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Negative emission technology is key to decarbonizing China's cement industry

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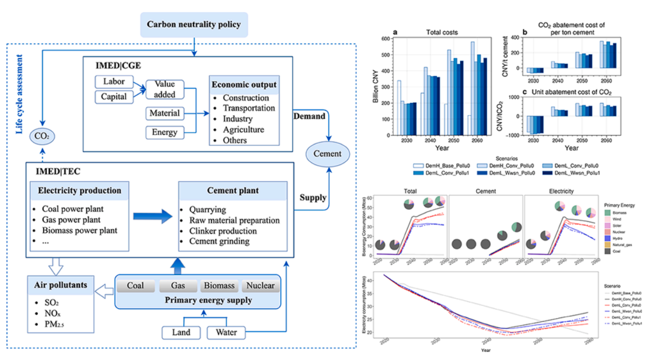
HIGHLIGHTS

- An integrated top-down and bottom-up modeling framework was developed.
- Improving energy efficiency will reduce SO_2, NO_x, and $PM_{2.5}$ by 33%, 35%, and 8%, respectively, by 2030.
- The share of kilns equipped with BECCS will increase to 68–75% by 2060.
- Biomass production will require 7–11 km^3 of water and 3–4 Mha of land by 2060.

GRAPHICAL ABSTRACT



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ABSTRACT

The cement industry, which contributes to 8 % of global CO_2 emissions and a large quantity of air pollutants, plays a pivotal role in achieving the carbon neutrality target. However, the question of how to decarbonize the cement industry toward net-zero emissions and the corresponding environmental impact remains unclear. An integrated assessment framework combining a top-down computable general equilibrium model, a bottom-up technology selection model, and a life-cycle assessment was developed to explore the cement industry's carbon–neutral pathways and associated environmental impact. Results show that promoting energy-efficient technologies is crucial for reducing CO_2 emissions in the short term, which can also significantly reduce air pollutant emissions. Improving energy efficiency contributes to reducing the emissions of SO_2, NO_x, and $PM_{2.5}$, by 33 %, 35 %, and 8 %, respectively, by 2030. In the long run, achieving net-zero carbon emissions requires implementation of bioenergy with carbon capture and storage (BECCS) and demand-side mitigation measures. The share of kilns equipped with BECCS would increase to 68–75 % by 2060. Corresponding unit abatement costs of CO_2 are 484–676 CNY/tonne CO_2. However, BECCS triggers adverse side effects by increasing water consumption and land cover by 7–11 km^3 and 3–4 Mha, respectively, in 2060. Thus, China should take full advantage of energy-efficient technologies to co-control CO_2 and air pollutant emissions while avoiding negative effects of BECCS.

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Nomenclature and acronym definitions

CCS	Carbon capture and storage
SDGs	Sustainable development goals
Gt	Gigaton
GHG	Greenhouse gas
IAMs	Integrated assessment models
LCA	Life-cycle assessment
BECCS	Bioenergy with carbon capture and storage
IMED|CGE	Integrated model of energy, environment, and economy for sustainable development/computable general equilibrium model
IMED|TEC	Integrated model of energy, environment, and economy for sustainable development/technology selection model
IEA	International Energy Agency
CESN	Consider electricity supply endogenously
GTR	Green Transition Roadmap
MFA	Material flow analysis
NET	National energy technology
MARKAL	Market allocation model
EFOM	Energy flow optimization model
TIMES	Integrated MARKAL-EFOM system
GAINS	Greenhouse gas and air pollution interactions and synergies
HCl	Hydrogen chloride
ECSC	Energy conservation supply curves
MACC	Marginal abatement cost curve
CTS	Clean technology scenario
MEF	Material efficiency variant
i	Sector
t	Year
$SDV_{i,t}^{BAU}$	Cement demand of sector i in year t under the BAU scenario
$SDV_{i,t}^{CN}$	Cement demand of sector i in year t under the carbon neutrality scenario
POP_tBAU	Population
I_tBAU	Per capita cement demand in year t
$share_{i,t}$	Share of cement consumption of sector i in total cement consumption
$PV_{i,t}^{BAU}$	Production values of sector i in year t under the baseline scenarios
a	Production values of sector i in year t under the carbon neutrality scenarios
C	Total system cost
st	Technology
β_{st}	Subsidy rate of technology st
α	Discount rate
L_{st}	Lifetime of technology st
IC_{st}	Initial investment cost of technology st
OMC_{st}	Operation and maintenance cost of technology st
se	Energy type
sm	Raw material including energy
$mpri_{sm}$	Price of raw material
$E_{sm,st}$	Raw material (sm) consumption per unit operation of technology st
VX_{st}	Operating quantity of technology st
sg	Gas type
TAX_{sg}	Emission tax on gas sg
VQ_{sg}	Emission quantity of gas sg
$TAXE_{se}$	Energy tax of energy se
VE_{se}	Energy consumption
$EM_{st,sg}^{0}$	Emission quantity of gas sg from operating a unit of technology st
γ_{sg}	Removal efficiency of air pollutants (sg) control technology
$emf_{se,sg}$	Emission factor of gas sg from energy se
EX_{st}	Energy-efficiency improvement ratio of technology st
$NE_{st,se}$	Proportion of energy (se) used for non-combustion for technology st
Q_{gg}	Maximum permissible limit on emissions of the gg group
$S_{st,sd}^{max}$	Maximum limit for share of service (sd) output of technology st
$S_{st,sd}^{min}$	Minimum limit for share of service (sd) output of technology st
$A_{st,sd}$	Service output per unit operation of technology st
T_{sd}	Total service output of all technologies
SDV_{sd}	Service demand
$\Omega_{sd,se}$	Combined group of internal energy and internal service (se,sd)
E_{se}^{max}	Maximum allowable supply quantity of se
E_{se}^{min}	Minimum acceptable supply quantity of se
VS_{st}	Stock quantity of technology st
η_{st}	Operating rate of technology st
SS_{st}	Stock quantity of technology st in the previous year
VR_{st}	Recruited quantity of technology st in the current year

1. Introduction

Achieving a 1.5 °C climate change target requires global net CO_2 emissions to reach net-zero by the mid-century [1,2]. The cement industry, which contributes 8 % of global CO_2 emissions [3], is pivotal for achieving the ambitious Paris climate goals. China, the world's largest CO_2 emitter, pledged to peak its CO_2 emissions by 2030 and achieve carbon neutrality by 2060. China is the largest global cement producer, and the cement sector contributes approximately-one-third of China's national industrial CO_2 emissions [4]. Attaining net-zero CO_2 emissions from the cement industry will be the bedrock for China's 2060 carbon–neutral commitment and provides a firm underpinning for holding the rise in global mean temperature below 2 °C. China still faces severe air pollution, even though it has battled air pollution for many years [5,6]. As a major air pollutant emitter in China [7], the cement industry is struggling to meet ultralow emission standards [8]. Therefore, it is important to explore the low-carbon transition pathway of the cement industry in China and assess its local environmental impact.

CO_2 emissions from cement production originate from direct combustion of fossil fuels (which account for approximately 30–40 % of total CO_2 emissions), process-related emissions from chemical reactions (50–60 %), and upstream emissions from electricity production (5–12 %) [9,10]. Massive process emissions from chemical reactions of limestone [11,12] make the cement industry-one of the most challenging sectors to achieve net-zero emissions. Currently, seven types of measures have been proposed to mitigate CO_2 emissions of the cement industry [10,13–19]: (1) improving energy efficiency by deploying advanced technologies; (2) switching to alternative low-carbon fuels such as bioenergy and hydrogen; (3) reducing the clinker-to-cement ratio; (4) introducing carbon capture and storage (CCS); (5) decarbonizing power generation to reduce indirect CO_2 emissions; (6) reducing cement demand by improving material efficiency; and (7) CO_2 uptake by concrete. Improving energy efficiency contributes to energy conservation and reduction of air pollutant emissions. The Chinese government has published a promotion catalog of national key energy-saving and low-carbon technologies to improve energy efficiency. Fuel switching can effectively reduce CO_2 and air pollutant emissions from combustion of fossil fuels [19]. However, production of alternative fuels such as bioenergy may trigger concerns regarding water consumption and land cover. For example, the global area under severe water stress is projected to double because of the irrigation of biomass plantations for combating climate change [20]. The land requirement for planting biomass plantations would increase by approximately 41 % if irrigation is prohibited [21]. CCS, which has been successfully piloted in a kiln precalciner, is crucial for reducing CO_2 emissions, especially unabated process-related emissions. Reducing service demand by implementing material efficiency measures can simultaneously reduce CO_2 and air pollutant emissions and resource consumption [15,22]. Hence, beyond CO_2 emission reduction, sound low-carbon transition pathways should also consider other local environmental dimensions to minimize trade-offs between climate change mitigation and other sustainable development goals (SDGs).

A growing number of studies have explored decarbonization in the cement industry, as summarized in Table 1. Most studies typically focused on reducing CO_2 emissions to certain levels (above zero) by the mid-century but failed to support policymakers in designing low-carbon transition pathways toward net-zero emissions. Thus, low-carbon transition pathways toward carbon neutrality in the cement industry are still lacking. Moreover, emerging research explores decarbonization of the cement industry using only one or two of the abovementioned supply-side measures. Among supply-side measures, improving energy efficiency [23], fuel switching [24], and CCS [25] are commonly studied. However, demand-side measures, such as improving material efficiency, have been widely overlooked, even though emerging studies have shown that a significant CO_2 reduction potential exists on the cement demand-side [15,26]. For example, Miller et al. showed that increasing longevity of cement by 50 % would result in a 0.4–0.7 Gt reduction in greenhouse gas (GHG) emissions in the USA, which could rival some low-carbon strategies that are commonly considered [26]. In addition to the cement demand-side, the cement industry is intertwined with upstream industries. For example, decarbonization of the power sector, which is a vital decarbonization priority for achieving the 1.5 °C climate change target [27], would lower indirect CO_2 emissions of the cement industry [28]. Recent literature suggests the importance of comprehensive mitigation strategies along the entire life-cycle stage of cement [29]; however, empirical research is still lacking.

Furthermore, employing decarbonization measures in the cement industry would also impact local resources and the environment; however, this has not been fully quantified in existing studies. Consequently, the feasibility of decarbonization pathways is highly uncertain. Most studies based on integrated assessment models (IAMs) [30] usually fail to include specific environmental impacts such as land use and water consumption. In contrast, studies based on life-cycle assessment (LCA) typically consider broad specific environmental impact [31]; however, it is difficult to account for changes in technology structure in the context of carbon neutrality. Given the many shared sources of CO_2 and air pollutants, mitigation measures aimed at CO_2 reduction can abate air pollution [32–35]. Bioenergy with carbon capture and storage (BECCS) has been touted to achieve net-zero emissions in the cement industry [12,36]. On one hand, substituting coal with biomass contributes to reducing CO_2 emissions from fossil fuel combustion. On the other hand, negative emissions produced by BECCS are crucial for offsetting unabated process-related emissions. However, production of large-scale biomass (e.g., energy plantations) has significant impact on local

Table 1
Relevant studies on low-carbon transition for the cement industry.

