Item	**Present?**	**Filename** **Whole original file name including extension. i.e.: Smith_SI.pdf. The extension must be .pdf**	**A brief, numerical description of file contents.** **i.e.: *Supplementary Figures 1-4, Supplementary Discussion, and Supplementary Tables 1-4.***
Supplementary Information	**Yes**	**Supplementary_Information_for_ NATSUSTAIN-25010459B.pdf**	***Supplementary Figures 1-25, Supplementary Tables 1-24, Supplementary Discussion and Supplementary Method.***
Reporting Summary	**Yes**	**Gu_Reporting Summary_Flat.pdf**	
Peer Review Information	**No**	***OFFICE USE ONLY***	

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Type	**Number** **Each type of file (Table, Video, etc.) should be numbered from 1 onwards. Multiple files of the same type should be listed in sequence, i.e.: Supplementary Video 1, Supplementary Video 2, etc.**	**Filename** **Whole original file name including extension. i.e.: *Smith_ Supplementary_Video_1.mov***	**Legend or Descriptive Caption** **Describe the contents of the file**

Supplementary Data	**Supplementary Data 1**	**Supplementary_Data_1-3.xlsx**	**Additional detailed information pertaining to sensitivity and uncertainty analyses.**
Supplementary Code	**Supplementary Code 1**	**Supplementary_Code.txt**	**The computational code for MSW generation projecting, physical component modeling, model testing, and figures generation.**

Parent Figure or Table	**Filename** **Whole original file name including extension. i.e.: *Smith_SourceData_Fig1.xls*, or *Smith_ Unmodified_Gels_Fig1.pdf***	**Data description** **i.e.: Unprocessed western Blots and/or gels, Statistical Source Data, etc.**
Source Data Fig. 1	Source_Data_Fig.1.xlsx	**Statistical Source Data**
Source Data Fig. 2	Source_Data_Fig.2.xlsx	**Statistical Source Data**
Source Data Fig. 3	Source_Data_Fig.3.xlsx	**Statistical Source Data**
Source Data Fig. 4	Source_Data_Fig.4.xlsx	**Statistical Source Data**
Source Data Fig. 5	Source_Data_Fig.5.xlsx	**Statistical Source Data**

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Editor Summary:

Developing strategies for reducing carbon emissions in municipal solid waste (MSW) management is essential to achieving the net-zero target. Here the authors systematically assessed strategy options of different countries for achieving net-zero MSW management.

Nationally localized strategies for zero-carbon municipal solid waste management

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Abstract

Strategies for achieving net zero emissions in municipal solid waste (MSW) management are crucial for a sustainable society, but insights that can guide global policy making are still scarce. Here, we provide a holistic view on this topic on a global scale. We first evaluated the spatiotemporal differences in global and national MSW-related emissions in 195 countries or regions in between 1980 and 2022, and determined the spatiotemporal heterogeneity and drivers of global and national MSW-related greenhouse gas emissions. Then we performed prospective scenario-based simulations and found that all countries can achieve net-zero in MSW management by 2100 but tailored measures are needed. We finally explored the strategies and challenges associated with achieving net zero via 1,024 scenarios while considering the combination of several measures from a local perspective. The results suggest that most developing countries should adjust their treatment measures and/or upgrade their technologies, while developed regions can achieve net-zero with a single measure, particularly recycling, which has substantial mitigation potential. These insights can help to develop localized MSW management strategies for different countries and eventually contribute to achieving the net-zero target globally.

To avoid irreversible, long-term climate disasters, countries worldwide have made climate commitments. However, achieving global net zero emission goals will depend entirely on the actions of all sectors in each country[1]. Achieving net zero emissions is uniquely challenging because of the heterogeneous dynamic physical components of municipal solid waste (MSW) and the numerous treatment and disposal measures[2]; thus, comprehensive local strategies are needed. MSW does not follow the environmental Kuznets curve and is projected to increase continuously[3]. Accordingly, MSW-related emissions have also continued to increase, thus necessitating collaboration across multiple departments, advancements in technology, changes in lifestyle, the enhancement of laws and regulations, and the optimization of policy mechanisms[4,5]. Reducing emissions involves multiple treatment techniques, including landfilling, incineration, composting, and recycling, which fall into several stages and events (e.g., waste source reduction, intermediate recycling, and terminal treatment and disposal)[6]. This highlights the need for a systems-based evaluation to investigate the earliest net zero achievement time and the optimal combination of reduction measures to better understand emissions and identify mitigation opportunities and challenges.

