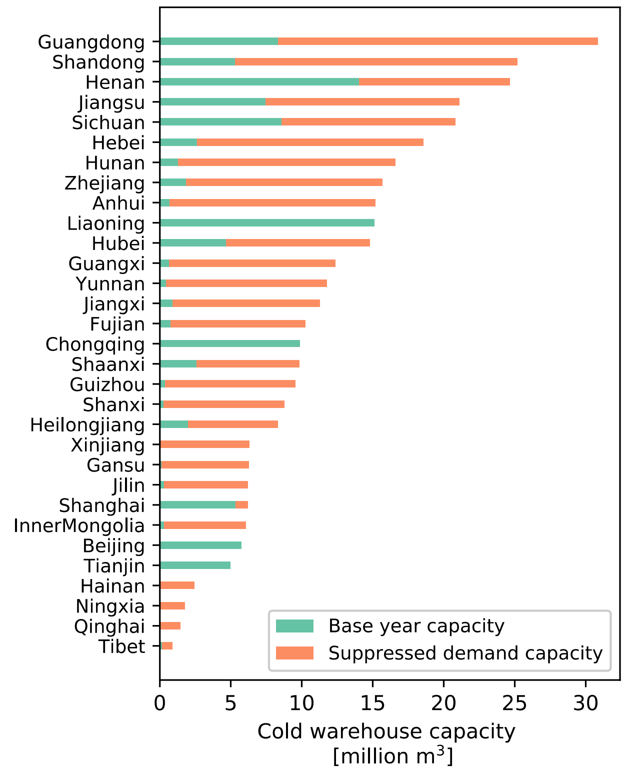

Fig. 2. Estimated cold warehouse capacity in 2060. Existing cold warehouse capacity in 2021(green) and suppressed capacity (orange). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

from cold warehouse operations rather than increased capacity. At saturated capacity with no improvements in refrigerants, energy efficiency, or grid emissions, the annual operation emissions would be approximately 30 $MtCO_2eq$, or about 0.3% of total 2018 GHG emissions in China (International Energy Agency, 2018). While a relatively small proportion in China, 30 $MtCO_2eq$ emissions are almost equivalent to the nationwide emissions in Sweden or Denmark in 2018 (International Energy Agency, 2018).

Fig. 3 also depicts emission trends associated with the four improvement scenarios of cleaner refrigerant (CR), cleaner electricity (CE), higher energy efficiency (HE), and cleaner cold warehouses (CCW).

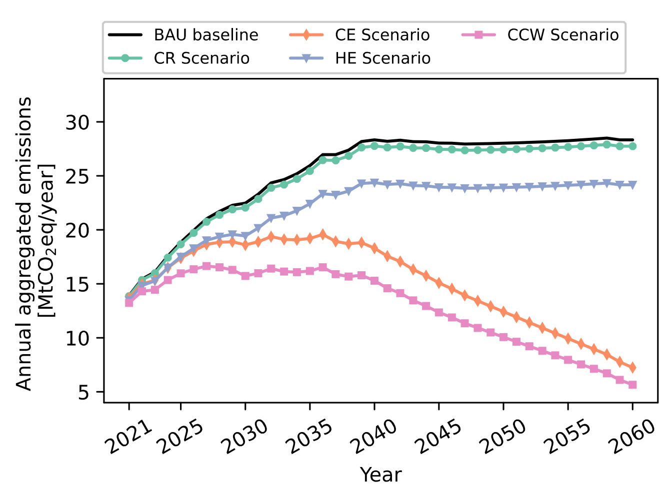

Fig. 3. Estimated annual cold warehouse emissions in China from 2021 to 2060, comparing the emission trend of five scenarios. CR: Cleaner refrigerant; CE: Cleaner electricity; HE: Higher energy efficiency; CCW: Cleaner cold warehouses; BAU: Business-as-usual.

Notably, cleaner electricity sources have the strongest influence on reducing cold warehouse emissions than the other interventions.