Study	Region period	Method	Net-zero	Environmental impact	Decarbonization of other stages CESN	Cement demand
[37]	China 2020–260	GTR GAINS	√	Air pollutants	√	x
[38]	Japan 2010–2050	MFA	√	x	√	√
[17]	A cement plant	Aspen Plus	x	x	x	x
[39]	China 2015–2050	NET	x	Air pollutants	√	x
[26]	USA 1900–2015	MFA	x	Resource (water, etc.)	x	√
[24]	A cement plant	Multidimensional model based on mass and enthalpy balances	x	Air pollutants, HCl and metals	x	x
[40]	Global 2015–2050	LCA	x	x	x	√
[41]	China 2010–2050	TIMES Stock-based model	x	x	√	x
[42]	China 2010–2020	Bottom-up optimization model	x	Air pollutants	x	x
[43]	China 2011–2050	Bottom-up optimization model	x	x	x	X
[23]	China 2011–2030	ECSC GAINS	x	Air pollutants	x	x
[33]	China 2011–2015	Marginal abatement cost	x	Air pollutants	x	X

Study	Low-carbon measures
[37]	Advanced efficiency technology application, use of alternative raw materials, alternative fuels, utilization of renewable electricity, application of CCS, and cement carbonation effects.
[38]	Improving energy efficiency, fuel switching, reducing clinker-to-cement ratios, lowering transportation emissions, decarbonizing electricity supply, and material efficiency strategies.
[17]	Substituting coal with hydrogen.
[39]	Improving energy efficiency, switching to alternative fuels, using alternative raw materials, and implementing CCS.
[26]	Increasing cement service-life.
[24]	Substituting coal with biofuels.
[40]	Material-based solutions, such as alkali-activated binders, calcined clay, etc.
[41]	Fuel switch, energy-efficient measures, and CCS.
[42]	Energy-saving technology, pollution control technology.
[43]	Energy efficiency improvement technology, waste heat recovery, CCS, alternative fuels, and clinker substitution.
[23]	Energy efficiency measures and end-of-pipe options.
[33]	Energy efficiency measures, CCS.

environmental concerns, especially land use change [21] and water scarcity [20]. Thus, quantifying local environmental impact is becoming significantly important in the context of net-zero emissions, which will provide decision-makers with potential co-benefits and trade-offs. This information would help decision-makers set a proper required sectoral mitigation effort based on local resource endowment to meet the national carbon neutrality target, considering that CO_2 abatement cost and potential differ between sectors. Consequently, an integrated framework that can depict dynamic improvement of technology structure on the supply side, change in service demand, and consider broad environmental indicators, is required.

To bridge these research gaps, (1) the possibility of achieving net-zero emissions for the cement industry in China; and (2) the questions on introduction of low-carbon measures, such as when, which, to what extent, and what are the potential costs and environmental impact, are investigated by establishing an integrated assessment framework. The integrated approach was developed by combining cutting-edge analytical tools of the top-down integrated model of energy, environment, and economy for sustainable development/computable general equilibrium (IMED|CGE), the bottom-up technology selection model (IMED|TEC), and LCA. This study has three novel features. First, it sheds new light on achieving net-zero emissions in the cement industry by incorporating negative-emission technology (BECCS), enabling us to go beyond the existing literature that focuses on mild decarbonization. Secondly, in contrast to earlier studies that only investigated CO_2 mitigation measures on the cement production side, this study also covers opportunities on the cement demand side through cement consumption reduction caused by the carbon neutrality policy, which is captured by coupling the demand-side IMED|CGE economic model with the supply-side IMED|TEC model. Third, in addition to air pollutant emissions quantified in earlier studies, associated water consumption and embodied land cover changes were also quantified in this study owing to the introduction of negative emission technologies crucial for achieving the net-zero emission target. Quantifying multiple environmental impact facilitates the integrated management of CO_2, air pollution, water, and land towards sustainable development. The IMED|TEC model was extended to include air pollutants and water consumption, which is further linked to the LCA approach to uncover environmental consequences related to the primary energy supply. A universal analysis framework has been constructed in this study that focuses on one of the most challenging industries, which will enrich the knowledge about tools and consequences for building a net-zero emission society for the international community and serve as a viable model for studies on other difficult-to-abate sectors.

The remainder of this paper is organized as follows. Section 2 introduces the methods including the model framework, specific models, scenarios, and data sources. Section 3 presents the results, including projected cement demand by 2060, technological evolution routes, energy consumption, cost, and environmental impact. Section 4 presents a discussion, and section 5 concludes the paper.

2. Methodology

2.1. Overview of the modeling approach

Complementary features of the top-down IMED|CGE, bottom-up (IMED|TEC), and LCA models have been incorporated in this study. Application of the IMED|CGE model helped to capture the impact of the carbon-neutrality target on China's cement demand. The IMED|CGE model can capture the dynamic evolution of China's national economy and interactions among industries in the context of carbon neutrality. More detailed information on the IMED|CGE model is available at https://scholar.pku.edu.cn/hanchengdai/imedcge. The IMED|TEC model enables optimization of future technology pathways to minimize the total cost under constraints of meeting cement demand and net-zero CO_2 emission targets. Further, LCA method was added to account for environmental impact of primary energy (coal, natural gas, biomass, and nuclear fuel) supply activities from the perspective of life cycle. This allowed, on the one hand, to capture the direct environmental impact of the cement production process as well as electricity production, and on the other hand, to cover environmental impact associated with primary energy production activity. LCA assessment included four stages: primary energy supply, electricity production, cement production, and cement consumption. In the primary energy supply stage, environmental impacts of air pollutant emissions, water consumption, and land cover were considered, which were obtained from other studies. In the electricity and cement production stages, CO_2 and air pollutant emissions, and water consumption of each sub-process were calculated using the IMED|TEC model. The study was conducted under the assumption of no environmental impact on the cement consumption process. The overall model framework is shown in Fig. 1, and a simplified technology framework is shown in Fig. 2.

To improve energy efficiency and reduce CO_2 emissions from the cement sector, the Chinese government has released a series of policies, including the catalog of industrial structure adjustment guidance [44], the national extension directory of significant energy-saving and low-carbon technologies [45], and the recommended catalog of national industrial energy-saving technologies [46]. Comprehensive effects of multiple mitigation strategies from both demand and production perspectives were investigated in this study based on the Chinese government's policy documents [44–47] and the technology development status in China. On the production side, CO_2 mitigation measures include (1) improving energy efficiency, (2) fuel switching (replacing coal with bioenergy), (3) implementing CCS, and (4) decarbonizing the power generation considered in this study. On the demand side, the cement consumption reduction resulting from implementing a carbon neutral policy on the entire economy is considered. The following two measures of reduction were not considered in this study: clinker-to-cement ratio and CO_2 uptake by concrete, because of the following reasons. On the one hand, China, with the lowest clinker-to-cement ratio [48] (0.60) compared to the global average [13] (0.78), has almost no room for improvement. On the other hand, CO_2 uptake by concrete is a relatively slow process [49], which introduces significant uncertainty to the creation of decarbonization pathways for the cement industry. The energy efficiency technologies are from the Chinese government's policy documents and recent studies on low-carbon transition in the cement industry, which are in Supplementary Tables S4-S9.

2.2. Cement demand projection

Cement demand under the baseline (BAU) and carbon neutrality scenarios were projected. The BAU was constructed to follow the current trajectory. Cement demand under the BAU scenario is projected based on population, per capita cement consumption, and share of different downstream industries. Cement demand is divided into five sectors: construction, transport, industry, agriculture, and others. The carbon neutrality policy impacts the economy and, thus, cement demand. This effect was reflected in the carbon neutrality scenario using the IMED|CGE model. More detailed information regarding cement demand projection is provided in the supplementary method.

Cement demand under the baseline scenario was projected based on population size and per capita cement consumption [50,51], as shown in Eq. (1).

$$SDV_{i,t}^{BAU} = POP_t^{BAU} \cdot I_t^{BAU} \cdot share_{i,t} \quad (1)$$

The IMED|CGE model was used to capture the impact of the carbon neutrality policy on China's cement demand. Considering the short economic radius of cement, cement demand was projected using the provincial IMED|CGE, and demand for cement in the five downstream industries under the carbon neutrality scenario was estimated based on their production value difference from the BAU scenario, as shown in Eq.

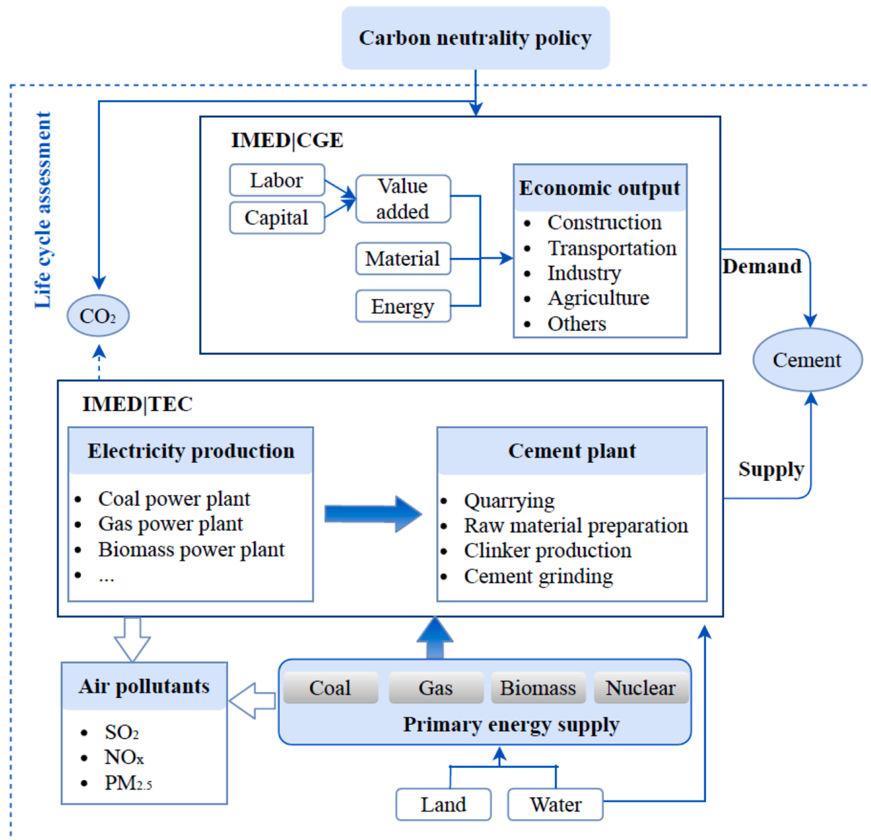

Fig. 1. Overview of the integrated model framework.