The achievement of net zero MSW, which involves several interconnected events, demands coordinated efforts and comprehensive strategies across different stages. With respect to the source of waste generation, studies have focused on exploring reduction strategies via waste reduction, increased collection, source separation and recycling[7]. Moreover, changes in the separation and recycling of MSW components can lead to changes in intermediate treatment structures (TSs), which in turn affect emissions during terminal disposal[8]. The choice of treatment measure, such as incineration heat recovery, landfill methane collection, material recovery, and composting, is another important factor in emission reduction, especially the combination of treatment measures[9]. From a terminal disposal perspective, the TSs—the adjustment and optimization of treatment measures—may cause waste from recyclable materials and substantial and/or bit emissions[10], with a high degree of uncertainty[11]. Direct and indirect emission reduction measures (involving carbon sources and sinks) constitute another complex challenge[12,13], especially incineration energy conversion[14]. Waste incineration for thermal recovery is a win-win process that can offset emissions and energy recovery. Recycling and composting not only yield resources and increase social wealth but are also important measures for reducing emissions[2]. Therefore, to decarbonize the MSW sector, different events, including the stages of generation, collection, treatment and disposal, must be considered.

Although numerous researchers have evaluated MSW-related emissions at the global level or in specific regions and countries by focusing on processes, technologies, pathways, and behavioral changes[15–17], little attention has been paid to local conditions and actionable measures. For example, the Intergovernmental Panel on Climate Change (IPCC) parameter is widely used to estimate emissions from waste treatment and disposal, but there are considerable variations in its emission estimates, potentially resulting in nonlocalized conclusions about net zero performance. Furthermore, notable regional and national differences in emission sources, structure and mitigation opportunities exist in MSW management due to disparities across countries in terms of population, economy, urbanization, lifestyle, and geographical location[18,19]. Though existing studies have covered 86% of the world's MSW, it is regrettable that the 43 highest MSW generation countries are included, especially with only three low-income countries, where are highly distinctive—90% of their MSW is treated through mismanagement. Approximately one-third of MSW directly enters the environment without proper treatment, of which 90% occurs in low-income regions wherein the MSW is either burned or dumped in open spaces[20]. Conversely, incineration heat recovery and recycling are the main treatment measures in high-income developed countries[21,22]. Such diverse treatment patterns, technical feasibilities, and emission characteristics and the underlying social economy suggest that distinct requirements are needed for achieving net zero from MSW management in different countries and regions.

Here, we evaluated the spatiotemporal differences in global and national MSW-related emissions in 195 countries or regions between 1980 and 2022. We then analyzed the potential for emission reduction across several sources and structures and performed prospective scenario-based simulations for 2023-2100. Finally, we explored the strategies and challenges associated with achieving net zero via 1,024 scenarios while considering several measures combinations from a local perspective. Our study provided customized strategies for different regions that maximize the mitigation of MSW-related emissions and expedite the achievement of the net-zero target.

Results

Global and national MSW-related GHG emissions

From 1980 to 2022, the global (total and per capita) MSW-related emission hotspots shifted from developed to developing countries, in **Fig. 1 (a1-a4)**. Global emissions increased from 678.3 to 1,542.5 Mt and per capita emissions increased from 218.8 to 282.4 kg (**Supplementary Fig. 1**). In 1980, the highest emissions were recorded in the USA (emission: 78.3 Mt CO_2e, contribution rate: 11.5%), followed by Russia (7.6%), India (7.6%), China (5.3%), and Germany (5.0%). Among these, 60% are advanced economies. In 1994, India and China, surpassed the USA for the first time in terms of emissions to occupy the top two positions. They remained the top two emitters until 2022, generating 86.9-237.8 Mt CO_2e and 111.8-209.3 Mt CO_2e, respectively (**Supplementary Fig. 2**), followed by the USA (97.3 Mt, contribution rate: 6.3%), Russia (3.9%), and Nigeria (3.1%). Notably, other than the USA, these countries are developing economies. At the regional level, Southern Africa (emissions: 93.5 Mt) and Southeast Asia (91.3 Mt) ranked among the top five emitters in 2022, contributing 5.9% and 5.7% of total global emissions, respectively, and surpassing 80.6% in terms of their contributions in these regions (**Supplementary Fig. 3**).

From 1980-2022, emissions from 18 developed economies—primarily located in Europe and the Organization for Economic Cooperation and Development (OECD)—peaked and then exhibited a downward trend, with a 63.0% reduction, in **Supplementary Fig. 4**. However, global emissions increased by a factor of 1.3, which can be attributed to the very high growth rates of over 3-fold in Africa, Southern Asia and Southeast Asia, with significant emission bases (**Supplementary Fig. 3**).

In total, global emissions reached 47.5 Gt from 1980-2022, of which China and India were the main contributors, accounting for 12.0% (5.7 Gt CO_2e) and 11.1%, respectively, followed by the USA (7.8%), Russia (5.0%), Mexico (2.7%). Among the 31 regions, the cumulative contributions of Northern Africa, Southeast Asia, Southern America, and Western Africa exceeded 3.5%, in **Fig. 1 (b)**. The notable change in contributions across countries clearly indicates that developing countries will become the primary contributors to emissions in the future. Consequently, a more in-depth examination of the emission source and structure is essential for understanding the causes of spatiotemporal emission heterogeneity and formulating targeted mitigation strategies.