Although there is a slight emission reduction in the CR scenario, the trend of emissions in the CR scenario is almost identical to the BAU scenario: both curves peak in 2040 and remain relatively stable afterward. Substituting R22 with R717 is the driver of the CR scenario and the results in Fig. 3 show that using cleaner refrigerants in cold warehouses does not have a strong impact on the trajectory of cold chain emissions in China. Fig. 4 indicates that the emissions related to refrigerant leakage and production contribute to less than 5% of aggregated GHG emissions over the 40 years period, in part because R717 is already a popular refrigerant for industrial refrigeration in China (China Cold Chain Logistics Alliance, 2016; Zhang et al., 2019). In 2060, the emissions in the CR scenario are approximately 2% lower than that of the BAU scenario. Even though refrigerant substitution does not have the highest improvement potential, R22 does have high global warming and ozone depletion potentials that make it important to phase out. Substituting cleaner refrigerants for R22 will play a critical role in the entire cooling services industry, which includes both refrigeration and the larger air conditioning market. China is the largest R22 producer in the world and consumes 70% of its R22 production (Zhang et al., 2019; Booten et al., 2020). Nevertheless, the disadvantages of R717 should be noted. Although R717 has excellent thermodynamic properties and negligible global warming potentials, R717 is toxic and flammable (Ciconkov, 2018). The proper operation of R717 refrigeration units requires strict standard enforcement.

The HE scenario shows moderate emission reductions over time. With energy efficiency improving as new warehouses are constructed, the anticipated annual emission in the HE scenario is 7% lower than BAU in 2025 and 13% lower in 2030. In order to align with the targets stated in the green cooling plan, efficiency improvements level off in 2030 (National Development and Reform Commission of People's Republic of China, 2019). Despite the assumption of no additional efficiency improvements post-2030, the model calculates potential GHG emissions reductions compared to BAU until 2040, due to newly constructed units being held to the higher efficiency standards. The overall effectiveness of the HE scenario is estimated to be 14% lower than BAU in 2060, although this intervention could result in additional savings if more stringent energy efficiency standards are adopted post-2030.

The CE scenario has the greatest emissions reduction potential of all of the individual interventions. Fig. 3 shows that after annual emissions increase gradually from 2021 to 2030, emissions plateau between 2030 and 2040, despite cold warehouse capacity increases. From 2030 to 2040, the total cold warehouse capacity is expected to increase by 32%, while the total emissions in the CE scenario remain relatively constant at 19 $MtCO_2eq$. This result suggests that the effects of cleaner electricity sources are strong enough to offset the emissions generated from greater installed cold warehouse capacity. Beyond 2040, emissions under the CE scenario are expected to decrease, as a result of stabilizing cold warehouse capacity and continued decreases in emissions associated with the electricity grid. Compared with the BAU scenario, the emissions in the CE scenario in 2030 and 2060 are 17% and 74% lower. Furthermore, the cumulative 40-year emissions in the CE scenario are 41% lower than that in the BAU baseline, as shown in Fig. 4. The trend of the CE scenario implies the significant potential of using cleaner electricity sources to control emissions in the refrigeration sector.

The HE and CE scenarios have similar emission reduction patterns prior to 2030. As noted above, we did not model the effects of higher energy efficiency beyond 2030 because (National Development and Reform Commission of People's Republic of China, 2019) does not include a green cooling target after 2030 and the scenarios only estimate the impact of existing policy efforts. Nevertheless, our results suggest that implementing energy efficiency measures and replacing older refrigeration devices with newer ones is an effective approach to reduce emissions in the short term even when electricity sources do not change. This finding is aligned with Kim et al. (2006) who found household refrigerator replacement is a practical approach to reduce household refrigerator emissions. Additionally, improving the energy efficiency of cold warehouses could be a better solution than using cleaner electricity sources in certain contexts. In reality, building new power plants to substitute existing thermal plants is a much larger project than changing the refrigeration devices in cold warehouses. Building new power plants is more time-consuming and requires large expenditures; hence, it is challenging for developing countries in the short term. Nevertheless, upgrading the national grid with renewable resources will not only affect the cold chain industry but also reduce emissions across all sectors, whereas improving the energy efficiency of refrigeration devices is a direct measure to reduce GHG emissions of cold warehouses. In the long term, reducing electricity grid emissions (e.g., reducing coal consumption in China) is the most effective approach to reduce cold warehouse emissions.