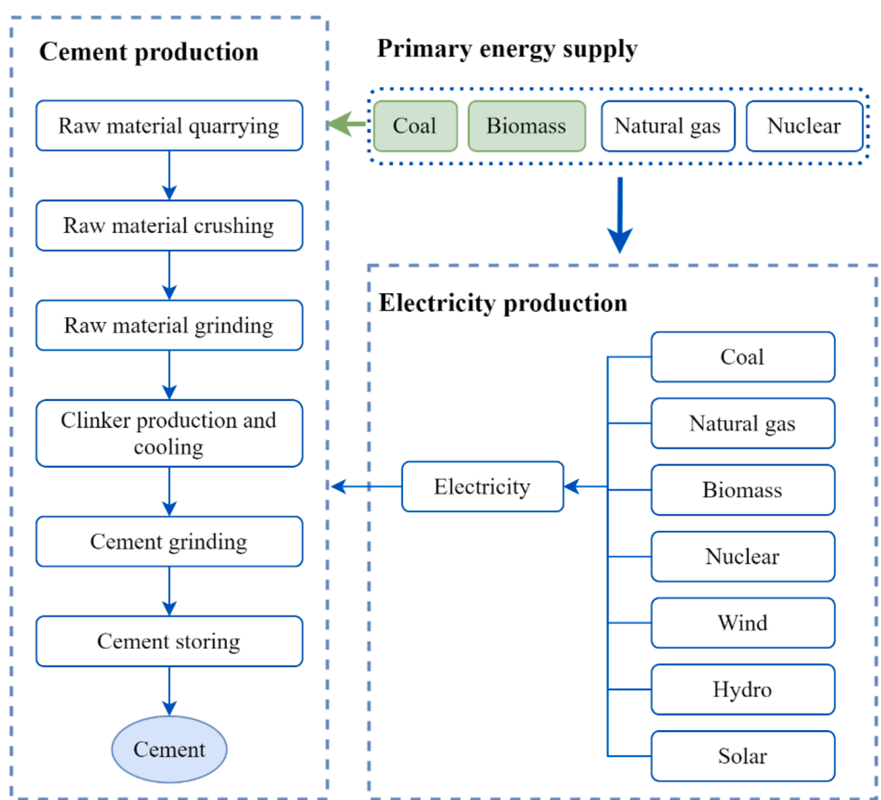

Fig. 2. Simplified technology framework of IMED|TEC. Coal and biomass can be used for cement and electricity production.

(2).

$$SDV_{i,t}^{CN} = SDV_{i,t}^{BAU} \cdot \frac{PV_{i,t}^{CN}}{PV_{i,t}^{BAU}} \quad (2)$$

where $SDV_{i,t}^{CN}$ is cement demand in the carbon neutrality scenario. $PV_{i,t}^{BAU}$ and $PV_{i,t}^{CN}$ are production values under baseline and carbon neutrality scenarios, respectively.

2.3. Technology-selection model

IMED|TEC is a bottom-up technology-selection model that was established as part of a previous research [50]. The model was extended in the current study by introducing air pollutants (SO_2, NO_x, and $PM_{2.5}$) and water consumption. The IMED|TEC model minimizes total cost, including technology investment cost, operation and maintenance costs, energy costs, etc., under constraints of service demand, climate change mitigation policies, and others, to optimize technology evolution pathways.

Objective function.

The objective function of the IMED|TEC model is to minimize total cost, encompassing technology investment cost, operation and maintenance costs, energy and raw material costs, energy tax, and emissions tax, as shown in Eq. (3).

$$C = \sum_{st}[IC_{st} \cdot (1-\beta_{st}) \cdot \frac{\alpha \cdot (1+\alpha)^{L_{st}}}{(1+\alpha)^{L_{st}}-1} + (OMC_{st} + \sum_{sm} mpri_{sm} \cdot E_{sm,st} \cdot VX_{st})] + \sum_{sg} TAX_{sg} \cdot VQ_{sg} + \sum_{se} TAXE_{se} \cdot VE_{se} \quad (3)$$

Emissions originate from process emissions and energy combustion, as shown in Eq. (4).

$$VQ_{sg} = \sum_{st} VX_{st} \cdot (1-\gamma_{sg}) \cdot [EM_{st,sg}^{0} + emf_{se,sg} \cdot (1-EX_{st}) \cdot E_{st,se} \cdot (1-NE_{st,se})] \quad (4)$$

Constraint conditions.

(1) Emission constraints.

Emission should not exceed maximum limit, as shown in Eq. (5). Emission limit can be set based on policies such as the climate change mitigation policy.

$$\sum_{sg \in gg} VQ_{sg} \le Q_{gg} \quad (5)$$

(2) Technology constraints.

The share of service output from a certain technology to all service outputs should fall within maximum and minimum limits as shown in Eq. (6).

$$S_{st,sd}^{\min} \cdot \sum_{st' \in T_{sd}} A_{st',sd} \cdot VX_{st'} \le A_{st,sd} \cdot VX_{st} \le S_{st,sd}^{\max} \cdot \sum_{st' \in T_{sd}} A_{st',sd} \cdot VX_{st'} \quad (6)$$

(3) Service supply and demand constraints:

Service output should satisfy service demand, as shown in Eq. (7).

$$\sum_{st \in T_{sd}} A_{st,sd} \cdot VX_{st} \ge SDV_{sd} \quad (7)$$

For internal energy and service group $\Omega_{sd,se}$ values, supply of internal services should meet demand for internal energy, as shown in Eq. (8).

$$\sum_{sd \in \Omega_{sd,se}} \sum_{st \in T_{sd}} A_{st,sd} \cdot VX_{st} \ge \sum_{se \in \Omega_{sd,se}} VE_{se} \quad (8)$$

(4) Energy constraints:

Energy supply quantity should fall within maximum and minimum limits.

$$E_{se}^{\min} \le VE_{se} \le E_{se}^{\max} \quad (9)$$

(5) Operating capacity constraints:

Technology operating quantity should not exceed stock quantity adjusted by operating rate.

$$VX_{st} \le (1+\eta_{st}) \cdot VS_{st} \quad (10)$$

(6) Dynamic balance of technology capacity.

Technology stock capacity in the current year is the sum of the remaining technology stock quantity of the previous year, considering retirement and recruited quantity in the current year.

$$VS_{st} = SS_{st} \cdot \left(1 - \frac{1}{L_{st}}\right) + VR_{st} \quad (11)$$

2.4. Life-cycle assessment modeling

LCA [52,53] is an holistic methodology widely adopted to evaluate potential environmental impact of products and services from the perspective of the entire life-cycle (i.e., cradle-to-grave). Activities such as raw material acquisition, production, use, recycling, and final disposal of waste are considered. Flow of energy and resources for each activity were quantified precisely. The International Organization for Standardization (ISO) 14040/14044 [52,53] provides a detailed description of the LCA methodology. This study not only considers direct environmental impact of CO_2 and air pollutant (SO_2, NO_x, and $PM_{2.5}$) emissions and water consumption quantified in the technology selection model, but also incorporates the life-cycle environmental impact coefficients of air pollutant emissions, water consumption, and land cover per unit primary energy (e.g., coal, natural gas, and biomass) supply. The life-cycle environmental impacts of coal, natural gas, nuclear fuel, and biomass has been detailed in Yuan et al. [54], Mu et al. [55], and other literature [56–59].

2.5. Scenario description

Cement demand under BAU and carbon neutrality scenarios were projected. In the bottom-up technology selection module, six scenarios were designed based on cement demand, decarbonization technology pathways of electricity, climate policy, and implementation of air pollutant removal technologies (Table 2). DemH_Base_Pollu0 is the baseline scenario without carbon emission constraints, in which electricity and cement production technology development were projected based on historical trends using trend extrapolation. Moreover, penetration rates of end-of-pipe air pollutant control devices were frozen in the base year. Carbon neutrality scenarios, in which CO_2 emissions from the cement industry, including electricity production, would gradually decrease from the present level (1127.59 million tonne, represented as Mt) to net-zero by 2060, constitute the other five scenarios. The five carbon neutrality scenarios differ from each other in their cement demand, technology structure for electricity production, and promotion of end-of-pipe air pollutant control devices. For example, DemH_Conv_Pollu0 indicates cement demand following the trend of higher demand (BAU); the limited share of electricity supply from hydropower (water),

Table 2
Scenario descriptions.

Scenario	Technology availability of electricity production	Climate policy	Cement demand in IMED|CGE	End-of-pipe control devices
DemH_Base_Pollu0	Base	No CO_2 constraint	BAU	Pollu0
DemH_Conv_Pollu0	Conv	CN	CN	Pollu0
DemL_Conv_Pollu0	Conv	CN	CN	Pollu0
DemL_Wwsn_Pollu0	WWSN	CN	CN	Pollu0
DemL_Conv_Pollu1	Conv	CN	CN	Pollu1
DemL_Wwsn_Pollu1	WWSN	CN	CN	Pollu1

wind, solar, and nuclear (WWSN) in 2060 to 65 %, and the gradual increase of share of end-of-pipe air pollutant control devices to 100 % by 2060. The means of "DemH" and "DemL," "Base," "Conv" and "WWSN," "Pollu0″ and "Pollu1″ are shown in Table 2. Impact of cement demand, decarbonization pathways for electricity production, and promotion of end-of-pipe air pollutant control on low-carbon transition pathways of the cement sector and related environmental impact were explored by comparing the results under five different scenarios. Detailed descriptions of the six scenarios are presented in Table 2.

Note: The terms in scenarios, "DemH" and "DemL" represent high and low cement demand cases, which are estimated under the BAU and carbon neutrality scenarios in the IMED|CGE model; "Base," "Conv," and "WWSN" represent the technology available in electricity production; "Base" means that future technology development of electricity production would continue the historical trend. "Conv" means that the share of electricity supply from hydropower (water), wind, solar, and nuclear (WWSN) in 2060 is limited to 65 %, which is projected based on China's NDC target, and the remaining electricity will be generated by coal or BECCS (90 %-biomass and 10 %-coal co-firing power plant equipped with CCS) based on the bottom-up technology selection module. "WWSN" indicates that the share of WWSN in 2060 will increase to 80 %, which is in line with the projected share of WWSN under the 1.5 °C target [60]; the remaining electricity will be generated by coal or BECCS based on the bottom-up technology selection module. "CN" indicates carbon neutrality policy, in which the cement industry's CO_2 emissions, including electricity production, would linearly decrease from the present level to net-zero by 2060. "Pollu0″ indicates the share of end-of-pipe air pollutants control devices will be frozen at the base year (2020). "Pollu1″ represents the share of end-of-pipe air pollutant control devices that will gradually increase to 100 % by 2060.