Differences in MSW-related GHG sources and structures

Substantial differences across regions exist in terms of historical evolution trends, sources, and structure (**Fig. 2**), but we found that generation intensity (GI), TS, and emission intensity (EI) were the key drivers (**Fig. 3**). Among the drivers, GI was the primary contributor to emissions in 83.9% of the regions, mostly in developing regions. In addition, TS inhibits emissions in 71.0% of the regions and is the most significant contributor to emission reduction, especially in developed and emerging economies. However, in the USA, Ukraine and Oceania, the impact of TS on emissions has shifted from inhibition to promotion over the last two decades. This could be attributed to the increased rate of MSW generation in the USA (12.1%), which has significantly exceeded that of resource treatment since 2010. Additionally, Ukraine has experienced a decline in recycling of 1.1%. Furthermore, inappropriate management in Oceania increased by 53.9% from 2010 to 2022

(**Supplementary Fig. 6**). Moreover, the EI shifted from being a promoting effect to an inhibitory effect in 74.2% of the regions after 2000, which can be attributed to technological advancements that enhance emission reduction efficiency.

In fact, GI, TS, and EI are complex concepts that involve MSW components, treatment measures, and efficiency. We further deconstructed these three indicators into four physical components and eight treatment measures to investigate the regional emission evolution trends, sources, and structures over time. In terms of GI, food waste is responsible for the most discharge worldwide, with cumulative emissions of 25.3 Bt CO_2e, accounting for 53.2%. At the regional level, in 54.8% of the countries, food waste significantly contributed to their emissions. Specifically, in India, Western Africa, Brazil, and Eastern Africa, the food waste-related emission contribution ranges from 64.5% to 77.1%, accounting for 12.2% of the total global emissions due to food waste. Paper-related emissions dominated in Türkiye, Russia, and South Korea, accounting for 27.1%, 26.1% and 25.8%, respectively, of their national MSW-related emissions. Plastic-related emissions have increased by 60.4% over the last decade and surpassed the growth rates of other components by 38.5%-40.7%. China exhibited an increase in plastic-related emissions of 242.6%, positioning it at the forefront of this trend.

From the perspective of TS, unsanitary landfilling was the main contributor to cumulative emissions, accounting for 40.6% (19.4 Gt CO_2e), followed by mismanaged open dumping (22.2%) and open burning (19.2%). In 25.8% of the regions, unsanitary landfills were the major sources of emissions, with cumulative contributions greater than 30.3%, especially in South Korea (96.1%), Russia (74.9%), and the USA (64.8%), accounting for 11.1% of global emissions. In Indonesia and Southern Africa, mismanagement has been identified as the primary contributor, accounting for more than 78.0% of the total emissions.

With respect to EI, incineration (energy recovery) has emerged as the leading contributor to emissions, with a contribution of 69.1% in Japan, attributed to electricity-heat conversion rates below 30%, which reduces electricity generation and undermines mitigation potential. In Canada and Türkiye, sanitary landfills represent a significant source of emissions due to low methane capture rates (60%) and biogas power generation rates of 36.74% and 33.83%, respectively (**Supplementary Fig. 7**).

Scenario analysis for determining mitigation potential

Various measures exhibit different mitigation potential across regions, with estimates ranging from -412.9% to 31.1% (**Fig. 4**). Under the SSPs2 pathway, that is, the business-as-usual scenario (S0), global emissions will reach 3,658.6 Mt by 2070 and even 5,197.2 Mt by 2100, suggesting the failure to meet net zero targets, especially in Western Africa (956.5Mt) and India (925.5Mt) (**Supplementary Fig. 8**). Furthermore, in Western Africa, food-related waste treatment is the leading contributor to emissions. Open dumping has been identified as the principal source of emissions in India, with projected cumulative emissions equivalent to 3.9 times the total global emissions in 2022 (**Supplementary Fig. 9**).

To achieve the net zero target, this study establishes ten scenarios based on the GI, TS, and EI to evaluate the mitigation potential. Modifying the TS demonstrates the highest mitigation potential to achieve net zero, ranging from -386.1% to -88.3%, followed by technology upgrades (-365.2% to -0.1%) and source reductions (-61.6% to -29.1%). Increasing recycling shows significant emission reduction potential across all countries. Eleven developed or emerging economies could achieve their climate objectives between 2029 and 2071 solely by increasing their recycling rates. Among them, Canada, Central Europe, South Korea, the OECD, and USA lead in reducing paper recycling emissions, which Mexico and Russia excel in glass recycling. Other regions, particularly China, show strong mitigation potential for plastic waste recycling (**Supplementary Fig. 10**). Furthermore, Japan and China exhibit considerable mitigation potential by improving heat-electricity conversion, which could achieve net zero targets by 2030 and 2051, respectively. Increasing methane capture could facilitate carbon neutrality attainment in Türkiye before 2060, and halving food waste would be most effective in South Korea. From a global emissions perspective, the majority of regions that could attain net zero via a single measure have a cumulative mitigation contribution rate below 3.0%, which is insignificant, in **Supplementary Fig. 11 (a)**. Other measures, such as halving paper and plastic generation, composting, and incineration (energy recovery) alone, are unlikely to ensure the achievement of net zero targets and could even result in increased emissions in South Korea, Japan, Canada, the USA, Türkiye, and Western and Central Europe.