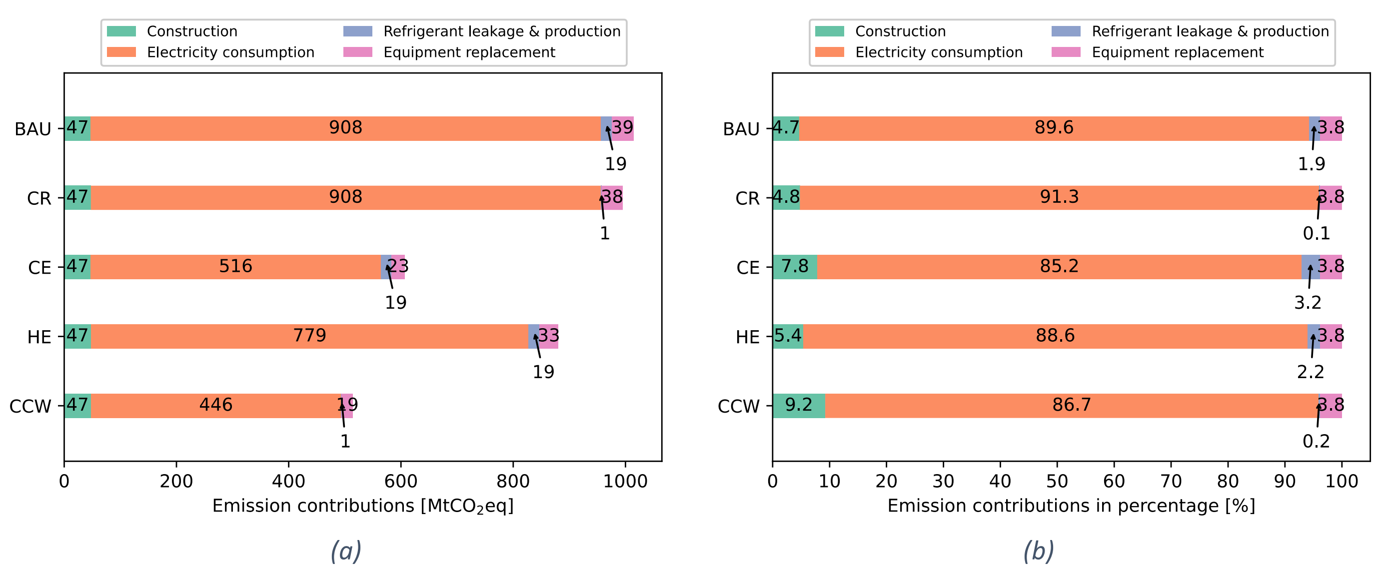

Fig. 4. 40-year accumulated emissions associated with construction, electricity consumption, refrigerant leakage/production, and equipment replacement. Equipment replacement includes those emissions from replacement, reproduction, and retirement. Panel (a) presents the emission contributions in absolute values ($MtCO_2$-eq) and Panel (b) presents emission contributions in percentage.

The CCW represents the combined influence of cleaner refrigerants, cleaner electricity sources, and higher energy efficiency of cold warehouses; hence, it results in the most significant emission reductions, as expected. Emissions in the CCW scenario are 30% lower than that in the BAU scenario in 2030 and 80% lower in 2060. If cleaner refrigerants, higher efficiency standards, and cleaner electricity sources are fully implemented as stated in existing policies, the 40-year cumulative emissions of cold warehouses would be equivalent to 5% of total emissions of 2018's level in China, as compared to over 10% under BAU. However, it should be noted that most emission reductions are achieved by using cleaner electricity sources implying the importance of renewable electricity transition in China. The trend of the CCW scenario in Fig. 3 also shows that cold warehouses are expected to have the highest emissions between 2025 and 2035, which is aligned with China's national pledge of reaching the maximum GHG emissions before 2030 (Chen et al., 2020; Mallapaty, 2020; The Oxford Institute for Energy Studies, 2020).

Overall, the emission trajectory analysis reveals the potential impacts of different regulations in China. Improving energy efficiency and using cleaner electricity sources are effective interventions to reduce the GHG emissions of cold warehouses; substituting traditional refrigerants with natural refrigerants is less efficient but necessary from the entire cooling services industry's perspective.