2.6. Data sources

Data used in this study included macro socioeconomic and technology parameters, which were collected from the literature, government documents and reports, and statistical yearbooks. The macro-socioeconomic parameters included the population China, cement consumption per capita, and prices. Predicted data for China's population during 2020–2060 were sourced from the study by Chen et al. (Table S1) [61]. Production value of the five downstream industries in China from IMED|TEC model is shown in Table S2. Cement consumption per capita was presumed to steadily decrease from the present level in 2020 to 1000 kg by 2060 (Tables S1,S3) [51]. Cement consumption structure is shown in Figure S1. Technical parameters considered were cost, energy and water consumption, technology penetration rate, CO_2, and air pollutant (SO_2, NO_x, and $PM_{2.5}$) emission factors. Technological parameters of the cement industry and electricity production are listed in Supplementary Tables S4–S14. Electricity and cement production technology development under DemH_Base_Pollu0 scenario is shown in Supplementary Tables S5, S8, S12, and S14. Energy price, CO_2, and air pollutant emission factors, water consumption, and other parameters are shown in Supplementary Table S15. Life-cycle environmental impact factors for primary energy supply are listed in Supplementary Table S16.

3. Results

3.1. Projections for cement demand

Future demand for cement under the BAU and carbon-neutrality scenarios is shown in Fig. 3, which is similar to the projections from other studies (Figure S2 and S3) [11,15,23]. Under the BAU scenario, cement demand is projected to decrease from 2394 Mt in 2020 [64] to 1313 Mt by 2060. The construction sector is the largest cement consumer, followed by the transport, industry, and agriculture sectors. Cement demand was predicted to be 504 Mt in 2060 for the construction sector and 299 Mt for the transport sector.

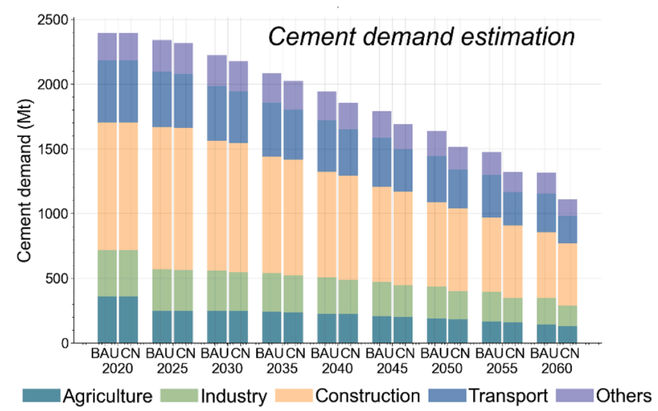

Fig. 3. Projections of cement demand in China during 2020–2060 under BAU and CN (carbon neutrality) scenarios.

In the context of carbon neutrality, cement demand would be reduced owing to decreased economic output. Cement demand is projected to be 1110 Mt in 2060 under the carbon-neutrality scenario, which is 15 % lower than that under the BAU scenario. Cement demand for construction is projected to be 482 Mt by 2060, which is 4 % (22 Mt) lower than that under the BAU scenario. However, construction remains the largest cement demand sector. Transport is the sector most affected, followed by industry. Under the carbon neutrality scenario, cement demand in 2060 for transport and industry will be 210 Mt and 156 Mt, which are 30 % and 24 % lower than those under the BAU scenario, respectively. Agriculture is the least affected sector, and its demand under carbon-neutrality scenario for cement is almost the same as that in the BAU scenario.

3.2. Technology pathway towards carbon neutrality

The optimal technology development pathway under the DemL_Conv_Pollu0 scenario is shown in Fig. 4 (Figures S4–S5 for the other scenarios). Energy-efficient technologies, which can reduce energy consumption and associated emissions, show similar development trends under different carbon neutrality scenarios. This indicates that under the carbon neutrality target, the technology evolution pathways of energy-efficient technologies are robust and insensitive to the decarbonization pathways of electricity production and future cement demand. Moreover, all the selected energy-efficient technologies will rapidly reach maximum penetration rates by 2030.

In the raw meal preparation process, six technologies, including a high-pressure roller press (PE4), efficient roller mills (LC1), variable frequency drive (LC5), bucket elevator (LC6), high-efficiency fan (LC7), and a new efficient coal separator (LC8), are suggested to be promoted as their share gradually increases to 100 % by 2030. In the calcination process, large-size new suspension pre-calciner (NSP) kilns (PE9) and advanced coolers (PE13) will become popular owing to their higher energy efficiency. Penetration rate of NSP kilns with a capacity greater than 1000 tonne may gradually increase to 51 % by 2060, whereas it may reach 100 % by 2044 for the advanced cooler. Penetration rates of most other energy efficiency technologies of the clinkering process show an increasing trend, which indicates that calcination is a key CO_2 emission reduction process and thus, should attract sufficient attention. Selected energy-efficient technologies include kiln shell heat loss reduction (LC11), energy management and process control (LC12), and adjustable speed drive for kiln fans (LC13). Three technologies, namely vertical roller mills (PE15), improved grinding media (LC28), and high-efficiency cement mill vent fans (LC29), were selected for promotion of the cement grinding process. Other technologies would gradually be withdrawn from the cement industry. Three general technologies, namely grinding aids (LC30), energy management and process control

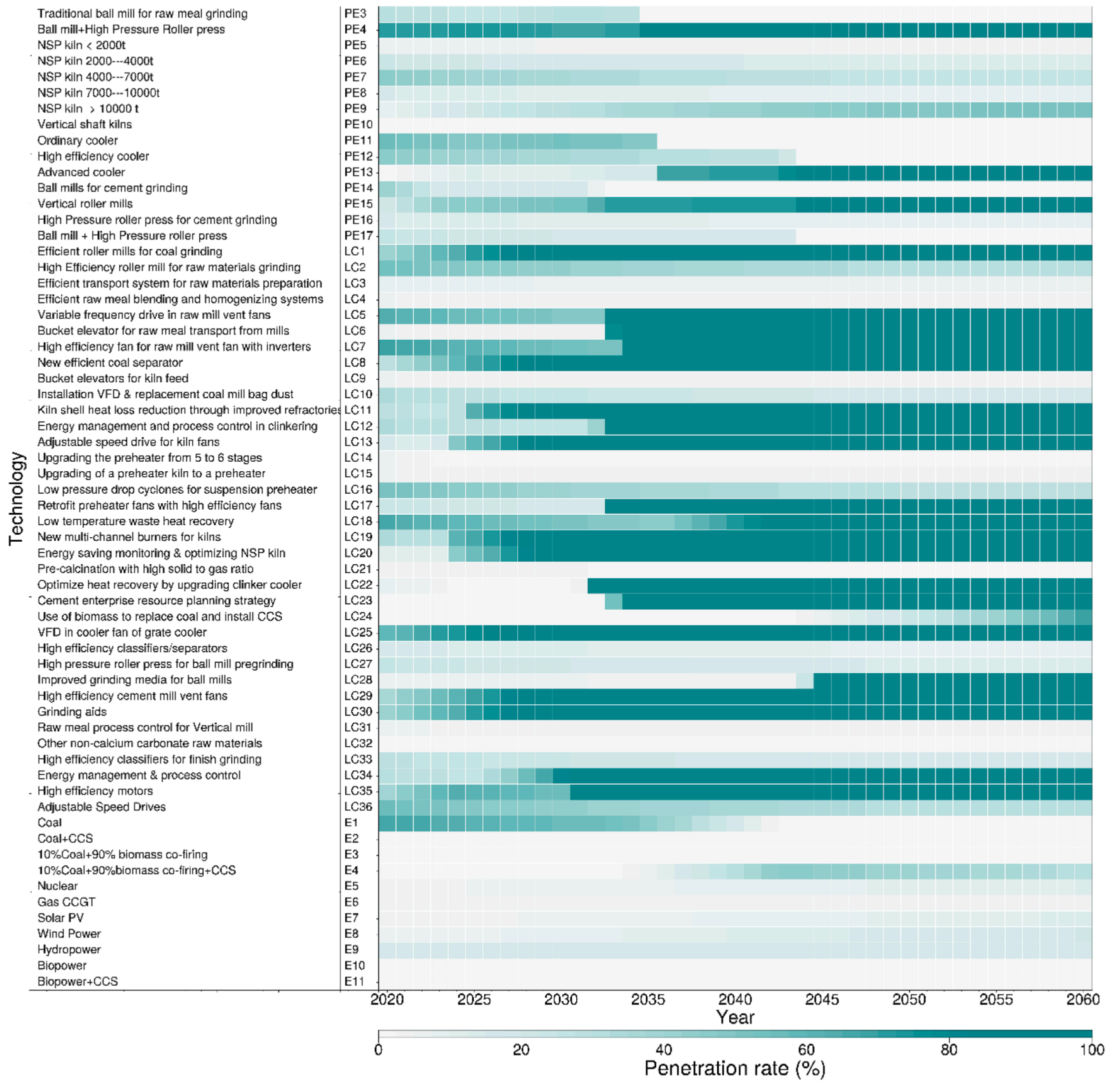

Fig. 4. Projections of penetration rates of low carbon technologies under the DemL_Conv_Pollu0 scenario.

(LC34), and high-efficiency motors (LC35), are encouraged.

However, promoting energy-efficient technologies is far from sufficient to meet net-zero emissions for the cement industry owing to thermodynamic limits [10] and a large quantity of process CO_2 emissions. Implementing other breakthrough technologies is pivotal for meeting net-zero CO_2 emissions from a long-term perspective. CCS is one of the most promising innovative technologies and is expected to be fully commercialized by 2030. CCS is projected to be gradually introduced into the cement industry after 2030, which is always accompanied by fuel switching (substituting 30 % coal with biomass). Penetration rate of CCS in the cement sector is projected to be 68–75 % in 2060, which is slightly lower than that estimated by the International Energy Agency (IEA) (85 %) [4]. The share of NSP kilns equipped with CCS in the cement industry is affected by the technology structure of electricity production. Under the DemL_Conv_Pollu0 scenario, the share of WWSN energy, including water (i.e., hydropower), wind, solar, and nuclear energies, in total electricity supply gradually increases to 65 % by 2060. Electricity produced by co-firing plants (90 % biomass and 10 % coal) equipped with CCS will appear from 2032, with its share increasing to 32 % by 2060. CCS (with fuel switching) is projected to appear in 2043, and its penetration rate in the cement industry will increase to 69 % by 2060. In contrast, under the DemL_Wwsn_Pollu0 scenario, a higher share of WWSN (80 % in 2060) in total electricity supply would result in a lower share of electricity from biomass co-firing plants equipped with CCS (17 % in 2060). Reduced negative CO_2 emissions from the BECCS of the electricity sector would require more CO_2 emission reduction in the cement industry. Thus, share of CCS (with fuel switching) in the cement industry is expected to increase to 75 % by 2060 under the DeL_Wwsn_Pollu0 scenario.

