
Contribution of concrete nitrogenation to global NO_x uptake

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NO_x sequestration efficiency

After the reaction process as shown in sketch Fig.S1, the flow reactor is assembled with a quartz tube in such a way that it established a connection between the synthetic air and NO₂ cylinders through the utilization of mass flow controllers. The RA is placed within a reactor that is tightly sealed, where it is exposed to a mixture of humidified NO₂ and air. The concentration of NO₂ at the outlet of the reactor is measured using a NO_x analyzer. By determining the initial and final concentrations of NO₂, we can test the absorption efficiency of NO₂¹. A fixed-bed flow reactor was employed to evaluate the NO₂ adsorption efficiency in the denitrification process using fresh concrete and concrete waste as reactants. The study encompassed a range of temperatures to simulate ambient conditions and the high temperatures encountered in cement kiln flue gas emissions. The findings revealed that fresh concrete exhibited higher adsorption efficiency due to its elevated reactant content (portlandite phase). However, it took longer for the breakthrough point, indicating peak efficiency, to be reached in fresh concrete. While fresh concrete approached saturation in approximately 120 minutes, concrete waste demonstrated a faster breakthrough rate owing to its loose structure, resulting in an increased reactive surface area that contributes to energy savings. Temperature effects were evident in the breakthrough curves, with concrete in lower temperature environments more easily reaching comparable saturation levels by the end of the 180-minute operating period (see Fig.S2). Overall, the adsorption capacity of concrete waste, particularly at high temperatures, was significantly lower. The reduced content of Ca(OH)₂ in concrete waste, compared to fresh concrete, can be attributed to the natural carbonation process, which gradually consumes Ca(OH)₂ over time. Concrete waste proves to be a viable option for adsorption in high-temperature environments, while the high-temperature disposal of fresh concrete is more suitable in terms of adsorption quantity. However, considering the structural implications associated with high temperatures, widespread use of fresh concrete becomes challenging, whereas recycled concrete aggregates (RCA) exhibit superior durability after denitrification. Consequently, high temperatures are primarily considered for the disposal of concrete waste rather than fresh concrete².

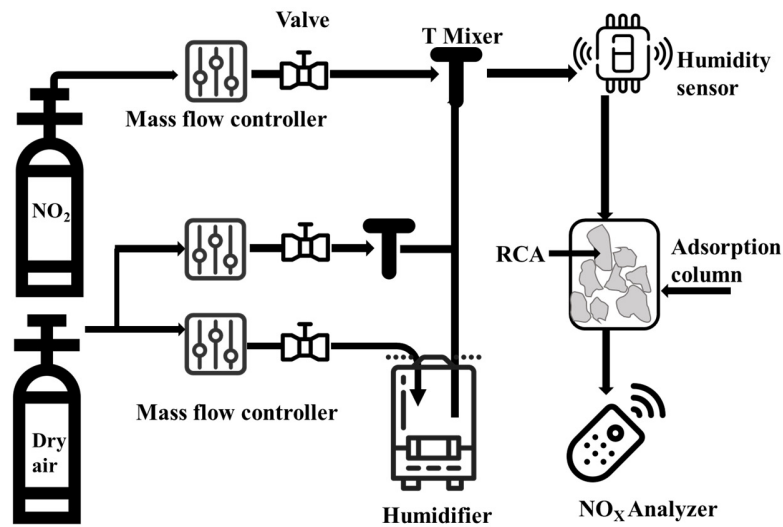


Figure S1 Sketch of the nitrogenation reaction

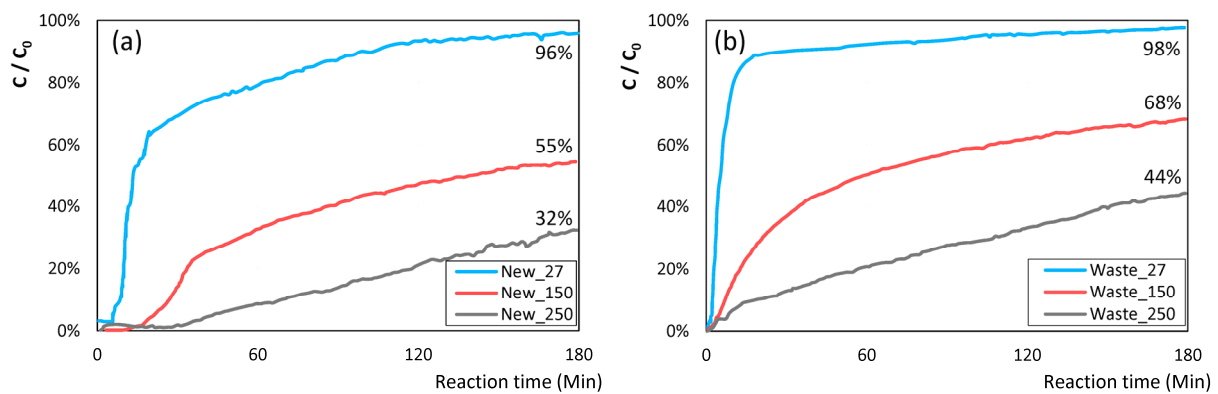


Figure S2 The NO_2 breakthrough curve with concrete materials at 27 °C, 150 °C and 250 °C. (a) For new concrete materials; (b) For concrete debris (old concrete materials)³. The initial concentration of NO_2 is 240 ppb. The adsorption data used are shown in Table S1.

Recycling of concrete debris

Recycling rates for concrete debris are contingent upon the prevailing status and advancements in the circular economy across different regions. Among construction waste materials, concrete waste ranks as the second most readily recyclable material after metals. Typically, recycled aggregates derived from concrete waste find application as backfill materials in road construction projects. Recycling endeavours predominantly transpire in urban areas and their surrounding regions, considering the strategic placement of recycling facilities and the availability of recycled materials within the market.

Fig.S3 provides a comprehensive overview of recycling rates for both urban and rural areas. In urban settings, concrete debris in Group 1 regions currently boasts a recycling rate surpassing 90%, with projections indicating a trajectory towards 100% by 2030. This rate is expected to be sustained from 2030 to 2050 in the Western Europe, Japan, and Korea region. Group 2 presently exhibits a recycling rate ranging between 60% and 70%, which is projected to elevate to 80% by 2030 and ultimately achieve 100% recycling by 2040, and maintaining that rate in 2040-2050 (USA, Central Europe, and Oceania). Group 3 currently reflects a recycling rate spanning 30% to 50%, with estimates predicting a rise to 60% by 2030, 80% by 2040, and eventual attainment of 100% recycling by 2050 in the South Africa, Turkey, and Russia region. Group 4, comprising Canada, Mexico, Brazil, Rest of South America, Northern Africa, Middle East, India, and China, presently demonstrates a recycling rate ranging from 10% to 25%. It is anticipated to ascend to 30% by 2030, 60% by 2040, and 80% by 2050. Group 5, encompassing Central America, Western Africa, Eastern Africa, Ukraine, Central Asia, South-eastern Asia, Indonesia, Rest of South Asia, and Rest of Southern Africa, currently exhibits a recycling rate below 10%. Projections indicate an upturn to 10% by 2030, 30% by 2040, and 60% by 2050.

Recycling activities in rural areas are solely considered within developed countries, where the recycling rate stands at half of that observed in urban areas. Table S2 furnishes a comprehensive listing of the countries encompassed within each geographical region.