Fig. 4 breaks down the cumulative 40-year emissions in China for each scenario and the emissions resulting from cold warehouse construction, electricity consumption, refrigerant leakage & production, and equipment replacement. The most apparent feature is that the emissions from electricity consumption dominate all scenarios. The emissions from electricity consumption constitute at least 85% of total 40-year emissions regardless of scenarios. This result aligns with results in Cascini et al. (2016) where they found the use phase of refrigeration responsible for the majority of emissions, contributing at least 67% of cumulative emissions over a 10 year period. The proportion of electricity consumption emissions is even higher in this study due to the 40-year timeframe.

The worst-case BAU scenario without improvements would be responsible for about 1013 $MtCO_2eq$ greenhouse gases over the study period, 89.6% of which are due to electricity consumption. The second-largest emission contributor is construction, accounting for 4.7%. The 40-year emissions in the CR scenario are 18 $MtCO_2eq$ smaller than the BAU, representing the contribution of cleaner refrigerants. The accumulated emissions in the CE and HE scenarios are 408 $MtCO_2eq$ and 145 $MtCO_2eq$ lower than the BAU scenario, respectively. The percentage of emissions from electricity consumption in the CE scenario is the lowest (85.2%) in all scenarios. This value additionally emphasizes the importance of reducing electricity consumption related emissions. If cleaner refrigerants, higher energy efficiency, and cleaner electricity source are fully implemented, the total emissions between 2021 and 2060 in the CCW scenario are roughly half the emissions associated with the BAU scenario. Note that the data in Fig. 4 are estimated assuming implementation of policies as scheduled; actual emissions will vary depending on a wide variety of factors, including the effectiveness of implementing regulations. To our knowledge, the results provide the first published estimates of the general emission trajectory of cold warehouses in China.

When using China as an example for broader implications of developing cold chain facilities, one should comprehensively understand the characteristics of each measure. Ideally, all three approaches (i.e., using cleaner refrigerants, improving energy efficiency, and increasing the penetration of renewable electricity in the national grid) should be implemented. However, other countries may wish to focus on different approaches to reduce emissions for cold chain facilities based on their individual circumstances.

The national-level estimation comes from aggregating results calculated at the provincial level. The GHG emission trajectories of individual provinces display a large degree of variability, which can be further analyzed to provide insights to a range of contexts that may be observed in developing and developed nations. Fig. 5 displays the emission trajectory and emission contributions in percentage in three examples: Beijing, Guangdong, and Qinghai. These three regions represent a province with fully developed cold warehouse capacity, a province with major anticipated capacity increases, and a province with a high penetration of renewable electricity, respectively.

First, Beijing has no suppressed cold warehouse capacity (Fig. 2); hence, Fig. 5 panel (a) indicates a scenario similar to what would be observed in developed countries where the cold warehouse capacity is nearly saturated. GHG emissions are merely from electricity consumption and refrigerant leakage and production due to devices operation and maintenance. Hence, the emission trajectory in the BAU scenario is relatively stable in 40 years. In 2030, the emissions in the HE scenario and CE scenario are 14% and 19% lower than that in the BAU scenario. More emission reduction in the CE scenario indicates that supporting the penetration of renewable electricity is of vital importance in developed countries. Meanwhile, although new cold warehouse construction is not expected, policies should continue regulating the energy efficiency of new devices to replace installed units.

Secondly, Fig. 5 panel (b) can be a potential scenario for developing countries with high populations and demanding large cold chain facilities in the future. In terms of overall percentage contributions of GHG emissions, Guangdong shows a roughly similar pattern to Beijing, with the majority of emissions deriving from electricity consumption. In contrast to Beijing, Guangdong province is anticipated to have the largest cold warehouse growth in the future (Fig. 2) due to anticipated population growth (Table S1 in the supplementary material). The trajectory curves of Guangdong show that the emissions in all scenarios are expected to peak in 2027 and step down in the following year. It is because the cold warehouse capacity is saturated in 2027 and the construction emissions are not generated afterward. The overall emission reduction trend in Guangdong follows the pattern at the national scale where the CE scenario shows the strongest mitigation followed by the HE and CR scenario.