3.3. Energy consumption by 2060

Energy intensities of cement under different scenarios are shown in Fig. 5. Under the DemH_Base_Pollu0 scenario, energy intensity decreases from 106 kgce in 2020 to 92 kgce by 2060 owing to the promotion of energy-efficient technologies. Under carbon neutrality scenarios, energy intensity would first decrease, driven by rapid promotion of energy efficiency technologies, and then it would increase with the introduction of CCS. Taking the DemL_Conv_Pollu0 scenario as an example, energy intensity would first decrease to 68 kgce by 2033 and then increase to 104 kgce by 2060, which is 13 % higher than that under the DemH_Base_Pollu0 scenario. This is because deploying CCS consumes additional electricity. Electricity intensity of cement under carbon neutrality scenarios is projected to increase by 41–60 % by 2060 compared with the DemH_Base_Pollu0 scenario. Thus, electricity consumption of CCS in combating climate change should draw sufficient attention.

Total primary consumption will decrease from 253 Mtce in 2020 to 121 Mtce in 2060 owing to decreasing cement demand and promotion of

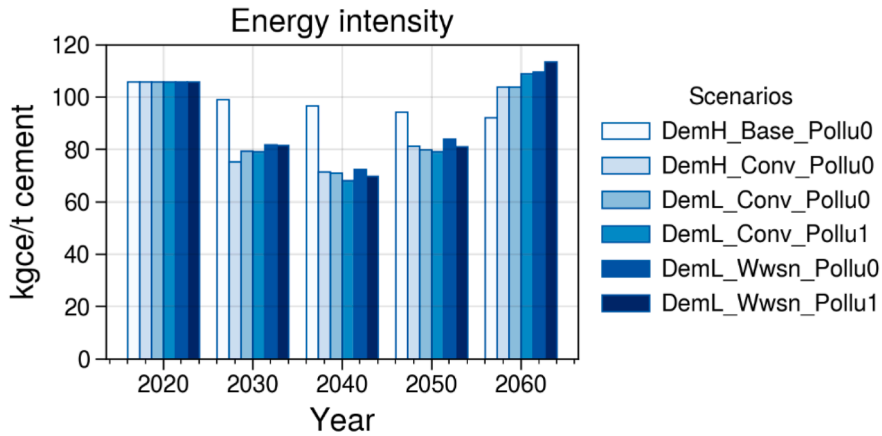

Fig. 5. Energy intensity under different scenarios.

energy-efficient technologies under the DemH_Base_Pollu0 scenario, as shown in Fig. 6. Under the carbon neutrality scenarios, total primary energy consumption first declined rapidly and then fluctuated slightly around 130 Mtce. Moreover, coal is gradually being substituted by renewable energy, especially bioenergy. Under the DemL_Conv_Pollu0 scenario, coal consumption will decrease from 219 Mtce in 2020 to 22 Mtce by 2060, whereas bioenergy consumption will increase from 2 Mtce in 2020 to 43 Mtce by 2060. Correspondingly, the proportion of coal in the total primary energy consumption portfolio will decrease from 86 % in 2020 to 19 % by 2060, while bioenergy will increase from 1 % in 2020 to 37 % by 2060. Bioenergy is mainly consumed by electricity production, accounting for 67 % of total bioenergy consumption by 2060 (Fig. 7). Electricity consumption showed a U-shaped trend. The increasing electricity consumption trend after 2043 is driven by CCS, which is projected to reach 23 Mtce by 2060. In comparison with the DemH_Conv_Pollu0 scenario, total primary energy demand would be reduced by 15 % (21 Mtce) by 2060 in the DemL_Conv_Pollu0 scenario due to cement demand reduction, of which 8 Mtce comes from bioenergy and 3 Mtce comes from coal. In addition, electricity consumption will be reduced by 16 Mtce (16 %) in 2060. A lower share of WWSN in the total electricity technology portfolio results in higher biomass consumption. Biomass consumption for electricity production under the DemL_Conv_Pollu0 scenario in 2060 is projected to be 29 Mtce, which is 76 % (13 Mtce) higher than that under the DemL_Wwsn_Pollu0 scenario. Thus, in the context of carbon neutrality, the potential of water, wind, solar, and nuclear resources available for electricity production has a crucial impact on biomass demand.

3.4. CO_2 emissions

Under the DemH_Base_Pollu0 scenario, total CO_2 emissions (including electricity production) declined from 1333 Mt in 2020 to 675 Mt in 2060 (Fig. 8) owing to the implementation of energy-efficient technology and cement demand reduction. Electricity production accounts for 15 % of total CO_2 emissions in 2020, which will gradually decrease to 12 % by 2060 owing to decarbonization of electricity production. Negative CO_2 emissions produced by BECCS are essential for neutralizing CO_2 emissions that are difficult to abate, especially process emissions, and achieving the net-zero emissions target. Under the DemL_Conv_Pollu0 scenario, BECCS can generate 535 Mt of negative CO_2 emissions by 2060, of which 75 % (402 Mt) comes from NSP kilns and 25 % (132 Mt) comes from electricity production.

The quantity of CO_2 that should be abated is affected by cement demand on the consumption side, thus impacting the technology

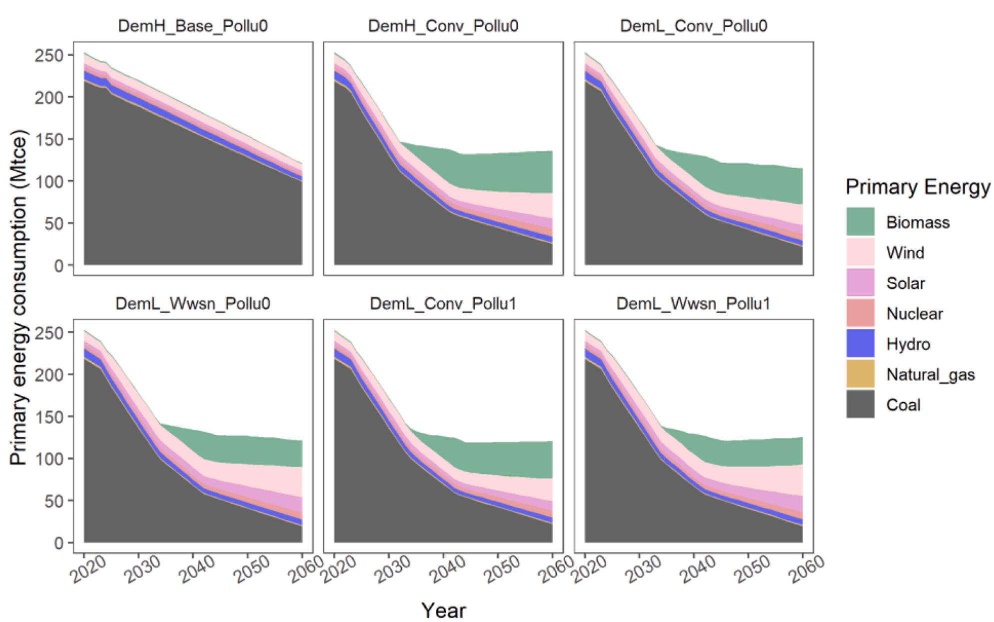

Fig. 6. Total primary energy consumption under different scenarios. Total primary energy consumption includes primary energy consumption from cement and electricity production.

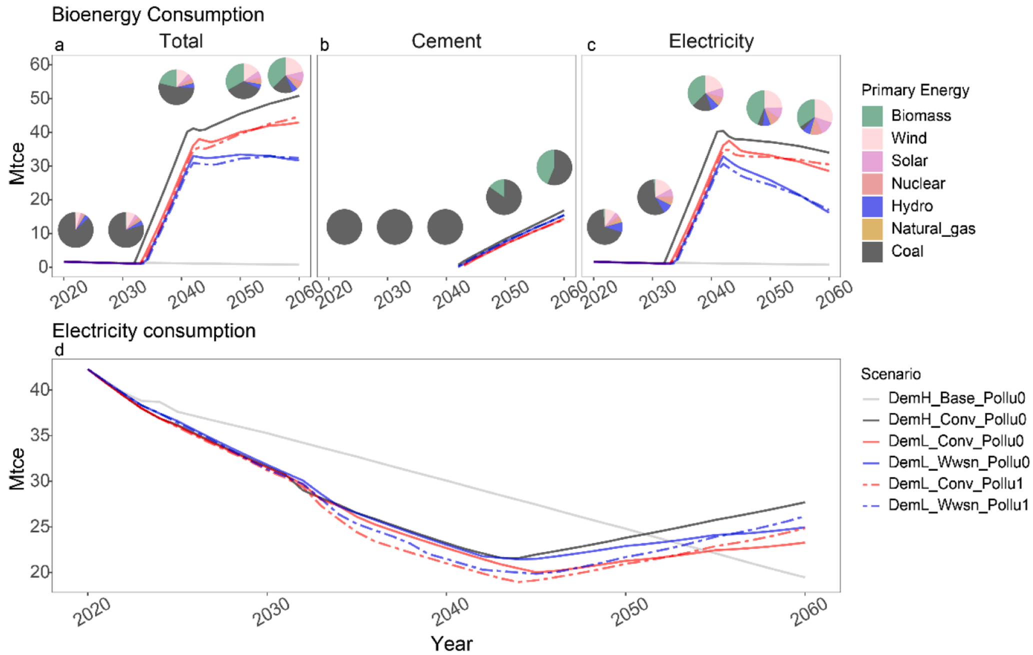

Fig. 7. Energy consumption under different scenarios. Bioenergy consumption of (a) total (both electricity and cement production), (b) cement production, (c) electricity production. Primary energy consumption structure under the DemL_Conv_Pollu0 scenario is shown as pie charts in (a)-(c), (d) electricity consumption of cement production.