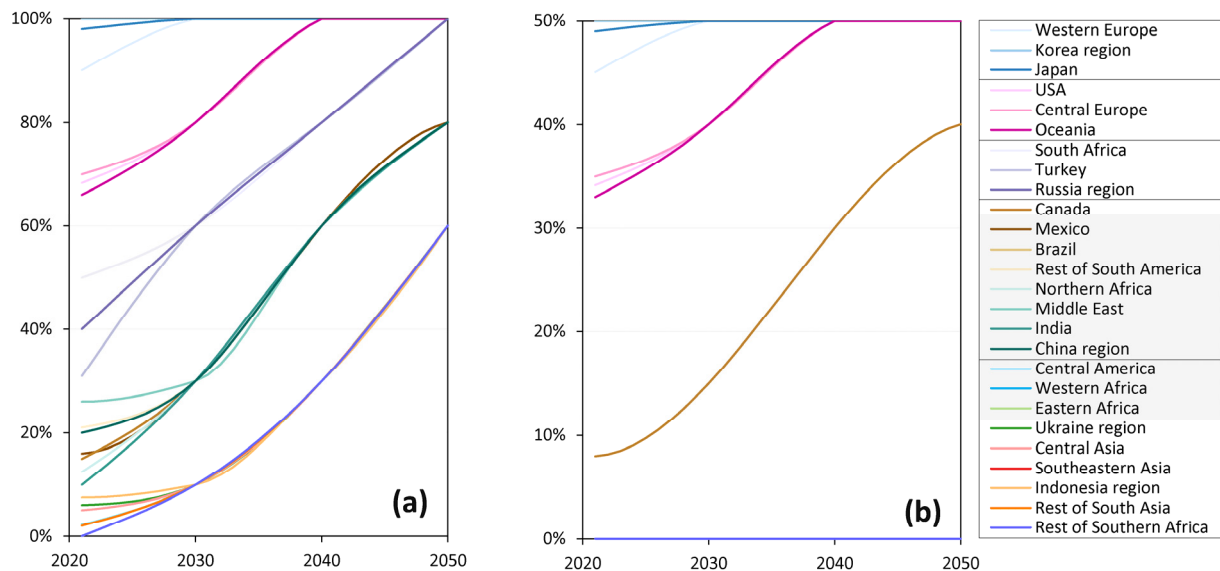


Figure S3 Recycling rate of concrete debris in global regions (a) Recycling rate of concrete debris in urban area; (b) Recycling rate of concrete debris in rural area ⁴⁻¹⁵

Flows of concrete materials

The determination of new concrete consumption and the generation of concrete debris revolves around analyzing the inflow and outflow of concrete materials within the built environment. These flow rates are estimated by considering the existing stock of concrete, which, in turn, relies on factors such as building material demand influenced by population dynamics, economic conditions, and the development of the service sector within each country (see Fig.S4). The estimation of flow rates takes into account the average lifespan of buildings in each country, with lifespan data conforming to a Weibull distribution ¹⁶.

The impact of urbanization becomes evident within this framework. As urban areas expand, there is a corresponding surge in the demand for concrete, while urban renewal projects contribute to the generation of concrete waste within cities. Simultaneously, the global adoption of circular economy practices plays a significant role in augmenting concrete recycling efforts in urban areas. In contrast, the construction landscape in rural areas tends to exhibit greater stability, with less pronounced fluctuations in concrete consumption and waste generation.

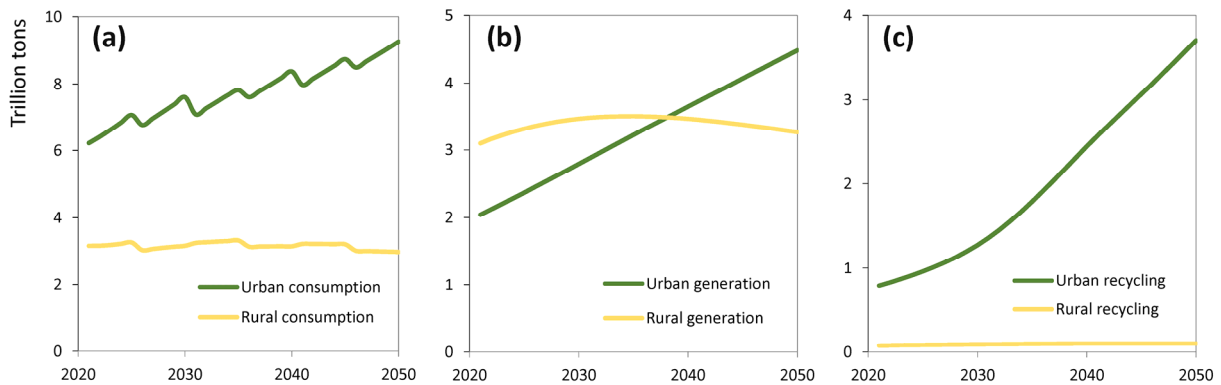


Figure S4 The dynamics of concrete materials (a) Inflow of concrete materials¹⁶; (b) Outflow of concrete debris¹⁶; (c) Recycled concrete debris (aggregates) at a global level from 2021 to 2050

Economic benefits by region

Fig.S5 portrays the spatial distribution of economic benefits stemming from the nitrogenation process. Notably, in Scenario 1 (S1), developed regions emerge as major contributors to the overall economic benefits, despite China absorbing a larger quantity of NO_x, as illustrated in Fig.3(c14). This outcome can be attributed to the superior waste management systems and well-established markets for recycled materials prevalent in developed countries. In regions such as the United States, Europe, Japan, and Korea, construction waste recycling companies levy higher fees for waste removal and transportation from construction sites compared to their counterparts in developing countries. Furthermore, the produced

nRCA enjoy stronger market demand and greater sales opportunities, resulting in higher profits that developing countries struggle to match.

Under S2, where the temperature treatment is implemented, the disparity in NO_x recovery between countries widens, highlighting the evident environmental and economic benefits derived from China's higher NO_x absorption compared to S1. In S2, instead of being traded, the nRCA is transported to landfills. China is presently in the process of formalizing its construction waste landfills and implementing gate fees, thereby contributing to the economic benefits observed in S2. With increasing recycling rates over time, China experiences a substantial upswing in economic gains, surpassing other regions in terms of overall economic benefits.

Detailed economic data can be found in Table S8. The items included in the economic calculations include labor cost, lease cost for plant, waste removal, nRCA trading, energy consumption, tax, water consumption cost, sewage discharge, equipment maintenance cost, NO₂ curing cost (including the cost of energy consumed in the curing process, rental of space for nitrogenation workshop, and amortization of equipment), transportation cost, and landfill gate fee, NO_x control investment savings.