Overall, 20 regions encompassing 148 countries, which collectively account for 80.5% of the total emissions, cannot achieve net zero targets via a single measure. Accordingly, we combined individual measures and created scenarios for each region and categorized the regions since the number of combined measures that would ensure achieving net zero as follows: very hard, hard, medium, and easy (the detailed classification criteria are shown in **Supplementary Table 3** and **Supplementary Fig. 12**). Furthermore, achieving this target poses challenges of varying degrees; thus, net zero strategies should be carefully tailored in the future.

Localized strategies toward net zero emissions

We conducted thorough uncertainty and sensitivity analysis for achieving net zero, both using the earliest time and the most convenient measure combination (**Fig. 5**). In very hard group, achieving the net zero target in these areas involves implementing 2-3 measures. Notably, if the advance of related measures declines by 50%, then 77.7% regions fail to achieve net zero (**Fig. 5a**). In Western Africa, the integrated implementation of six measures can achieve a contribution rate of 16.3% to emission reductions and realize the net zero target 28 years earlier. Nonetheless, considering the existing infrastructure (**Supplementary Fig. 13**), promoting such measures will be even more challenging if the net zero target is to be realized earlier. Increasing the MSW collection rate is particularly crucial in this region (**Fig. 5b**). In Central America, Southern Asia, Middle Africa, Western Africa, and Northern Asia, achieving net zero will be unattainable without increasing MSW collection rates. Additionally, enhancing recycling efforts is crucial in Brazil, Southern Africa, Eastern Africa, and Ukraine.

In hard group, all regions can reach the target by employing combinations of two measures. In contrast, India, Indonesia, and South Africa can only meet the target via hard combinations. To attain net zero at the earliest opportunity, this group needs to implement five or more measures simultaneously (**Fig. 5a**). India, has the potential to contribute 14.1% and 19.5% to global emission reductions by the hard and very hard combinations, respectively, while advancing the timeline for achieving net zero to 2079 and 2066, respectively. Additionally, this region should prioritize improving the treatment structure. Southern America should focus on increasing composting (**Fig. 5c**). In Asia, such as Indonesia, Southeast Asia, and the former Soviet Union, promoting incineration (energy recovery) is crucial, especially in India. Furthermore, Oceania, Latin America, and Hong Kong and Macao should prioritize increasing their MSW collection rates.

Except for the Middle East, which needs to implement two treatment measures, all other regions, where are developed and emerging economies, can reach the net zero target by implementing recycling alone in medium group (**Fig. 5a**). Notably, 80.0% of these regions could reach net zero before 2040, particularly Canada, which has the earliest possible attainment of net zero in 2032. Additionally, Mexico exhibits the greatest potential for net zero acceleration (34 years) among all cases, reaching the target by 2056 via five targeted interventions. It should be noted that solely improving recycling in Mexico could result in the failure to attain net zero. In Canada and Western Europe, recycling should be prioritized. In addition, the Middle East should prioritize enhancing incineration (energy recovery). Russia, Mexico, and regions of the OECD should focus on upgrading their technological capabilities (**Fig. 5d**).

The easy group, comprising predominantly developed economies, could achieve net zero via a single measure by 2050, in **Fig. 5 (a, e)**. To expedite the net zero timeline to before 2037, a combination of 3-6 measures is needed. The USA has the potential to increase its contribution to

11.9% by enhancing incineration (energy recovery), recycling, and technological upgrades, reaching net zero by 2031. More than half of Japan's and China's portfolio of measures for achieving net zero involves enhancing recycling and electricity-heat conversion, which should be implemented promptly. South Korea should prioritize reducing food waste at the source.

Overall, the implementation of recycling has emerged as the most critical measure, accounting for 14.3%, followed by increasing collection rates (10.9%), heat-electricity conversion (10.6%), incineration (energy recovery) (10.5%), and reducing food waste at the source (9.7%), in **Supplementary Fig. 14**. It is essential to focus on measures and/or regions with significant emission reduction potential and a high likelihood of achieving net zero. However, varying degrees of challenge exist in each region for achieving net zero.

Discussion

Decarbonization via implementing combined measures

There are 20 regions where net zero targets cannot be achieved via a single measure, accounting for 80.5% of global emissions. This indicates that attaining the global net zero target will rely on governments executing well-structured, integrated, and proactive strategies. All countries in the very hard group should increase collection and recycling to achieve net zero, in which the average collection and recycling rates are currently 58.2% and 6.7% (**Supplementary Fig. 15**), respectively. In the very hard group, predominantly comprising low-income countries, the informal recycling sector frequently assumes a pivotal role in the collection and recycling of MSW. For example, in Africa, the informal sector is responsible for 50% of the collection of unmanaged MSW, whereas in Jakarta, it contributes to 25% of MSW recycling[20]. Therefore, it is advisable for relevant countries to promote the gradual formalization of this informal sector by fostering multiparty cooperation, upgrading technology, and enacting supporting legislation. Moreover, collaborative efforts in emission reduction among nations have the potential to significantly curb emissions.