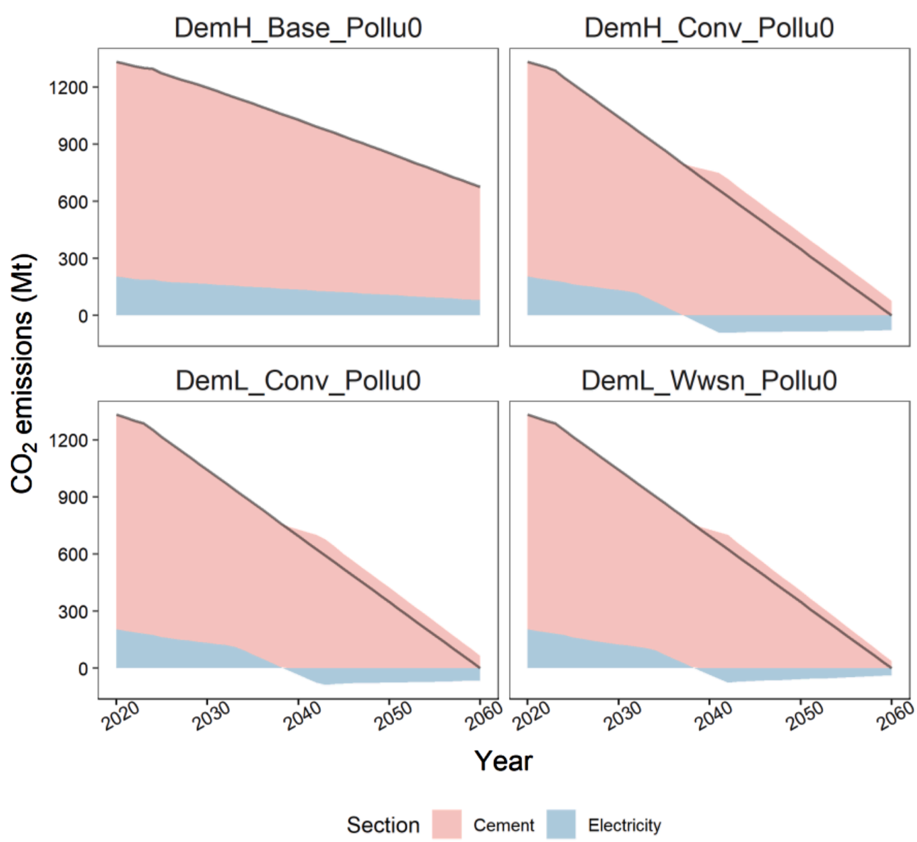

Fig. 8. CO_2 emissions of cement and electricity production under different scenarios.

portfolio of the cement industry and electricity production. Under the DemL_Conv_Pollu0 scenario, 490 Mt of negative CO_2 emissions are projected to be produced by BECCS in 2060, which is 15 % (88 Mt) lower than that under the DemH_Conv_Pollu0 scenario. Of these, 65 Mt of the reduced negative CO_2 emissions came from the cement industry, and 23 Mt from electricity production. Moreover, decarbonization of the electricity and cement industries is interdependent. 398 Mt of negative CO_2 emissions are projected to be generated from NSP kilns in 2060 under the DemL_Wwsn_Pollu0 scenario, which is 8 % (29 Mt) higher than that under the DemL_Conv_Pollu0 scenario. The required higher negative CO_2 emissions from NSP kilns under the DemL_Wwsn_Pollu0 scenario are driven by lower negative CO_2 emissions from electricity production. In this scenario, decarbonization of electricity depends mainly on the WWSN.

CO_2 emissions from specific technologies are shown in Fig. 9. Under the DemL_Conv_Pollu0 scenario, CO_2 emissions from NSP kilns in 2060, including those from fuel consumption and process emissions, are projected to reach 537 Mt. CCS will capture 369 Mt of CO_2 by 2060, and the selected energy-efficient technologies will reduce 103 Mt of CO_2. Of these, CO_2 reduction of energy management and process control technology (LC34) is apparent, with 40 Mt of CO_2 in 2060, followed by kiln shell heat loss reduction (16 Mt) and energy-saving monitoring and optimization of the NSP kiln system (13 Mt). CO_2 emissions from coal power generation are projected to be 56 Mt, and 121 Mt will be captured by CCS in co-firing (90 % biomass and 10 % coal) power plants.

A detailed description of technologies is shown in Supplementary Table S4 and Table S7.

3.5. Economic costs

Total system costs, including annualized technology investment, operation, and maintenance, as well as energy and raw material costs, of production of electricity and cement are shown in Fig. 10a. Under the DemH_Base_Pollu0 scenario, total cost shows a descending trend, mainly because of the decline in cement demand, and is projected to decrease to 122 billion CNY by 2060. Under carbon neutrality scenarios, promoting low-carbon technologies results in an increasing trend in total cost. Total cost is projected to increase to 450–580 billion CNY by 2060. Compared with the total cost projected under DemH_Conv_Pollu0 scenario, that under the DemL_Conv_Pollu0 scenario is projected to be reduced by 21 % by 2060 due to reduced cement demand. Rapid decrease in costs of renewables may result in a lower total cost under the DemL_Wwsn_Pollu0 scenario compared with the DemL_Conv_Pollu0 scenario. Total cost under the DemL_Wwsn_Pollu0 scenario is projected to be 450 billion CNY by 2060, which is 1 % (7 billion CNY) lower than that under the DemL_Conv_Pollu0 scenario. Moreover, under the DemL_Conv_Pollu1 and DemL_Wwsn_Pollu1 scenarios, total costs were projected to increase by 10 % (44 billion CNY) and 7 % (30 billion CNY), compared to those of the DemL_Conv_Pollu0 and DemL_Wwsn_Pollu0 scenarios, respectively, by 2060. This is attributed to the installation of air pollutant control technologies.

Unit reduction cost per tonne of CO_2 and per tonne of cement under the carbon neutrality scenarios are shown in Fig. 10b–c. Similar to total cost, unit abatement costs showed an increasing trend. Under carbon-neutrality scenarios, large-sized kilns with higher energy efficiency and lower investment costs are introduced. Moreover, reduced energy costs could also contribute to negative values of unit abatement costs by 2030. After 2030, increase in unit reduction cost is mainly driven by introduction of CCS. In 2060, unit abatement costs of CO_2 emissions and CO_2 abatement cost per tonne of cement under carbon neutrality scenarios are projected to be 484–676 CNY/tonne CO_2 and 295–348 CNY/ tonne cement, respectively, in 2060. Under the DemL_Conv_Pollu0 scenario, unit abatement cost of CO_2 emissions is 494 CNY/ tonne CO_2, which is 27 % lower than that under the DemH_Conv_Pollu0 scenario driven by lower cement output. Compared with the unit abatement costs of CO_2 emissions under the DemL_Wwsn_Pollu0 scenario, those are projected to increase by 45 CNY/tonne of CO_2 reduction in 2060 under the DemL_Wwsn_Pollu1 scenario, due to the installation of air pollutant control technologies. Moreover, costs of decarbonization pathways relying more on WWSN tend to be lower than those relying more on BECCS because of the higher energy cost of biomass. For example, the unit reduction cost of CO_2 emissions is projected to be 484 CNY/tonne

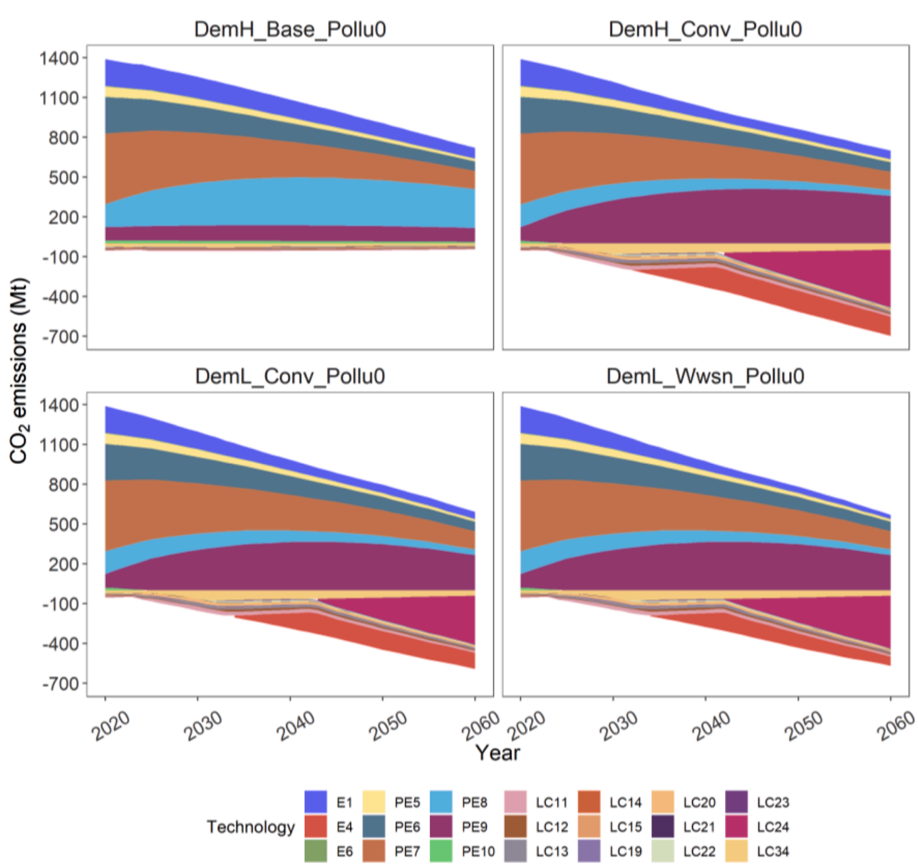

Fig. 9. CO_2 emissions of each technology under different scenarios. Negative values stand for CO_2 emissions removed by CCS.

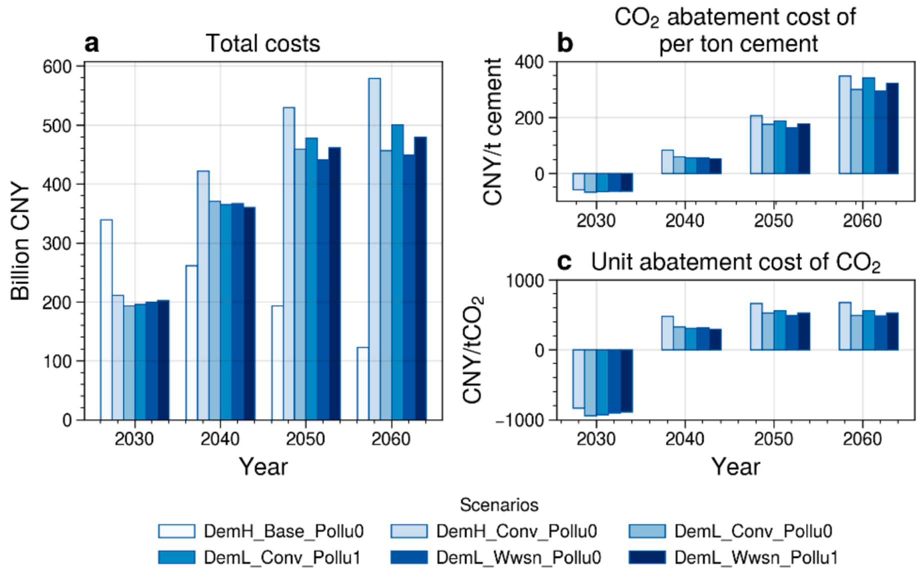

Fig. 10. Cost under six scenarios. (a) total cost, (b) CO_2 abatement cost per tonne of steel and (c) unit abatement cost of CO_2 emission reduction.