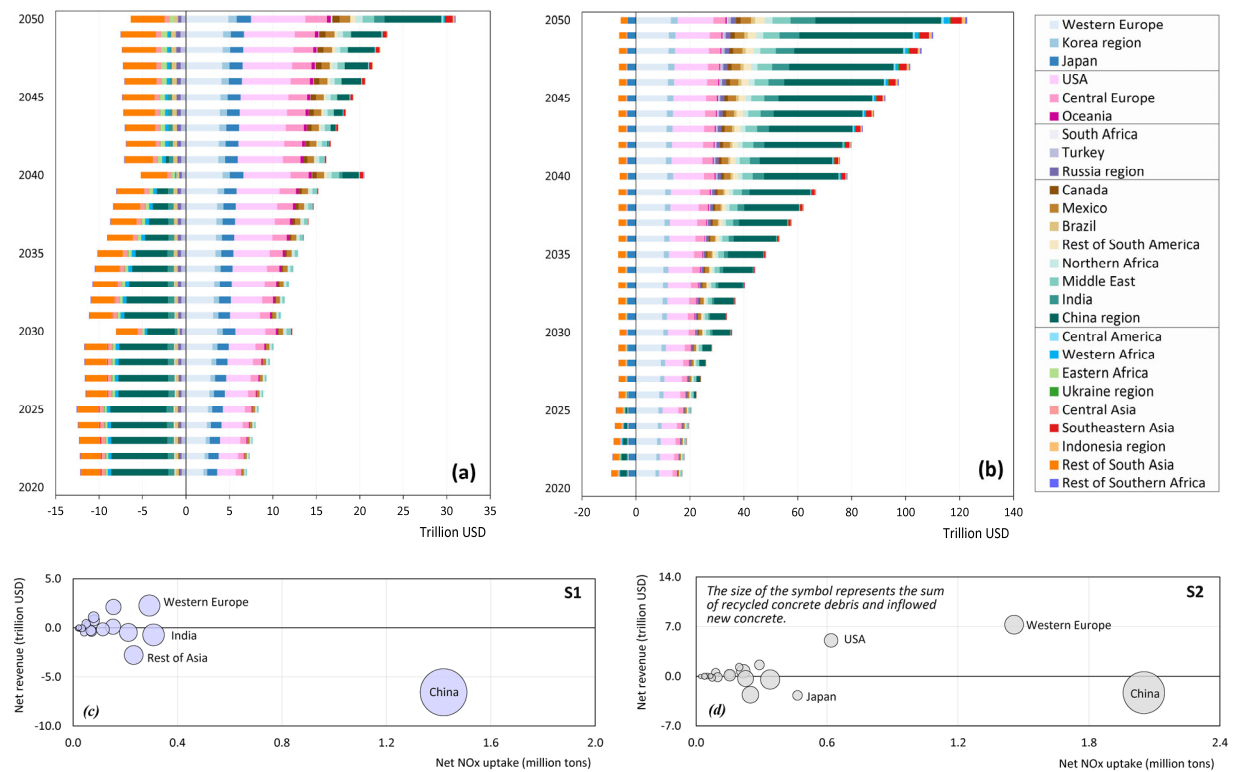


Figure S5 The global economic analysis by regions. (a) Economic benefits in S1; (b) Economic benefits in S2; (c-d) Total net economic and environmental benefits by country.

The breakdown of NOx uptake and emissions

As shown in Fig.S6, emissions associated with this technology exhibit regional variations, with China leading in material processing and consequently generating the highest emissions volume. However, the proportion of emissions attributed to each region does not exhibit huge differences between the two scenarios. The notable observation lies in S2, where a slight reduction in emissions from Group 1 regions is discernible.

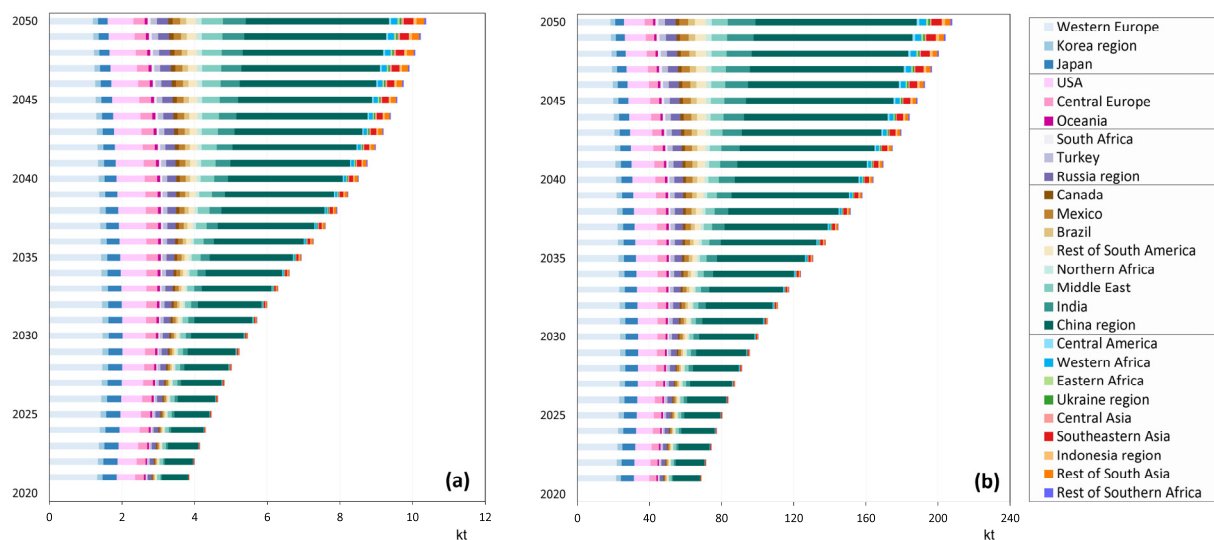


Figure S6 The NOx emissions caused nitrogenation. (a) Emissions in S1; (b) Emissions in S2

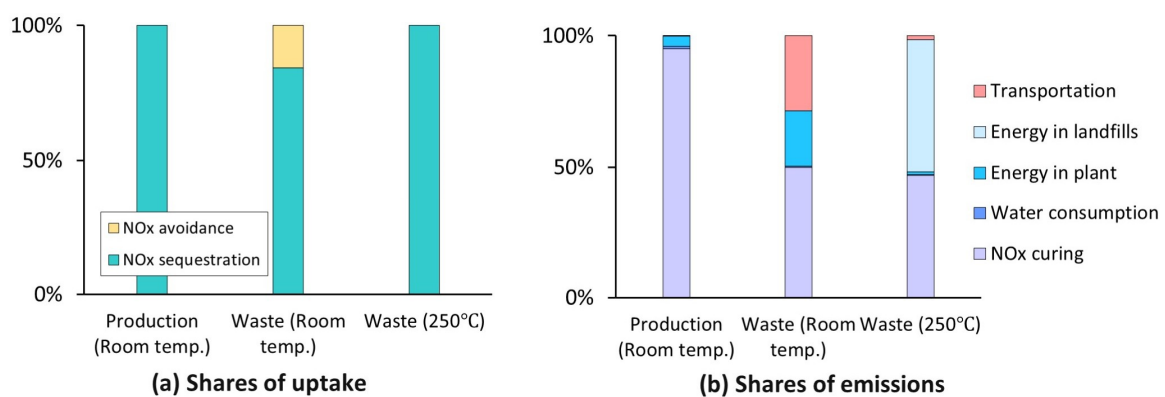


Figure S7 The breakdown of NOx uptake and emissions in 2021-2050.

Accelerated carbonation of concrete debris

The accelerated carbonation of concrete debris and the CO₂ curing of recycled concrete represent widely embraced technological endeavours. Owing to the finite presence of alkaline constituents within concrete, a discernible competitive dynamic emerges between carbonation and nitrogenation mechanisms. Consequently, we conducted a comparative scrutiny encompassing the economic and environmental advantages inherent to these two technologies across diverse regions. The datasets pertinent to the life cycle assessment (LCA) emissions and CO₂ absorption during the carbonation process were sourced from two antecedent published study undertaken by our research group^{17,18}. In these studies, we applied LCA method to analyse the emissions and CO₂ sequestration of carbonated recycled concrete, achieved through accelerated CO₂ conditioning and CO₂ curing across a spectrum of global locales (see Fig.S8). These datasets form the cornerstone of Figure 6 within the primary discourse.

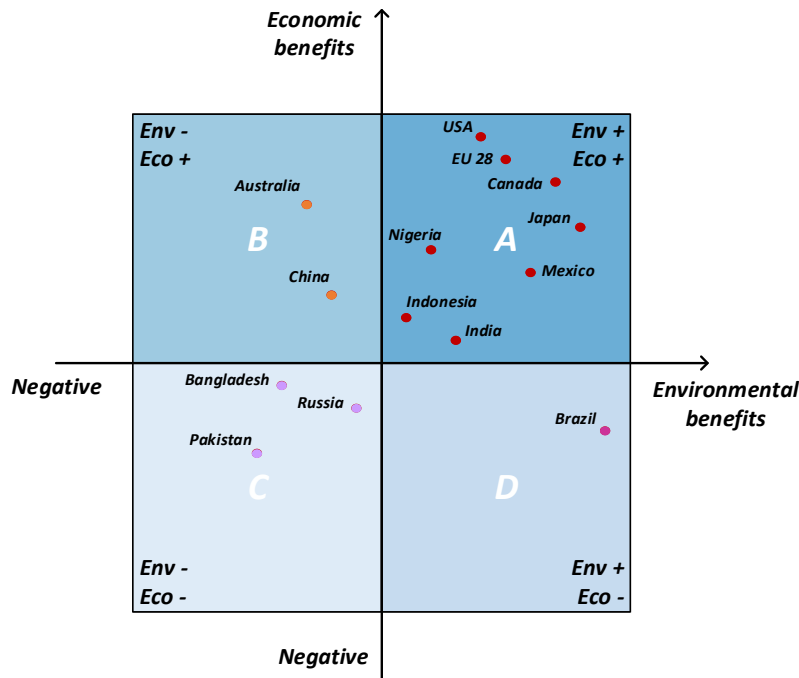


Figure S8 The environmental and economic accounting of concrete carbonation by region¹⁸.