In addition, the implementation of a single measure in certain countries may inadvertently lead to an increase in emissions; therefore, a comprehensive combination of strategies is essential. In Canada, which is characterized by a high carbon content, indiscriminately enhancing incineration (energy recovery) could result in elevated emissions. It is thus crucial to combine the recycling of high-carbon physical components with incineration for power generation to achieve net zero by 2036. In Japan, the promotion of composting has resulted in a 31.1% increase in emissions. However, when composting is combined with improved electricity-heat conversion, it has the potential to mitigate emissions by 219.1%, thereby achieving net zero by 2030, in **Supplementary Fig. 11 (b)**. Additionally, this study posits that reducing recyclable waste (especially plastics and paper) may inadvertently result in increased emissions, which needs to be combined with structural improvements and technological upgrades to achieve mitigation in certain regions. More details are given in **Section 5** of the Supplementary Information.

Prioritization of categories and measures for recycling

Globally, landfilling and incineration currently account for up to 63.1% of total emissions in MSW treatment, serving the major emitters across 11 regions. In contrast, recycling demonstrates substantial mitigation potential (**Fig. 2**), which provides an emission reduction potential ranging from -412.9% to -32.4%. Additionally, many developed and emerging countries could achieve net zero through recycling implementation (**Figs. 4-5**). Moreover, increasing the recycling advance speed by 50% could advance the net zero timeline by 17-26 years.

Notably, paper and plastics recycling contribute the most significant emission reduction potential, accounting for over 40% of total mitigation (**Supplementary Fig. 10**). However, the recycling rates of these materials in these regions are disappointingly low, at only 17.93%, which is far below the targets set in Europe and the USA (**Supplementary Fig. 15**). This situation likely arises if the petrochemical industry can efficiently and cheaply produce new polymers, rendering virgin materials highly valuable and thus suppressing the market demand for recycled materials[13].

While implementing the extended producer responsibility (EPR) policy, tax reduction measures for recyclables should be promoted to encourage producers to use recyclable materials. Similarly, the EPR system of South Korea resulted in a substantial 32.3% increase in the recycling of MSW[23]. Additionally, it is imperative for relevant government authorities to implement environmental taxes on paper and plastic products and deposit return schemes (DRSs) and impose user fees on consumers to reduce waste[24]. The implementation of DRSs in England, Wales, and Northern Ireland could cut single-use paper cup litter by 85%[25]. Moreover, creating a fair global recycling market is key to maximizing renewable resources. The USA, with over 55% recyclables, could supply recycled materials to resource-scarce regions, such as Africa.

Enhancing incineration (energy recovery) also presents substantial mitigation potential, second only to recycling globally (**Supplementary Fig. 14**). Particularly for India, we recommend the prompt implementation of incineration (energy recovery) with an importance level of 12.7%, which is higher than that of other measures (**Fig. 5**). Given that the initial batch of incineration generators was imported from abroad[26], implementing the build-operate-transfer (BOT) pattern is a good measure that could mitigate the upfront investments by the Indian government while capitalizing on the technological expertise and management experience of foreign companies. Similar strategies may also be employed in Indonesia and Southeast Asia to facilitate the adoption of incineration technology for energy recovery. Furthermore, the significance of incineration (energy recovery) in South Africa has reached 11.6%. In early 2022, South Africa launched its “Development Roadmap” to increase incineration according to the International Energy Agency[27]. However, South Africa's incineration (energy recovery) remains at only 3.71%. The main challenge is inadequate funding, and a reportedly requires a 2.5-fold increase in environmental investment is required[28]. Future government efforts should prioritize economic incentives—such as tax exemptions and international green financing—to accelerate the adoption of waste-to-energy events.

Refining advancements in technology

The mitigation potential of technological upgrades is significant, ranging from -365.2% to -0.1%. In China and Japan, despite varying physical compositions (**Supplementary Figs. 16-17**), relying on enhancing heat and electricity conversion rates is required in most net zero scenarios (**Figs. 4-5**). It is therefore imperative that these governments corresponding conversion measures strictly, as their high feasibility aligns with the development direction outlined in China's "The 14th Five-Year Plan" and Japan's "Sixth Energy Plan". In China, it is advisable to prioritize the separation of food waste from noncombustible waste, which will help ensure an adequate calorific value of the waste and promote efficient energy recovery[29]. The USA Department of Energy reported that combined heat and power (CHP) technology could increase energy efficiency by 85-90%[30]. Therefore, in North China, where heating is essential in winter, CHP could maximize the utilization of heat resources. Nonetheless, it is imperative for the government to preemptively address the “not in my backyard” sentiment among residents[31]. In Japan, the application of advanced technologies to increase the thermoelectric conversion efficiency is recommended. For example, the integration of a supercritical carbon dioxide cycle with an organic Rankine cycle system has the potential to increase overall efficiency by 10.73%[32].