CO_2 in 2060 under the DemL_Wwsn_Pollu0 scenario, which is 2 % lower than that under the DemL_Conv_Pollu0 scenario.

3.6. Environmental impact

Environmental impact, including impact of air pollutant emissions (SO_2, NO_x, and $PM_{2.5}$), water consumption, and land cover, are shown in Figs. 11–13. Under the DemH_Base_Pollu0 scenario, total emissions of SO_2, NO_x, and $PM_{2.5}$, are projected to decrease from 0.7, 1.5, and 0.15 Mt in 2020 to 0.3, 0.7, and 0.08 Mt, respectively, by 2060 (Fig. 12) owing to decreased cement demand and implementation of energy efficient technologies. Promotion of energy-efficient technologies and fuel switching contribute to reducing air pollutant emissions. Under the DemH_Conv_Pollu0 scenario, in 2060, total emissions of SO_2, NO_x, and $PM_{2.5}$ are estimated to be 122, 332, and 71 kt (thousand tonne), respectively, which are 64 %, 54 %, and 11 % lower than the respective values under the DemH_Base_Pollu0 scenario. Compared with SO_2 and NO_x, the drop in $PM_{2.5}$ is limited, which can be explained by the proportion of $PM_{2.5}$ that comes from process emissions in addition to fuel combustion. Thus, reduction of $PM_{2.5}$ mainly depends on air pollutant control technologies. By implementing air pollutant control technologies, total emissions of SO_2, NO_x, and $PM_{2.5}$ are projected to be 15, 75, and 13 kt, respectively, in 2060, under the DemL_Conv_Pollu1 scenario, which is 96 %, 90 %, and 84 % lower than the respective values under the DemH_Base_Pollu0 scenario.

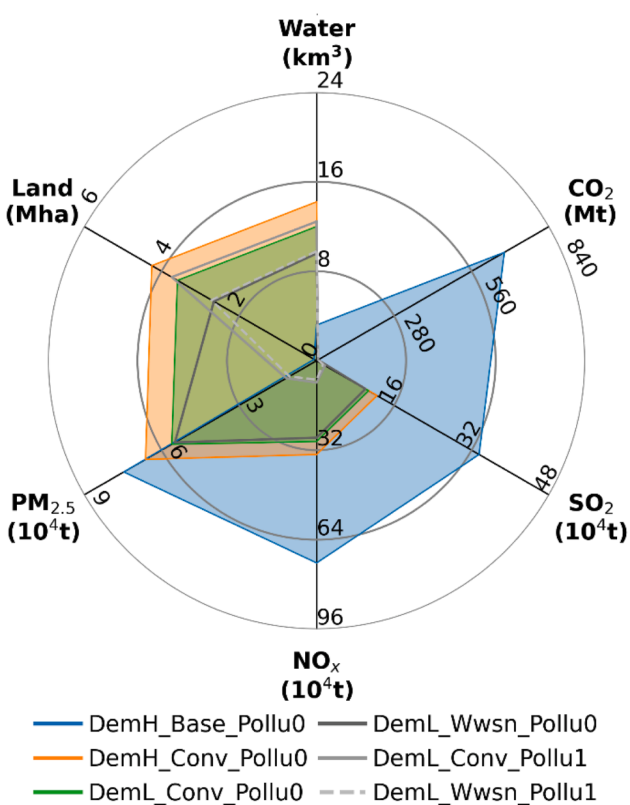

Fig. 11. Total environmental impact under six scenarios in 2060.

Increased use of biomass to mitigate CO_2 emissions would substantially increase water use and land cover during the planting stage. Under the DemH_Base_Pollu0 scenario, total water consumption would decrease from 6.1 km^3 in 2020 to 3.2 km^3 in 2060. However, total water consumption is projected to increase to 11 km^3 in 2060 under the DemL_Conv_Pollu0 scenario, which is 276 % higher than that under the DemH_Base_Pollu0 scenario. Water consumption of biomass supply in 2060 increases from 0.2 km^3 under DemH_Base_Pollu0 scenario to 9.4 km^3 under the DemL_Conv_Pollu0 scenario. Correspondingly, the share of water consumption from biomass supply in total water consumption increased from 5 % to 78 %. The resource potential of water, wind, solar, and nuclear resources available for electricity production has a crucial impact on biomass demand, and thus on water consumption. Water consumption for biomass supply under the DemL_Wwsn_Pollu0 scenario is 6.9 km^3, which is 26 % (2.5 km^3) lower than that under the DemL_Conv_Pollu0 scenario. Water consumption of the cement production stage is projected to decrease from 3.7 km^3 in 2020 to 1.7 km^3 by 2060, driven by declining cement output. Under the DemH_Base_Pollu0 scenario, water consumption for electricity production is to decrease from 1.3 km^3 in 2020 to 0.7 km^3 by 2060. Under carbon neutrality scenarios, water consumption of electricity production shows an increasing trend after 2040 with diffusion of renewable energy technology. Land required to plant biomass is projected to be 4.3 million ha (Mha) in 2060 under the DemH_Conv_Pollu0 scenario, which would be reduced by 16 % under the DemL_Conv_Pollu0 scenario due to decreased cement demand. Furthermore, land demand for biomass planting could be further decreased to 2.6 Mha under the DemL_Wwsn_Pollu0 scenario because of reduced biomass demand for electricity production.

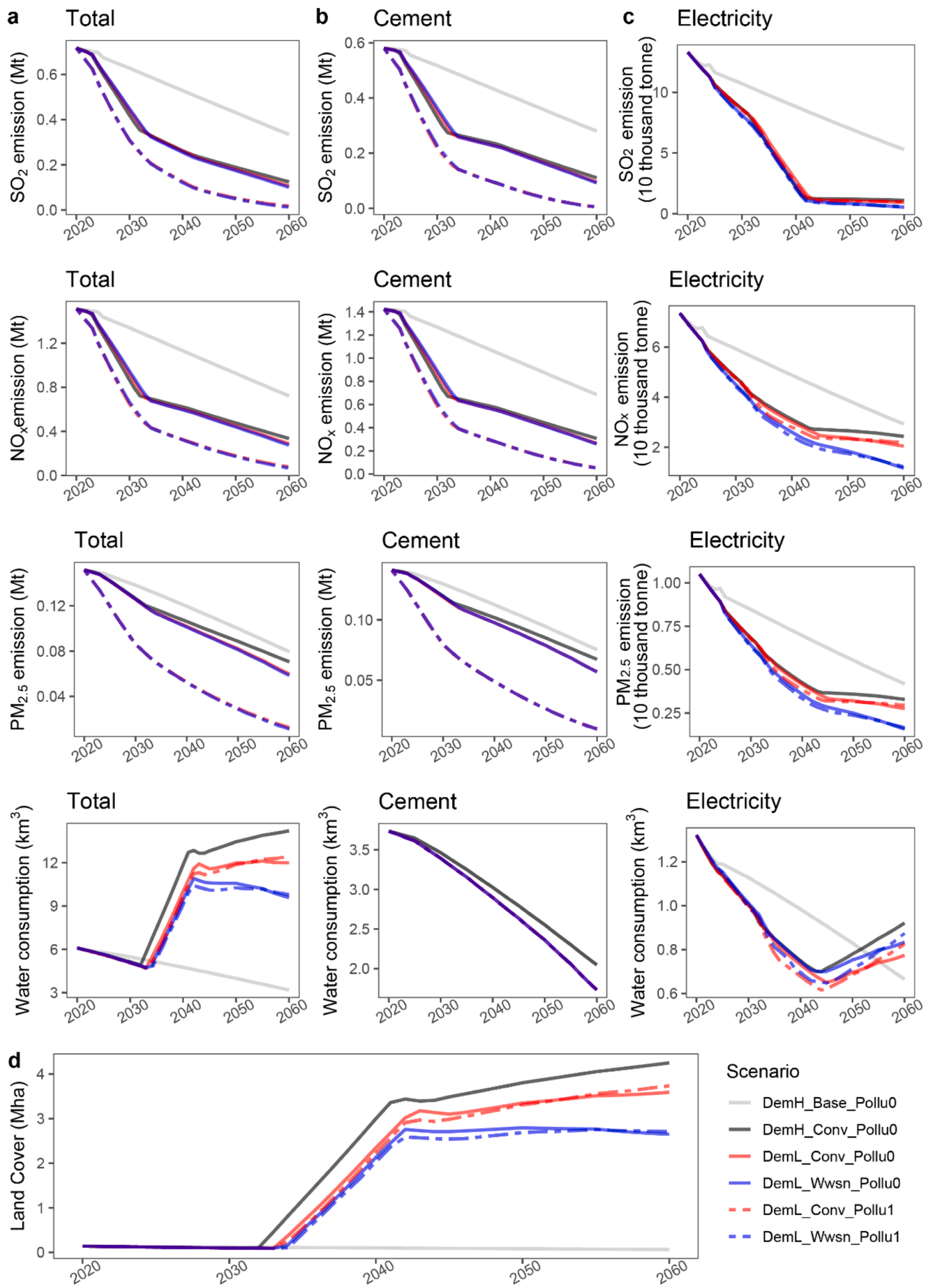

Fig. 12. Environmental impact under six scenarios over 2020–2060. Environmental impact of (a) total, including cement and electricity production and primary energy supply, (b) cement production, (c) electricity production, (d) land cover of energy crop plantation.