Electricity emission factor

Electricity emissions are calculated using Eq.1, considering the global energy mix. It is worth noting that as countries globally transition towards low-carbon development, the share of clean energy sources in the electricity generation mix is anticipated to rise progressively. This shift towards cleaner energy sources is expected to lead to a reduction in both carbon emissions and NO_x emissions, as demonstrated in Fig.S9.

The proportions of the energy mix used in the calculations are based on estimates provided by BP company ¹⁹.

$$E_m^n = \sum_i E_i^n \times S_i^n \quad (1)$$

where E_m^n is the NOx emission factor of energy mix in year n . E_i^n represent the emission factor of the i th energy source in year n . S_i^n refer to the share of the i th energy source in energy mix in year n . The considered energy sources are coal, gas, hydro, solar, wind, oil, nuclear, and bioenergy.

Table S6 presents the comprehensive global energy mix, showcasing the composition of diverse energy sources. Table S7, on the other hand, offers a detailed account of emission factors pertaining to various energy types.

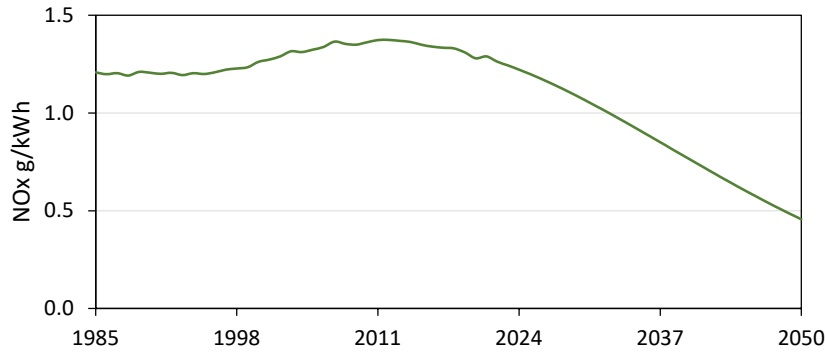


Figure S9 Global average NOx emission factors of electricity

Transportation distance of concrete materials

This study examines four distinct stages of transportation distances within the context of concrete materials: (1) the transportation of fresh concrete from the manufacturing plant to the construction site (urban or rural); (2) the transportation of demolished concrete debris from the construction site (urban or rural) to the designated recycling facility; (3) the transportation of room-temperature nitrogenated recycled concrete aggregates (nRCA) from the recycling facility to the market; and (4) the transportation of high-temperature nRCA from the recycling facility to the landfills. Some of these four transport processes share a common transport distance.

Fig.S10 provides a visual representation of the aforementioned transportation stages. The term "Urban" denotes the distances involved in transporting nitrogenated new concrete from the factory to urban construction sites, as well as the distances covered when transporting urban concrete debris from

demolition sites to recycling facilities. On the other hand, "Rural" signifies the transportation distances required for conveying nitrogenated new concrete from the factory to rural construction sites, as well as the distances entailed in transporting concrete debris from rural demolition sites to recycling facilities. The term "Post-treatment" refers to the distances involved in transporting the resulting nRCA from the factory either to the landfill or to the market.

From Fig.S10, it is evident that developed regions exhibit a more advanced circular economy, thereby resulting in a higher density of recycling facilities for construction and demolition waste and subsequently shorter transportation distances. Areas with higher population densities also experience a higher density of construction sites, leading to reduced transportation distances.

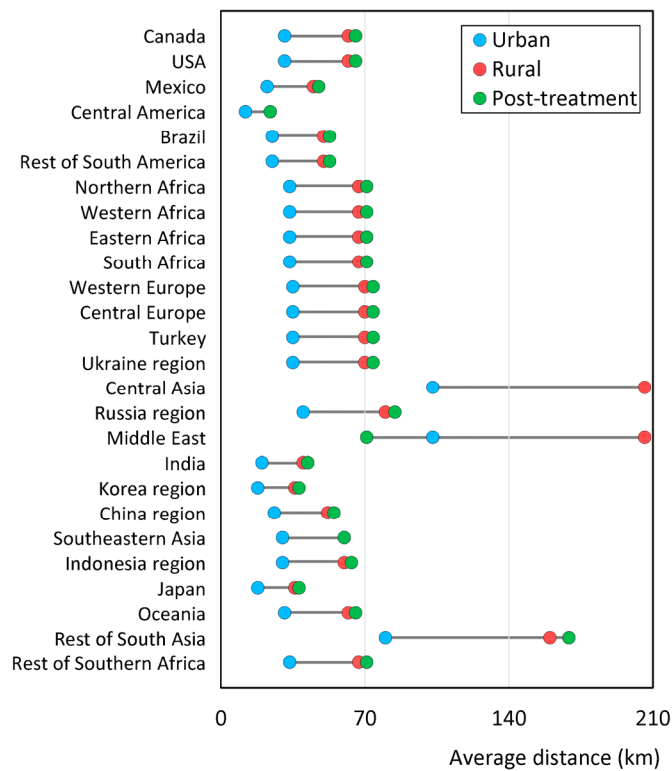


Figure S10 Transportation distance of concrete materials

NOx emissions during different stages

The transportation and landfilling stages of the process entail substantial energy consumption and have notable implications for environmental emissions. The use of gasoline or diesel fuel during transportation introduces NOx emissions, which partially offset the environmental advantages gained from NOx abatement. The comprehensive emissions are presented in Fig.3 of the main text and Figs.6-7 of this

publication. These emissions predominantly arise from NO_x treatment, material production, landfilling, and transportation across different treatment scenarios (see Fig.S11). Among these, the denitrification process of fresh concrete, which obviates the need for preliminary crushing and screening steps, emerges as the most energy-intensive procedure. In the case of concrete waste, employing high-temperature disposal renders it less suitable for reuse, necessitating landfilling. Landfill sites involve the deployment of large-scale construction machinery, such as excavators, bulldozers, and loaders. Comparative analysis reveals that, in the scenario of high-temperature denitrified concrete waste, landfilling constitutes a significant proportion of emissions. Conversely, under room temperature conditions, the energy demand for NO_x curing is lower, resulting in a magnified contribution of emissions from RCA production and transportation in this particular scenario.

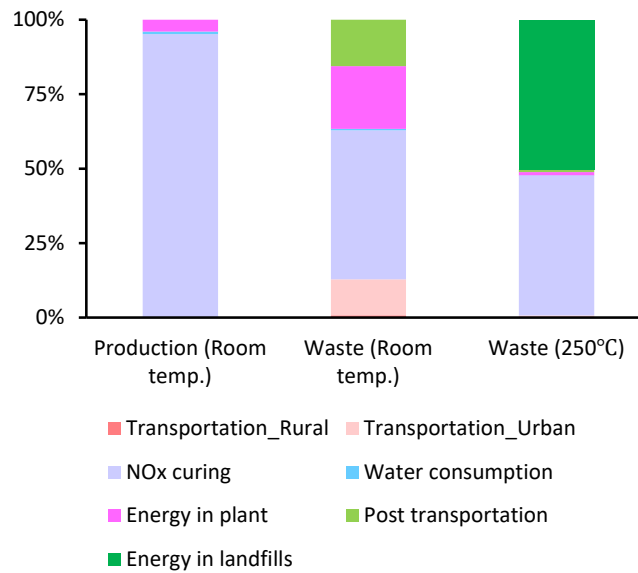


Figure S11 Detailed NO_x emissions during different life stages

Post impact of concrete debris

Elevated temperatures pose a significant risk to the structural integrity of concrete, leading to notable reductions in its durability. Hence, in Scenario 2 (S2), nRCA treated at 250°C are disposed of in landfills. We have conducted estimations of the resulting NO_x emissions arising from the transportation and machinery employed in the landfilling process. However, it is crucial not to overlook the potential environmental impact associated with land occupation during landfill activities (see Fig.S12). The land area utilized for this purpose is directly proportional to the quantity of nRCA generated in S2, as outlined in Eq.2. Nevertheless, in countries where construction and demolition waste management practices are inadequate,

such land occupation activities are likely to be deemed illegal, thereby increasing the probability of adverse effects such as land subsidence, soil erosion, and ecological damage.