In Türkiye, enhancing the methane capture rate alone would enable target attainment (**Fig. 4**). It is imperative for the government to improve the gas collection system and increase the methane capture rate to 83% by increasing the number of natural gas extraction wells[33]. Furthermore, this study revealed that in Türkiye, over 60% of the MSW is organic waste, which provides abundant potential for compost byproducts. Therefore, covering landfill sites with compost byproducts to reduce methane emissions is suitable for application in Türkiye[34].

Reducing source-based waste generation and emissions

Our findings indicate that emission hotspots have shifted to densely populated regions, such as China (emission contribution: 13.6%) and India (15.4%), accounting for 18.0% (1,416.9 million people) and 17.9%, respectively, of the world's population (**Fig. 1**). Additionally, the global population will continue to increase according to the UN[35]. China and India should therefore implement measures to regulate urban population size in their first-tier cities, through stringent household registration policies, industrial decentralization, and other strategies, guiding the population toward small and medium-sized cities. From a regional perspective, satellite cities in China could markedly reduce emissions by 75% to 82% by 2050[36]. In Shanghai, population diversion could reduce MSW-related emissions by 0.3%[37]. Moreover, from an international standpoint, the United Nations has integrated the multicentered city system into its Sustainable Development Goals, recognizing it as a key strategy for mitigating population density issues, achieving a reduction in MSW and addressing climate change[38].

This study highlights that food waste is the primary contributor to emissions (**Supplementary Fig. 18**), especially in Brazil, Western Africa, India, and Eastern Africa, where smallholder farmers are economically active and food waste is commonly generated during the transportation process[39]. We propose that local governments prioritize promoting the entry of clean vegetables into cities while improving cold chain technology to decrease the amount of food waste generated during fruit and vegetable transportation. To improve emission reduction potential, cooperation across sectors and regions, which could yield significantly greater results with less effort, is essential.

Methods

Data collection

We compiled data on the generation, physical components, treatment measures, and collection rates of MSW and national socioeconomic indicators, including population, economy and urbanization, from 195 countries between 1980 and 2022, as well as emission factors for different components and treatments, via a review of the literature. Furthermore, the data presented in this study and the results from the literature exhibit reasonable differences. Comprehensive comparative data and detailed source information is provided (**Supplementary Tables 5-8**). These rigorous comparative analyses provide a robust scientific foundation for the MSW management net zero strategy drawn as follows, thereby ensuring its scientific validity and rationality.

Owing to the extensive scale of the data and the lengthy time series, MSW generation and physical component data in certain countries appear to be missing. To address this issue, we employed the Hausmann, LM, and F tests to select a fixed effects model to input the missing MSW generation data while utilizing a random effects model to estimate the missing data related to food, paper, and plastic; the remaining components were then allocated on the basis of their fixed relative proportions. The results of these tests, along with their interceptions, are presented in detail (**Supplementary Tables 9-11**). MSW generation is calculated through the following equation:

$$lnY_{c,t} = \alpha lnX_{c,t} + \beta lnZ_{c,t} + \varepsilon + d_c + d_t \quad (1)$$

where Y represents per capita generation of MSW, with c denoting the country and t denoting the year; X represents per the capita gross domestic product (GDP); Z represents the urbanization rate; α and β are coefficients; and ε represents error. The term d_c indicates interceptions for different countries, and the term d_t represents interceptions for different years. The MSW physical components are calculated through the following equation:

$$lnC_{i,c,t} = \alpha lnX_{i,c,t} + \beta lnZ_{i,c,t} + \varepsilon \quad (2)$$

where C represents the per capita generation of the MSW component i, which refers to one of three components: food, paper, or plastic.

For instances of missing data regarding the TS and collection rates of certain countries in specific years, we supplemented this information with data from the most recent year available. According to the statistical data, there are nine countries for which relevant information is unavailable. Therefore, it was replaced with the average data from the respective continents to which these countries belong. For further details, please refer to **Section 2** of the Supplementary Information.

Estimation of MSW-related GHG emissions

Generally, MSW management can be divided into two categories: collected treatment and uncollected treatment. Collected treatment includes landfilling, incineration, composting, and recycling, whereas uncollected treatment includes open burning or open dumping. We calculated the emissions for each of the eight treatments individually using the carbon equivalents of CO_2, CH_4, and N_2O due to their significant global warming potentials. The main scope of the emission and mitigation opportunities for each treatment measure are shown in **Supplementary Fig. 19**. The full GHG accounting equations for each type of treatment measure followed IPCC guidelines and are provided in **Section 3** of Supplementary Information. The emission factor, thermoelectric conversion efficiency, and biogas power generation rate were compiled from published literature, while the remaining parameters were obtained from the IPCC. The appropriate treatment methods for each component were derived from the parameters used in the Greenhouse Gas and Air Pollution Interactions and Synergies (GAINS) model (**Supplementary Table 12)**.