4. Discussion

Achieving a net-zero emissions cement sector requires a joint effort at various stages of its life-cycle. Reducing cement demand can substantially reduce CO_2 emissions and deployment needs for CO_2 emission mitigation technologies. Implementing the carbon neutrality policy in China would result in a cement demand that is 15 % lower than that under the BAU scenario in 2060, similar to the projections put forward by the IEA by adopting material efficiency strategies (Figures S2S3). The lifetime of buildings in China is approximately 30 years (no more than 15 years for rural houses) [65], which is much less than that in the USA (74 years), France (102 years), and the UK (130 years). Thus, extending the lifetime of the construction sector, the largest cement consumer, would play a critical role in meeting carbon neutrality for China's cement industry. Other material efficiency strategies, including reducing over-design and material loss and more intensive use and reuse, should also be considered. This type of measure tends to have multiple benefits, which, in addition to reducing CO_2 emissions, can also

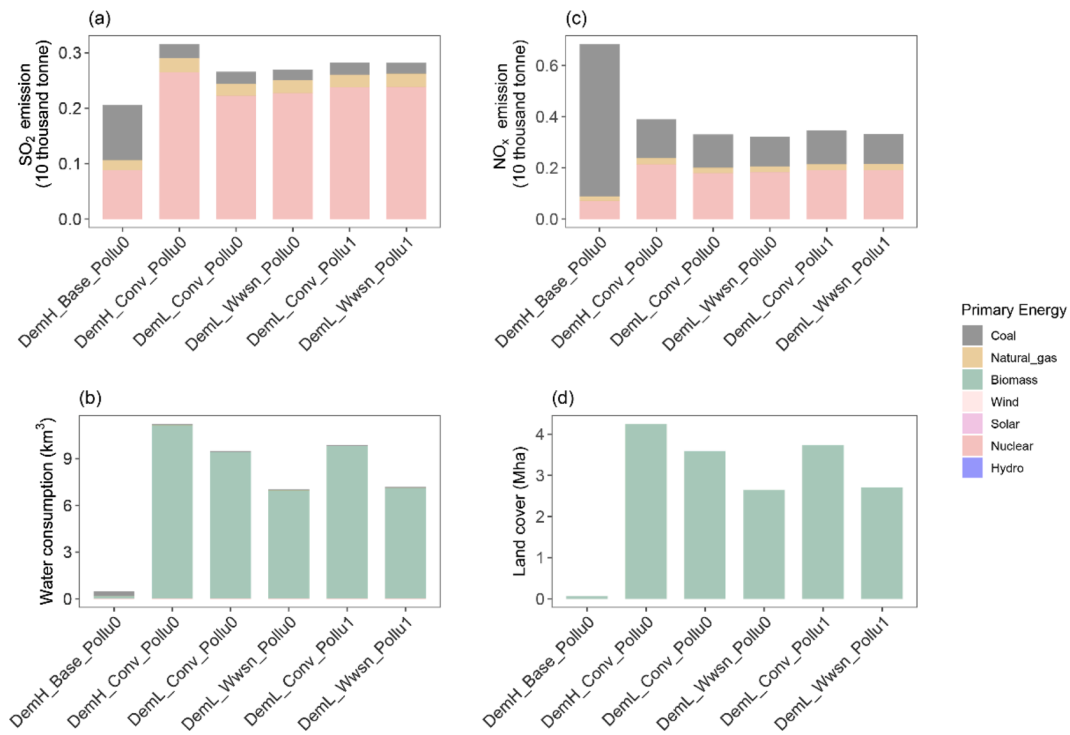

Fig. 13. Environmental impact of primary energy supply consumed by electricity and cement production under six scenarios in 2060. (a) SO_2 emission, (b) water consumption, (c) NO_x emission, (d) land cover. Primary energy includes coal, biomass, natural gas, and nuclear fuel.

benefit local air quality, water, and land and contribute to sustainable development [26,65].

Promoting energy-efficient technologies is crucial for reducing CO_2 emissions in the short term, which can also create air quality co-benefits by significantly reducing air pollutant emissions, especially SO_2 and NO_x. Although the share of efficient dry kilns is reported to be more than 90 % of the market, energy efficiency of China's cement industry has been substantially improved with promotion of energy efficient technologies [66]. However, up to a 60 % gap in efficiency exists between large and small kilns [48,67]. In China, the share of kilns with capacity above 7000 tonne/day in total kilns is less than 25 % [48]. Substantial room exists for energy efficiency improvement with promotion of large-scale kilns and energy-efficient technologies. Thus, China should make full use of this opportunity to co-control air pollutants and CO_2 emissions.

Negative emission technologies are necessary for meeting the carbon neutrality target of the cement industry owing to the large quantity of process emissions. Fuel substitution (biomass substitution of 30 % coal in the kiln) and CCS can be a type of BECCS [68], which can generate negative emissions and offset unavoidable CO_2 emissions. Biomass demand is projected to increase to 35–51 Mtce in 2060, which accounts for 17–25 % of the bioenergy supply potential from marginal lands or accounts for 7–10 % of agricultural residues [59]. It may require 7–11 km^3 of water and cover 3–4 Mha of land, if biomass (35–51 Mtce) came from energy plantations, and trigger multiple land-based sustainability concerns. Using agricultural and forestry residues as bioenergy could be an attractive proposition that benefits local rural areas by creating a new income source and reducing air pollution. However, the use of bioenergy to generate negative emissions may face many obstacles, such as biomass supply chains, biomass collection and transportation costs, and local biomass endowments. Supportive policies are crucial to address these obstacles, which should fully consider resource endowments and geological conditions, among other factors.

BECCS facilitates simultaneous decarbonization of the electricity and cement industries. Unlike the electricity sector, the hard-to-decarbonize cement sector has almost no alternative to CCS. Considering environmental impact (especially NO_x emissions) and quality of the clinker, a fuel substitution rate of 30 % has been suggested (biomass to substitute 30 % coal in kilns) [68,69]. The low share of biomass in total fuel consumption of NSP kilns limits the negative potential of BECCS in the cement sector. Moreover, variations in the CO_2 concentration and scattered distribution over the territory of cement plants would result in higher CO_2 capture and storage costs. Coal power plants dominate current electricity production in China. Retrofitting coal power plants to co-fire with biomass (e.g., 90 % biomass and 10 % coal) and installing CCS (BECCS) generates negative emissions. Negative emissions from BECCS can deal with the risk of stranded assets for coal-fired power capacities. Moreover, negative emissions of the power sector can also offset the CO_2 emissions from the cement sector, which requires a well-designed economic framework to convert negative emissions of BECCS in the power sector into negative emission credits and sell them to the cement sector.

Due to a lack of data on using hydrogen as an alternative fuel and the slow process of CO_2 uptake by concrete, these two low-carbon technologies were not included in this study. The results would be slightly affected if these two technologies were included. However, the conclusions would remain unchanged. For instance, using hydrogen as an alternative fuel would marginally reduce the demand for biomass and thus reduce water consumption and land cover. But a large amount of biomass is still required to neutralize the unabated process-related emissions in the context of net-zero CO_2 emissions because it is the essential energy to generate negative emissions when equipped with CCS. Therefore, BECCS will be pivotal in meeting the carbon neutrality target for the cement sector; however, it may trigger sustainability concerns. Theoretically, concrete's maximum CO_2 uptake (calcination CO_2 emissions) can equal the CO_2 emissions from calcination [49]. CO_2 uptake by concrete is a relatively slow process, which occurs during all phases of a concrete product's lifetime and is affected by multiple factors such as humidity, temperature, porosity, etc. Recent studies [36,49] suggested that the CO_2 uptake can be 20 % of the maximum uptake potential. Thus, biomass is still the key to mitigating the large amount of CO_2 from calcination and fossil fuels.

This study has some limitations. Hydrogen has been proposed as an alternative fuel [18] and is estimated to reduce CO_2 emissions by 44 % in cement production [17]. However, pure hydrogen has explosive properties, and the clinker-burning process requires significant modification [13]. Hydrogen was not included in this study because of the limited available data for the modification cost, fuel substitution ratio, etc. Furthermore, in the technology-selection model, the concept of BECCS was simplified by neglecting CO_2 transport infrastructure and storage, which may increase uncertainty of BECCS costs. These limitations should be addressed in future studies. Further in-depth studies exploring the role of hydrogen in CO_2 mitigation in cement production are expected, especially on green hydrogen generated from renewable electricity via water electrolysis. Moreover, there is an urgent need to investigate spatially explicit mitigation strategies at plant level, considering biomass availability, biomass transportation costs, local resources, and environmental endowments.

5. Conclusion

The cement industry, which contributes 8 % of global CO_2 emissions, is pivotal for achieving the ambitious Paris climate goals. However, most existing studies focus on mild decarbonization by adopting one or two commonly mentioned CO_2 mitigation measures in the cement production stage and fail to support policymakers in designing low-carbon transition pathways toward net-zero emissions. In this aspect, the current study ensures remarkable progress by exploring transition pathways toward carbon neutrality for the cement industry in China from a life-cycle perspective based on an integrated model framework. Moreover, local resource and environmental impacts are comprehensively quantified, which contributes to the integrated management of CO_2, air pollution, water, and land towards sustainable development. In addition to the commonly studied energy efficiency technologies on the cement production side, innovative low-carbon measures, including BECCS, were involved in the IMED|TEC model, which makes it possible to explore deep decarbonization pathways for the cement industry. Impact of the carbon neutrality target on China's cement demand was captured using the IMED|CGE model. Moreover, environmental impact of primary energy production was incorporated into the LCA. Using this holistic and innovative framework to analyze a highly representative case study nation, the following conclusions can be drawn:

(1) Promoting energy-efficient technologies is crucial for reducing CO_2 emissions in the short term, which can also reduce air pollutant emissions, especially SO_2 and NO_x. Penetration rate of selected energy-efficient technologies, as shown in Fig. 4, will rapidly increase to 100 % by 2030. Energy efficiency technologies are projected to reduce SO_2, NO_x and $PM_{2.5}$ emissions by 33 %, 35 %, and 8 %, respectively, by 2030.
(2) BECCS is pivotal for meeting the carbon neutrality target for the cement sector from a long-term perspective; however, it may trigger sustainability concerns. The share of NSP kilns equipped with BECCS in total kilns is projected to increase to 68–75 % by 2060, which contributes to a 55–64 % CO_2 emission reduction by 2060. However, energy-crop plantations require 7–11 km^3 of water and 3–4 Mha of land.
(3) BECCS facilitates simultaneous decarbonization of the electricity and cement industries. However, introduction of CCS increases electricity consumption. BECCS can, on the one hand, decarbonize electricity production and reduce indirect CO_2 emissions of the cement sector and, on the other hand, generate negative emissions to offset unavoidable CO_2 emissions. Approximately 7–13 % of CO_2 emissions from cement kilns will be offset by negative CO_2 emissions from electricity production in 2060.
(4) Achieving net-zero emissions in the cement sector requires a joint effort at various stages along its life-cycle, including energy supply and cement production and consumption. Cement demand reduction can substantially reduce CO_2 emissions and reduce deployment requirements of CO_2 emission mitigation technologies. Unit abatement costs of CO_2 emissions are projected to decrease by 27 % (from 676 CNY/ tonne CO_2 to 494 CNY/ tonne CO_2) in 2060, driven by lowered cement output.

CRediT authorship contribution statement

Ming Ren: Conceptualization, Methodology, Resources, Writing – original draft, Writing – review & editing. **Teng Ma:** Software, Visualization. **Chen Fang:** Software, Visualization. **Xiaorui Liu:** Methodology. **Chaoyi Guo:** Methodology. **Silu Zhang:** Methodology. **Ziqiao Zhou:** Methodology. **Yanlei Zhu:** Methodology. **Hancheng Dai:** Methodology, Supervision, Funding acquisition. **Chen Huang:** Writing – review & editing, Software, Visualization, Funding acquisition.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

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