$$L_{area} = \frac{Q_{nRCA}/D_{nRCA} \times k_{ltc}}{H_l} \quad (2)$$

where land occupation of landfilling (L_{area}) is equal to the (compacted) volume of the landfill divided by the depth of the landfill (H_l). The volume here refers to the loose volume of nRCA, and it is the weight of nRCA (Q_{nRCA}) divided by its loose density (D_{nRCA}). In landfills, the construction and demolition waste will be compacted, so we need to use loose-to-compacted coefficient (k_{ltc}) to convert the loose volume into compacted volume.

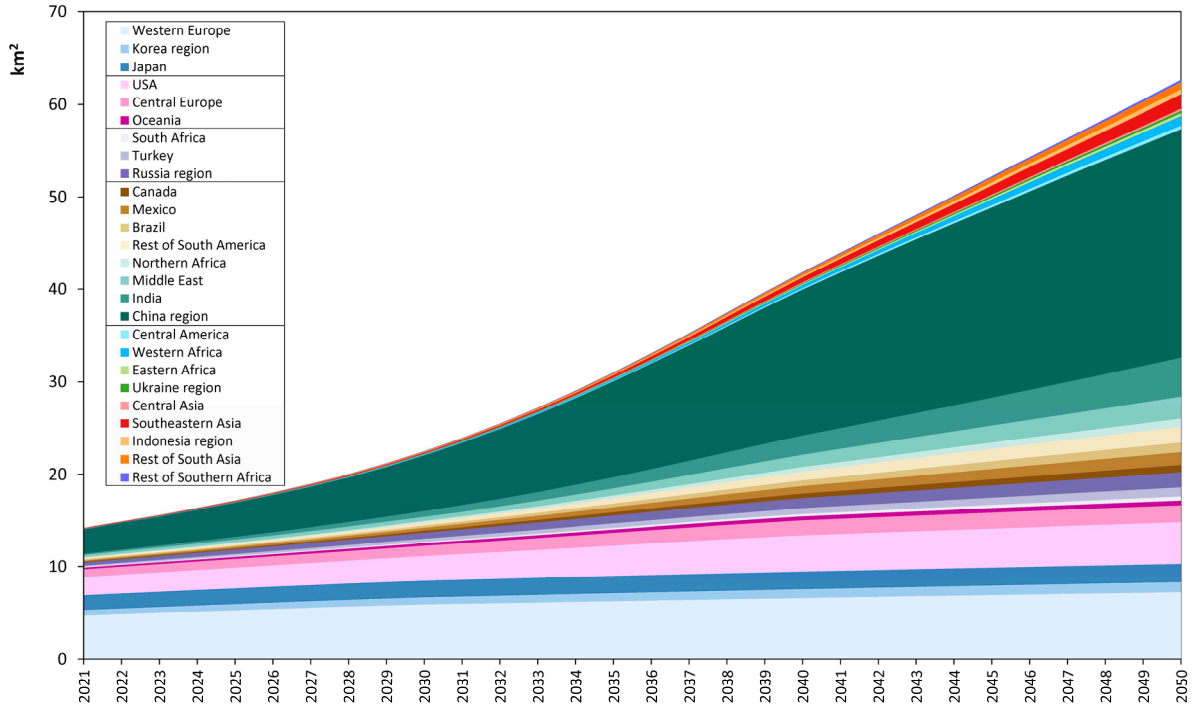


Figure S12 The land occupation caused by nRCA landfilling in S2

Sensitivity analysis

When conducting sensitivity analysis, we examined the impact of building lifespan, transportation distance, equipment energy consumption, and industrial pollution on the net NO_x sequestration and economic contribution of the technology. As depicted in Fig.S13, these factors display significant variations in their influence on the results. Regarding environmental benefits, in scenarios S1 and S2, only building lifespan exerts a substantial impact on the net adsorption, particularly notable in scenario S2

(Figs.S13a,b). Conversely, factors other than equipment energy consumption significantly affect economic benefits (Figs.S13c,d). An increase in building lifespan leads to a reduction in concrete debris generation, resulting in decreased NO_x absorption and economic contribution. Changes in industrial pollution emissions do not affect absorption because the efficiency of the technology remains unchanged. However, they do impact economic benefits, as pollution management costs increase due to diminishing marginal returns with reduced pollution. Therefore, reducing industrial pollution enhances overall economic benefits by avoiding high pollution control costs.

However, it is crucial to acknowledge that the socio-economic development context also shapes the benefits of this technology. Economic benefits are typically influenced by intricate mechanisms such as technological competition, government air governance policies, and circular economy technology subsidy policies, which necessitate discussion within a broader framework.

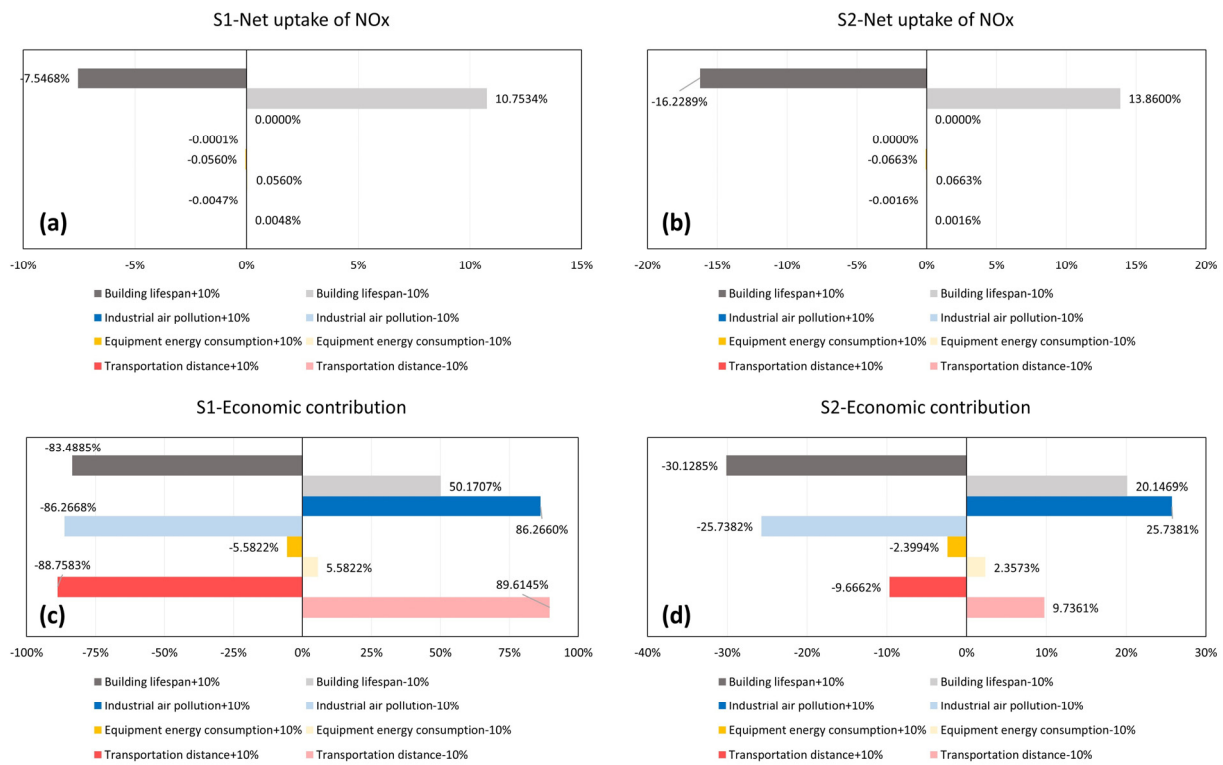


Figure S13 Sensitivity analysis of parameters affecting the NO_x uptake and economic contribution (Average value from 2021 to 2050). (a) Net NO_x uptake in S1 scenario; (b) Net NO_x uptake in S2 scenario; (c) Economic contribution in S1 scenario; (d) Economic contribution in S2 scenario