Driving force analysis

An in-depth analysis of three aspects of MSW-related GHG emissions, source generation, TS, and technological upgrades, was carried out in this study. Thus, the Kaya identity can be further extended by decomposing the internal drivers of emissions into MSW treatment, TS, EI, and GI. The logarithmic mean Divisia index (LMDI) model, which is derived from the incremental dynamic analysis model, is the most widely utilized method for decomposition analysis aimed at elucidating the relationships among emissions resulting from various influencing factors[40]. The LMDI approach is employed to dissect the drivers of emissions originating from MSW treatment in accordance with the Kaya identity.

First, we employ the Kaya identity to analyze the drivers of emissions:

$$G = \sum_i G_I = \sum_i \frac{G_I}{M_i} \times \frac{M_i}{M} \times M \quad (3)$$

$$\Delta G = \Delta G_t - \Delta G_O = \Delta G_{EI} + \Delta G_{TS} + \Delta G_{GI} \quad (4)$$

Second, we employ the LMDI model to analyze and decompose the underlying driving factors:

$$\Delta G_X = \sum_i \frac{G_{i,t}-G_{i,O}}{lnG_{i,t}-lnG_{i,O}} \times ln\frac{X_{i,t}}{X_{i,O}} \tag{5}$$

where G denotes the emissions from MSW treatment, M denotes MSW generation, X denotes the three decomposition factors, i denotes the treatment measure i, and t and O denote the selected year and base year, respectively.

In addition, we investigated a secondary index based on three divisors. We decomposed the GI into four physical components, namely, food waste, paper, plastic, and others, because these are the primary components. Furthermore, we decomposed the EI and TS into eight treatment measures: unsanitary landfills, sanitary landfills, incineration (energy recovery), traditional incineration, composting, recycling, open burning, and open dumping. The emission structure was further analyzed using these secondary divisors.

Scenario setting

To limit global climate warming to 1.5°C, we aggregate the net zero time for 31 regions, ranging from 2050 to 2100, according to the IMAGE model and the MESSAGE-GlOBIOM model of the CMIP6 scenario simulations[41](**Supplementary Fig. 20**). Additionally, we follow the SSPs2 development pathway, which is most likely to occur given current energy policies and investment options, as outlined by the International Energy Agency[42].

We established ten scenarios on the basis of the identified secondary indicators: (1) halving food waste generation (S11), (2) halving paper generation (S12), (3) halving plastic generation (S13), and (4) halving the generation of other waste (S14), representing source reduction from various physical components. Additionally, four scenarios were designed to address TSs: (5) increasing the MSW collection rate (S21), (6) implementing organic waste composting (S22), (7) promoting incineration for electricity generation (S23), and (8) increasing the recycling of nonorganic waste (S24). Furthermore, two scenarios were formulated to improve EI through technological upgrades: (9) increasing the methane capture efficiency of landfills (S31), and (10) enhancing the conversion efficiency of electric heating in both incineration (energy recovery) and sanitary landfills (S32), in **Supplementary Table 13**. We hypothesized that the implementation of improvement measures in each scenario would progress linearly from 2023. Notably, each given measure would be fully implemented by the net zero achievement time, as predicted by the CMIP6 model, with the average annual growth rate calculated via Equation (6):

$$R = \frac{T_{2022} - T_N}{Y_N - Y_{2022}} \tag{6}$$

where R denotes the growth rate of the treatment measure, T_{2022} denotes the current treatment measure, T_N denotes the proportion of the treatment measure needed to reach carbon neutrality at the end of the century, and Y_N denotes the time for reaching carbon neutrality at the end of the century. In addition, this study integrated individual measures through various arrangements and combinations, resulting in a total of 1,024 combined measures. There are a total of 15,059 scenarios illustrating how net zero targets can be achieved across different regions. The specific data are presented in Supplementary Data.

Uncertainty analysis and sensitivity analysis

We apply the Monte Carlo analysis method to test the uncertainty and sensitivity. The sampling number for the uncertainty evaluation is 10,000. The number of sensitivity coefficient is 93,600 (3*195*10*16 = 93,600) based on scenario setting, where 3 represents the efficiency of measures: aggressive, stable, and conservative; 195 represents the nation and/or region global; 10 represents carbon reduction measures; 16 represents years. The number of the best scenario combinations is 394 (2*195+1+3 = 394), where 2 represents the earliest net zero time and the worst measure combination, respectively; the representative of 195 as explained above; 1 represents another earliest measure in Brazil; and 3 represents the other three best combinations of measures in Asia.

Reporting summary

Further information on research design is available in the Nature Portfolio Reporting Summary linked to this article.