India has a similar context to Guangdong. The country has over one billion population and great cold chain development potential, despite that India already has a large cold warehouse capacity (Salin, 2018). However, over 70% of electricity was solely from coal (International Energy Agency, 2018) and a small improvement in either energy efficiency or electricity sources can be amplified by the large cold warehouse capacity from the national scope of India. From a positive perspective, both China and India pledge to be carbon neutral in the 21st century (The Oxford Institute for Energy Studies, 2020; Vaidyanathan, 2021). Accelerating the penetration of renewable electricity in the world not only reduces GHG emissions in the cold chain industry but also contributes across all industrial sectors.

Finally, Qinghai has the highest non-thermal electricity supply in China with over 70% of power supply is from renewable sources (Ding et al., 2017), and also has high anticipated cold warehouse demand. Qinghai can potentially be used to illustrate scenarios in developing countries with significant renewable electricity. The percentage of construction-related emissions is much higher, while electricity consumption does not exceed 65% in any scenario. After peaking in 2043, the emissions in 2045 in the CR scenario are 7% lower than that in the BAU scenario. Such reduction is identical to that in the CE scenario indicating that using cleaner refrigerants can be as effective as using cleaner electricity sources in countries with high renewable electricity. Taking Brazil as an example, hydropower accounts for about 60% of electricity in 2018 (International Energy Agency, 2018) and the cold warehouse capacity increased by 18% from 2014 to 2018 (Salin, 2018). With fast-growing cold chain facilities and a relatively clean national grid, using cleaner refrigerants has a more important position in reducing GHG emissions from cold chain facilities in Brazil.