Table S1 NO_x sequestration efficiency

Temp.	Sequestration efficiency			
	Concrete debris	Unit	New concrete	Unit
250°C	0.1024	mmol/g	0.1247	mmol/g
150°C	0.0588	mmol/g	0.0832	mmol/g
27°C	0.0063	mmol/g	0.0078	mmol/g

Table S2 Global region classification ²⁰

Regions	No.	Included countries
Canada	1	Canada
USA	2	St. Pierre and Miquelon, United States
Mexico	3	Mexico
Central America	4	Anguilla, Aruba, Bahamas, The, Barbados, Belize, Bermuda, Cayman Islands, Costa Rica, Dominica, Dominican Republic, El Salvador, Grenada, Guadeloupe, Guatemala, Haiti, Honduras, Jamaica, Martinique, Montserrat, Netherlands Antilles, Nicaragua, Panama, Puerto Rico, St. Kitts and Nevis, St. Lucia, St. Vincent and the Grenadines, Trinidad and Tobago, Turks and Caicos Isl., Virgin Isl. , Virgin Islands
Brazil	5	Brazil
Rest of South America	6	Argentina, Bolivia, Chile, Colombia, Ecuador, Falklands Isl., French Guyana, Guyana, Paraguay, Peru, Suriname, Uruguay, Venezuela, RB
Northern Africa	7	Algeria, Egypt, Arab Rep., Libya, Morocco, Tunisia, Western Sahara
Western Africa	8	Benin, Burkina Faso, Cameroon, Cape Verde, Central African Republic, Chad, Congo, Dem. Rep., Congo, Rep., Cote d'Ivoire, Equatorial Guinea, Gabon, Gambia, The, Ghana, Guinea, Guinea-Bissau, Liberia, Mali, Mauritania, Niger, Nigeria, Sao Tome and Principe, Senegal, Sierra Leone, St. Helena, Togo
Eastern Africa	9	Burundi, Comoros, Djibouti, Eritrea, Ethiopia, Kenya, Madagascar, Mauritius, Reunion, Rwanda, Seychelles, Somalia, Sudan, Uganda
South Africa	10	South Africa
Western Europe	11	Andorra, Austria, Belgium, Denmark, Faeroe Islands, Finland, France, Germany, Gibraltar, Greece, Iceland, Ireland, Italy, Liechtenstein, Luxembourg, Malta, Monaco, Netherlands, Norway, Portugal, San Marino, Spain, Sweden, Switzerland, United Kingdom, Vatican City State
Central Europe	12	Albania, Bosnia and Herzegovina, Bulgaria, Croatia, Cyprus, Czech Republic, Estonia, Hungary, Latvia, Lithuania, Macedonia, FYR, Poland, Romania, Serbia and Montenegro, Slovak Republic, Slovenia
Turkey	13	Turkey
Ukraine region	14	Belarus, Moldova, Ukraine
Central Asia	15	Kazakhstan, Kyrgyz Republic, Tajikistan, Turkmenistan, Uzbekistan
Russia region	16	Armenia, Azerbaijan, Georgia, Russian Federation
Middle East	17	Bahrain, Iran, Islamic Rep., Iraq, Israel, Jordan, Kuwait, Lebanon, Oman, Qatar, Saudi Arabia, Syrian Arab Republic, United Arab Emirates, Yemen, Rep.
India	18	India
Korea region	19	Korea, Dem. Rep., Korea, Rep.
China region	20	China, Hong Kong, China, Macao, China, Mongolia, Taiwan
Southeastern Asia	21	Brunei, Cambodia, Lao PDR, Malaysia, Myanmar, Philippines, Singapore, Thailand, Vietnam
Indonesia region	22	East Timor, Indonesia, Papua New Guinea
Japan	23	Japan
Oceania	24	American Samoa, Australia, Cook Isl., Fiji, French Polynesia, Kiribati, Marshall Islands, Micronesia, Fed. Sts., Nauru, New Caledonia, New Zealand, Niue, Northern Mariana Islands, Palau, Pitcairn, Samoa, Solomon Islands, Tokelau, Tonga, Tuvalu, Vanuatu, Wallis ans Futuna Island
Rest of South Asia	25	Afghanistan, Bangladesh, Bhutan, Maldives, Nepal, Pakistan, Sri Lanka
Rest of Southern Africa	26	Angola, Botswana, Lesotho, Malawi, Mozambique, Namibia, Swaziland, Tanzania, Zambia, Zimbabwe

Table S3 Successful commercialization of carbonation of concrete materials

Company	Country	Carbonation scope	Source of CO ₂	Source of concrete materials	Advantage
Blue Planet Systems	United States	Carbonation of mineral waste to produce carbonated recycled aggregates	Cement plants, steel mills, natural gas power stations, refineries, direct air capture, hydrogen/SMR. CO ₂ does not need to be purified or liquefied and the product can be carbonated in a minimum 5% CO ₂ gas stream. Ability to utilize CO ₂ gas directly from flue gas or pure CO ₂ from DAC or process streams.	Concrete debris; Cement kiln dust; Steel slag; Fly ash/APCr; Bauxite slag; Silicate rock	The company's technology is less expensive than typical post-combustion CCS programs. There is no need to purify, liquefy and/or transport CO ₂ .
Carboncure	Canada	Ready-mix concrete; waste from slurry tanks; carbonated precast (mainly Coreslab Structures); carbonated concrete blocks.	CO ₂ is sourced from local industrial gas supply companies that have large CO ₂ capture facilities (often referred to as "CO ₂ recovery plants") in strategic locations around the world. In these recovery plants, they use flue gas streams from refineries, ethanol plants, ammonia plants, etc. to obtain, capture, purify and distribute CO ₂ to their customers.	New concrete	Capable of producing a wide range of carbonated products. A "carbon credit" measurement system based on a CO ₂ removal rate methodology designed for customers creates incentives for manufacturers to adopt the technology.
Neustark AG	Switzerland	Carbonization of recycled aggregates and waste slurries	Procurement of CO ₂ from the nearby Ara Region Bern sewage treatment plant. The CO ₂ from the plant is captured and liquefied for transportation. Transportation is carried out using a biogas-fueled truck with a special container for 20 tons of liquid CO ₂ and transporting the CO ₂ to the storage plant.	Recycled aggregate from Kästli Bau AG	In addition to carbon sequestration, new CO ₂ emissions can be reduced because the amount of cement in fresh concrete can be reduced to a regulatory minimum without compromising quality.
HeidelbergCement	Germany	Carbonated concrete based on low-calcium clinker (CO ₂ curing)	Use of exhaust gases from cement production kiln systems (flue gases escaping from clinker production).	Low-calcium clinker developed from recycled cement paste	Low-calcium clinker has a low calcium requirement. This maximizes the CO ₂ reduction potential in cement production and saves resources.
HeidelbergCement	Norwegian subsidiary	Carbonation of recycled concrete aggregate (fines)	Carbonation of recycled concrete by exhaust gases from the kiln system of cement production (flue gases escaping from clinker production).	Recycled concrete fines from precast production	Carbon source and materials are from the same company.