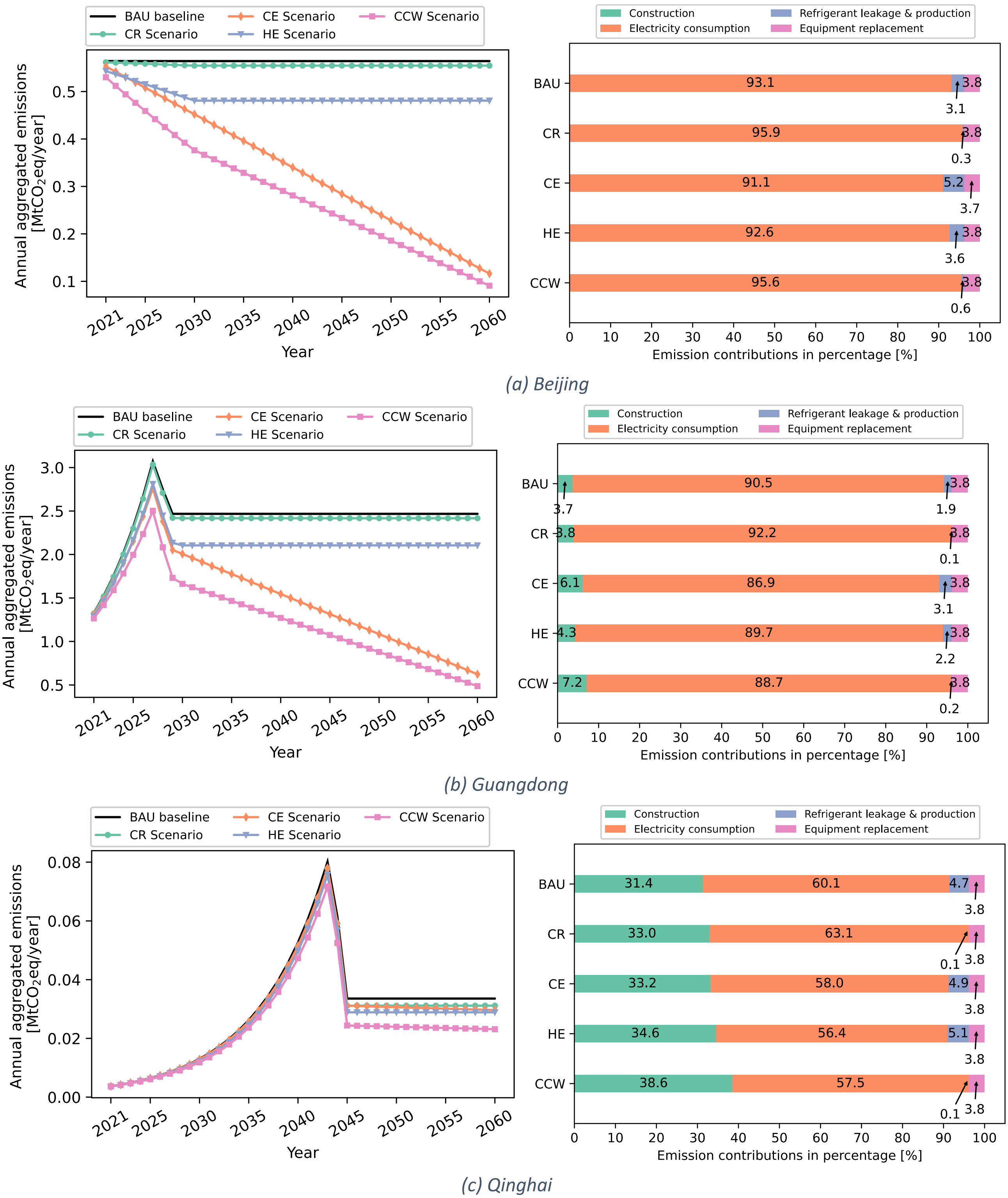

Fig. 5. Estimated annual cold warehouse emissions in three provinces (regions) from 2021 to 2060 and Emission trajectory and 40-year accumulated emissions break down by emission contributions. Panel (a): Beijing; Panel (b): Guangdong; Panel (c): Qinghai.

5. Conclusions

Cold chain logistics prolong the shelf life of perishable products and is critical in the food system. Meanwhile, it is widely agreed that we need to develop the cold chain sustainably. Researchers have been studying the environmental impacts of the cold chain system; however, quantitative estimations on cold chain facilities are lacking and the literature emphasizes more on the life cycle emissions of perishable food products. Therefore, this article fills the gap taking the context of China and quantitatively investigating the greenhouse gas emissions of cold chain infrastructures. We use a hybrid environmental input-output and process-based analysis to quantitatively investigate the GHG emissions of cold warehouses in China in 40 years from 2021 to 2060. Five scenarios are also designed to compare the effectiveness of using cleaner refrigerants, improving energy efficiency, and using cleaner electricity sources in cold warehouses in China. We find that fully implementing all measures (i.e., cleaner refrigerants, higher energy efficiency, and cleaner electricity sources) can achieve approximately 80% of emission reduction compared to business as usual. More importantly, over 85% of total emissions in 40 years are expected from cold warehouses electricity usage. Hence, we conclude that improving energy efficiency and using cleaner electricity resources are more effective than using cleaner refrigerants to control the GHG emissions of cold warehouses. In the short term, improving the energy efficiency of refrigeration devices can offset the emissions from the capacity increase. Rapid implementation of energy efficiency measures can result in significant improvements as lower-carbon electricity facilities are developed. The regulation of improving the energy efficiency of refrigeration devices should also be issued after 2030. In the long term, upgrading renewable electricity sources in the national grid is the most beneficial not only to the cold chain industry but also to the whole industrial sector. The results of our study can guide the emission of cold chain facilities in other developing countries so that they can adjust different rules to regulate the construction and operation of cold chain facilities accordingly.

Finally, each of the defined scenarios included in this study is limited by the current regulations in China. The effectiveness of each scenario will vary according to actual implementation. As with any long-term forecast, the developed scenarios highlight overall expected trends and provide insights into the magnitude of the specific interventions, but contain a high level of uncertainty. Maintaining the accuracy of life cycle inventory data is also a common challenge in studies using the LCA method. As such, this article represents one of the earliest quantitative studies on the GHG emissions of cold warehouses and seeks to provide insights into the effectiveness of a suite of interventions. In the future, research should keep tracking the regulations on the refrigeration and cold chain industry, collect more accurate life cycle inventory data, and adjust computations to enhance the model accuracy to eventually support sustainable decision-making for the cold chain industry.

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Declaration of competing interest

All authors declare that there are no financial or personal interests that affected this work. Any opinions, findings, and conclusions in this article reflect the view of authors not any funding sources.

Appendix A. Supplementary data

The supplementary materials present ancillary figures and tables of intermediate calculations and results. Supplementary data to this article can be found online at https://doi.org/10.1016/j.spc.2022.03.017.

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