Table S4 Main equipment used in recycling and nitrogenation workshops²¹

Recycling equipment	Equipment	Unit energy (diesel)
	Crusher	0.20-0.28 L / t concrete debris
	Sieving machine	0.083 L / t concrete debris
	Excavator	0.29 L / t concrete debris
	Tipper	0.11 L / t concrete debris
	Lorry (20t)	0.084 L / t concrete debris
	Weighbridge	-
Nitrogenation equipment	Equipment	Unit power (room temp.)
	Mass Flow Controller	7.22E-03 Watt / t RCA
	Mixer	-
	Flow Reactor	-
	Humidifier	2.23E-01 Watt / t RCA
	Humidity Sensor	4.64E-06 Watt / t RCA
	Environmental Chamber	1.16E+00 Watt / t RCA
	Spectrometer	2.17E-01 Watt / t RCA
	NOx analyzer	7.25E-01 Watt / t RCA

Table S5 Main NOx emission factors used in the LCA ^{22,23}

Items	Emissions	Laminations	Units
Diesel (15% NO ₂ and 85% NO)	1.60E-03	Developing	kg NOx / kg diesel
	8.78E-04	Developed	
24-ton truck	4.00E-04	Developing	kg NOx / km
	2.20E-04	Developed	
Landfilling	4.25E-05	Developing	kg NOx / t landfilling
	2.33E-05	Developed	
Tap water	4.86E-04	For industrial use	kg NOx / t water
Electricity	Fig. S9		
Recycling	Table. S2		

Table S6 Global average electricity mix ¹⁹

Time	Coal	Gas	Hydro	Solar	Wind	Oil	Nuclear	Bioenergy	Other renewables excluding bioenergy
1985	37.93%	14.43%	20.03%	0.00%	0.00%	11.22%	15.07%		
1986	37.72%	14.08%	19.71%	0.00%	0.00%	11.46%	15.67%		
1987	38.04%	14.22%	19.06%	0.00%	0.00%	11.07%	16.26%		
1988	37.71%	13.84%	18.84%	0.00%	0.00%	11.26%	16.98%		
1989	37.55%	14.83%	17.91%	0.00%	0.02%	11.56%	16.69%		
1990	37.29%	14.96%	18.05%	0.00%	0.03%	11.41%	16.72%		
1991	37.28%	14.85%	18.07%	0.00%	0.03%	11.05%	17.15%		
1992	37.68%	14.83%	17.90%	0.00%	0.04%	10.77%	17.12%		
1993	37.50%	14.79%	18.58%	0.00%	0.05%	10.05%	17.34%		
1994	37.84%	14.90%	18.23%	0.00%	0.06%	10.08%	17.22%		
1995	37.64%	15.22%	18.56%	0.00%	0.06%	9.41%	17.35%		
1996	38.25%	15.23%	18.24%	0.01%	0.07%	9.03%	17.44%		
1997	38.17%	16.07%	18.13%	0.01%	0.09%	8.81%	16.92%		
1998	37.93%	16.60%	17.79%	0.01%	0.11%	8.92%	16.76%		
1999	37.67%	17.42%	17.42%	0.01%	0.14%	8.49%	16.91%		
2000	38.21%	18.13%	17.52%	0.01%	0.21%	7.83%	16.75%	0.99%	0.35%
2001	38.19%	18.85%	16.88%	0.01%	0.25%	7.61%	16.94%	0.94%	0.34%
2002	38.52%	19.50%	16.55%	0.01%	0.33%	7.21%	16.54%	0.99%	0.33%
2003	39.70%	19.63%	16.00%	0.01%	0.39%	7.08%	15.83%	1.03%	0.33%
2004	39.20%	20.14%	16.37%	0.02%	0.50%	6.67%	15.70%	1.08%	0.33%
2005	39.67%	20.33%	16.35%	0.02%	0.59%	6.42%	15.13%	1.17%	0.32%
2006	40.32%	20.73%	16.27%	0.03%	0.72%	5.67%	14.74%	1.20%	0.32%
2007	41.02%	21.40%	15.75%	0.04%	0.88%	5.54%	13.79%	1.26%	0.31%
2008	40.37%	21.62%	16.44%	0.06%	1.12%	5.23%	13.52%	1.32%	0.32%
2009	40.02%	21.89%	16.53%	0.10%	1.41%	4.87%	13.40%	1.44%	0.34%
2010	39.98%	22.66%	16.31%	0.15%	1.65%	4.54%	12.84%	1.55%	0.32%
2011	40.75%	22.22%	16.08%	0.29%	2.04%	4.82%	11.90%	1.59%	0.31%
2012	39.99%	22.95%	16.45%	0.43%	2.39%	4.95%	10.85%	1.68%	0.31%
2013	40.84%	21.88%	16.54%	0.58%	2.81%	4.66%	10.61%	1.78%	0.31%
2014	40.58%	21.94%	16.50%	0.84%	3.06%	4.31%	10.56%	1.89%	0.32%
2015	38.75%	23.10%	16.36%	1.08%	3.50%	4.28%	10.58%	2.03%	0.33%
2016	37.99%	23.50%	16.46%	1.35%	3.95%	3.95%	10.46%	2.01%	0.33%
2017	38.05%	23.31%	16.18%	1.78%	4.54%	3.49%	10.25%	2.07%	0.33%

Time	Coal	Gas	Hydro	Solar	Wind	Oil	Nuclear	Bioenergy	Other renewables excluding bioenergy
2018	38.06%	23.24%	16.06%	2.19%	4.86%	3.07%	10.07%	2.11%	0.33%
2019	36.73%	23.63%	15.94%	2.66%	5.38%	2.81%	10.33%	2.19%	0.34%
2020	35.40%	23.43%	16.50%	3.24%	6.04%	2.71%	10.03%	2.30%	0.35%
2021	36.39%	22.74%	15.21%	3.68%	6.65%	2.74%	9.86%	2.40%	0.34%

Table S7 NOx emissions from different electricity sources ²⁴

Energy source	NOx (kg/MWh)	Ave. NOx (kg/MWh)
Hard coal	0.3–3.9	2.1
Lignite	0.2–1.7	0.95
Natural gas	0.2–3.8	2
Oil	0.5–1.5	1
Nuclear power	0.01–0.04	0.025
Biomass	0.08–1.7	0.89
Hydropower	0.004–0.06	0.032
Solar energy	0.15–0.40	0.275
Wind	0.02–0.11	0.065

Table S8 Economic factors used in LCC calculation

Econ. items	Labor	Place	Waste acceptance	nRCA	Diesel	Tax	Industrial energy	Water	Wastewater	Equipment maintenance	NO ₂ cuing		Energy in recycling	Waste trans.		Equipment	Net salvage value	Post trans.	Landfill gate fee	Landfilling energy
Unit (USD)	/t debris	/t debris	/t debris	/t nRCA	/L	-	/kWh	/m ³		/t debris	/t RCA h (room)	/t RCA h (250)	/t debris	/t debris (urban)	/t debris (rural)	/t debris	/t debris	/t nRCA	/t nRCA	/t nRCA
1	(1.26)	(0.75)	29.99	5.00	(0.73)	26%	(0.09)	(1.50)	(1.37)	(0.31)	(0.22)	(3.95)	(0.71)	(2.38)	(4.75)	(1.21)	0.63	(5.03)	(22.16)	(0.03)
2	(1.68)	(1.20)	35.00	6.10	(0.65)	26%	(0.14)	(1.08)	(1.09)	(0.31)	(0.32)	(5.71)	(0.63)	(2.12)	(4.23)	(1.21)	0.63	(4.48)	(10.63)	(0.03)
3	(0.38)	(0.42)	14.13	2.00	(0.72)	30%	(0.19)	(0.25)	(0.05)	(0.31)	(0.44)	(7.85)	(0.70)	(0.04)	(0.07)	(1.21)	0.63	(3.60)	(2.88)	(0.03)
4	(0.54)	(0.46)	7.00	3.00	(0.79)	30%	(0.21)	(2.06)	(2.78)	(0.30)	(0.49)	(8.86)	(0.77)	(0.80)	(1.59)	(1.21)	0.63	(1.59)	(2.88)	(0.03)
5	(0.49)	(0.31)	1.29	2.34	(0.95)	34%	(0.14)	(1.21)	(1.98)	(0.31)	(0.33)	(5.92)	(0.92)	(2.49)	(4.99)	(1.21)	0.63	(5.28)	(2.88)	(0.04)
6	(0.44)	(0.48)	4.04	9.70	(1.00)	35%	(0.02)	(0.34)	(0.04)	(0.30)	(0.06)	(1.01)	(0.97)	(2.10)	(4.20)	(1.21)	0.63	(4.44)	(2.88)	(0.04)
7	(0.36)	(0.72)	5.31	3.61	(0.15)	23%	(0.04)	(0.15)	(0.11)	(0.30)	(0.09)	(1.59)	(0.15)	(0.42)	(0.84)	(1.21)	0.63	(0.89)	0.00	(0.01)
8	(0.20)	(0.09)	5.21	12.13	(0.64)	30%	(0.08)	(0.41)	0.00	(0.31)	(0.18)	(3.32)	(0.62)	(2.25)	(4.51)	(1.21)	0.63	(4.76)	0.00	(0.03)
9	(0.37)	(0.41)	5.21	4.40	(0.82)	30%	(0.14)	(0.79)	(0.59)	(0.30)	(0.33)	(6.00)	(0.80)	(2.31)	(4.62)	(1.21)	0.63	(4.88)	0.00	(0.03)
10	(0.48)	(0.50)	16.00	4.19	(0.90)	28%	(0.08)	(3.73)	(0.19)	(0.30)	(0.18)	(3.19)	(0.87)	(2.53)	(5.07)	(1.21)	0.63	(5.36)	(32.83)	(0.04)
11	(1.32)	(0.68)	23.59	13.48	(1.21)	21%	(0.14)	(1.16)	(0.27)	(0.31)	(0.33)	(5.91)	(1.17)	(4.43)	(8.86)	(1.21)	0.63	(9.37)	(9.81)	(0.05)
12	(0.87)	(0.46)	33.08	13.48	(1.11)	19%	(0.29)	(2.55)	(2.38)	(0.30)	(0.67)	(12.13)	(1.08)	(3.26)	(6.53)	(1.21)	0.63	(6.90)	(7.53)	(0.05)
13	(0.70)	(0.58)	5.31	2.77	(1.23)	23%	(0.18)	(0.64)	(0.32)	(0.30)	(0.42)	(7.60)	(1.19)	(3.62)	(7.23)	(1.21)	0.63	(7.65)	(3.13)	(0.05)
14	(0.30)	(0.38)	7.35	3.50	(0.73)	18%	(0.08)	(0.66)	(0.88)	(0.30)	(0.19)	(3.36)	(0.71)	(2.15)	(4.29)	(1.21)	0.63	(4.54)	(1.14)	(0.03)
15	(0.12)	(0.14)	5.21	3.61	(0.70)	29%	(0.12)	(0.17)	(0.08)	(0.31)	(0.28)	(4.95)	(0.68)	(7.57)	(15.14)	(1.21)	0.63	(16.01)	0.00	(0.03)
16	(0.34)	(0.55)	1.63	1.63	(0.55)	20%	(0.10)	(0.60)	(0.44)	(0.31)	(0.22)	(4.03)	(0.53)	(2.31)	(4.62)	(1.21)	0.63	(4.89)	(12.90)	(0.02)
17	(0.36)	(0.72)	5.31	3.61	(0.15)	23%	(0.04)	(0.15)	(0.11)	(0.30)	(0.09)	(1.59)	(0.15)	(1.30)	(2.60)	(1.21)	0.63	(0.89)	0.00	(0.01)
18	(0.13)	(0.24)	3.61	6.06	(0.81)	30%	(0.10)	(0.47)	(0.12)	(0.31)	(0.23)	(4.20)	(0.79)	(1.70)	(3.40)	(1.21)	0.63	(3.60)	(1.04)	(0.03)
19	(0.90)	(0.86)	21.89	2.63	(1.05)	28%	(0.08)	(0.61)	(0.72)	(0.30)	(0.19)	(3.48)	(1.02)	(1.59)	(3.18)	(1.21)	0.63	(3.36)	(16.94)	(0.04)
20	(0.40)	(0.23)	5.21	9.90	(0.81)	25%	(0.09)	(0.77)	(0.17)	(0.31)	(0.22)	(3.90)	(0.79)	(2.21)	(4.42)	(1.21)	0.63	(4.68)	(2.91)	(0.03)
21	(0.19)	(0.28)	5.21	6.06	(0.59)	20%	(0.08)	(0.49)	(0.05)	(0.30)	(0.17)	(3.15)	(0.57)	(1.49)	(2.97)	(1.21)	0.63	(2.97)	0.00	(0.03)
22	(0.20)	(0.09)	5.21	6.06	(0.61)	22%	(0.07)	(0.33)	0.00	(0.31)	(0.17)	(3.11)	(0.59)	(1.92)	(3.84)	(1.21)	0.63	(4.06)	(0.04)	(0.03)
23	(1.39)	(1.10)	18.13	7.85	(0.88)	30%	(0.20)	(2.00)	(1.70)	(0.31)	(0.45)	(8.18)	(0.85)	(1.66)	(3.33)	(1.21)	0.63	(3.52)	(74.51)	(0.04)
24	(1.45)	(0.60)	22.07	14.29	(0.92)	30%	(0.24)	(1.78)	(0.40)	(0.31)	(0.56)	(10.12)	(0.89)	(2.99)	(5.99)	(1.21)	0.63	(6.33)	(25.86)	(0.04)
25	(0.07)	(0.21)	5.21	6.06	(0.84)	30%	(0.08)	(0.09)	(0.10)	(0.31)	(0.20)	(3.53)	(0.81)	(7.06)	(14.11)	(1.21)	0.63	(14.93)	0.00	(0.04)
26	(0.07)	(0.26)	5.21	4.40	(0.60)	30%	(0.05)	(0.53)	(0.10)	(0.30)	(0.10)	(1.89)	(0.58)	(1.69)	(3.38)	(1.21)	0.63	(3.57)	0.00	(0.03)

Table S9 Cumulative reduced DALYs (per 100,000 population) in 2021-2050

No.	Reduced DALYs in S1	Reduced DALYs in S2
1	5.33	18.31
2	3.17	16.61
3	3.34	9.99
4	2.43	4.38
5	2.06	5.13
6	2.83	7.17
7	1.83	3.88
8	1.10	1.55
9	0.86	1.12
10	2.98	7.67
11	4.68	26.29
12	4.62	22.53
13	3.49	11.66
14	2.35	5.15
15	1.50	2.56
16	3.08	11.85
17	3.42	7.82
18	2.08	3.55
19	3.77	20.46
20	6.84	19.39
21	2.27	3.82
22	0.94	1.66
23	4.16	27.49
24	4.09	17.32
25	1.20	1.74
26	0.89	1.23

Table S10 Global NOx emissions in 2020

Regions	Annual NOx emissions (Kt)	Population	Per capita emissions (kg/yr)
1	1464	38,005,000	38.53
2	7244	331454849	21.86
3	2301	124,013,861	18.55
4	1075	80,304,008	13.38
5	2993	210,166,592	14.24
6	3200	214,660,856	14.91
7	2117	200,009,351	10.58
8	2048	529,949,824	3.87
9	996	366,979,810	2.71
10	1925	57,339,635	33.57
11	6163	423,915,776	14.54
12	2111	30,550,121	69.11
13	865	83,731,000	10.33
14	858	56,768,506	15.12
15	1201	152,043,312	7.90
16	4241	236,658,527	17.92
17	6341	258,956,458	24.49
18	10025	1,369,003,306	7.32
19	1143	77,402,971	14.76
20	24510	1,437,753,767	17.05
21	4446	388,879,447	11.43
22	2841	277,657,915	10.23
23	1149	125,960,000	9.12
24	1614	32,980,789	48.94
25	1953	471,530,787	4.14
26	665	178,259,348	3.73

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