Data availability

The data underpinning the findings of this study were primarily sourced from the official statistical agencies of respective countries (specific URLs are provided in the Supplementary Information). Municipal solid waste (MSW)-related data for all countries were retrieved from two authoritative repositories: the World Bank database (https://data.worldbank.org.cn/) and United Nations Environment Programme database (https://unstats.un.org/unsd/envstats/), For European nations, MSW data were obtained from Eurostat (https://ec.europa.eu/eurostat/en/), while Organisation for Economic Co-operation and Development (OECD) member states' MSW data were drawn from the OECD Data Explorer (https://data-explorer.oecd.org/). Future socioeconomic trajectories were informed by the Shared Socioeconomic Pathways (SSPs) database (https://tntcat.iiasa.ac.at/SspDb/dsd?Action=htmlpage&page=about), emission factors for processing activities were derived from the European Life Cycle Database (ELCD) (https://eplca.jrc.ec.europa.eu/globalLCA.html), 2006 IPCC Guidelines for National Greenhouse Gas Inventories (https://www.ipcc-nggip.iges.or.jp/public/2006gl/chinese/index.html) and Carbon Footprint (https://www.carbonfootprint.com/international_electricity_factors.html). The base map is sourced from Resource and Environmental Science Data Platform (ref.[43], https://www.resdc.cn/). All data sources can be found in the Supplementary Information. The source data of all figures in the main manuscript are provided as source data Figs.1-5. For data processing, we employed R 2.1.0, Stata 18.5, and open LCA 2.5.0. Visualization and figure preparation were carried out using Origin 2021, ArcMap 10.8, Microsoft PowerPoint 2021, Adobe Photoshop CS5, and Adobe Illustrator 2024.

Code availability

The computational code for MSW generation projecting, physical component modeling, model testing, and figures generation that is provided in the Supplementary Code. For technical inquiries, please contact the corresponding author.

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Author contributions

B.G. and M.Z. contributed equally to this work, including methodology, formal analysis, writing (review and editing), visualization, formal analysis and funding acquisition. B.G., M.Z., M.Zh., H.F., Q.H., C.G., Y.W., T.F., L.L., W.Z., Y.L., Z.W., and W.J. were involved in methodology, formal analysis, writing (review and editing), and formal analysis. B.G., M.Z., and Y.B. led the drafting of the manuscript. All authors contributed significantly to the final writing of the manuscript.

Competing interests

No conflict of interest (financial/personal interest or belief that could affect author's objectivity) exists in the manuscript. I would like to declare on behalf of my co-authors that the work described is original research, and neither the entire paper nor any part of its content has been published or has been accepted elsewhere. It is not being submitted to any other journal. All authors have agreed to the submission.

Figure Legends

Fig. 1 MSW-related GHG emissions worldwide and by individual countries from 1980 to 2022.

a1-a4: National total and per capita emissions in 1980, 1995, 2010, and 2022. b: National cumulative contribution to emissions from 1980 to 2022, highlighting the top five countries and regions with contribution rates exceeding 3%; the black label on the lower left indicates the region where the country is located. The 31 regions were classified according to the IMAGE model and the MESSAGE-GlOBIOM model of the Coupled Model Intercomparison Project Phase 6 (CMIP6) scenario. Refer to **Supplementary Tables 1-2** and **Supplementary Fig. 5** for further details.

Fig. 2 Regional trends, sources and structures of emissions from 1980 to 2022.

The eight color schemes indicate eight treatment measures, and the four-color schemes denote the four physical components of MSW. Components that are not food, paper, and plastic waste are minor and are categorized as "others". The specific details are provided in **Section 2.2** of Supplementary Information.

Fig. 3 Effects of treatment structure on emissions across the 31 regions.

The contributions of GI, TS, and EI to emissions at the regional level at ten-year intervals from 1980-2022, except for the last period, which lasts from 2010-2022.

Fig. 4 Mitigation potential of different measures implemented regionally.

a: Variations in the implementation of diverse measures across different regions. b: Different colors represent the division of regional groups, and the yellow circles indicate a singular measure capable of attaining net zero.

Fig. 5 Analysis of strategies for achieving net zero emissions in 31 regions.

a: The first column provides the name of each region, whereas the second column provides the net zero achievement timeline under the 1.5°C pathway as projected by the CMIP6 model. The third to sixth and seventh to tenth columns provide the earliest achievable net zero achievement time, the combination of measures employed, the contribution to mitigation and an assessment of the difficulty associated with achieving this target under the simplified local scenario and at the earliest net zero achievement time, respectively. Notably, "*" and different colors denote the degree of difficulty. The degree of difficulty was determined on the basis of the number of measures implemented and the number of combined treatment systems in **Supplementary Table 4**. b-e: Importance of the top 5 measures in each region of the four groups. A sensitivity analysis was performed by adjusting the advance speed of 10 measures by ±50% to assess the emission. Net zero timing variations (added in Columns 3 and 7) reveal that “2100+” denotes scenarios that would preclude net zero attainment this century.

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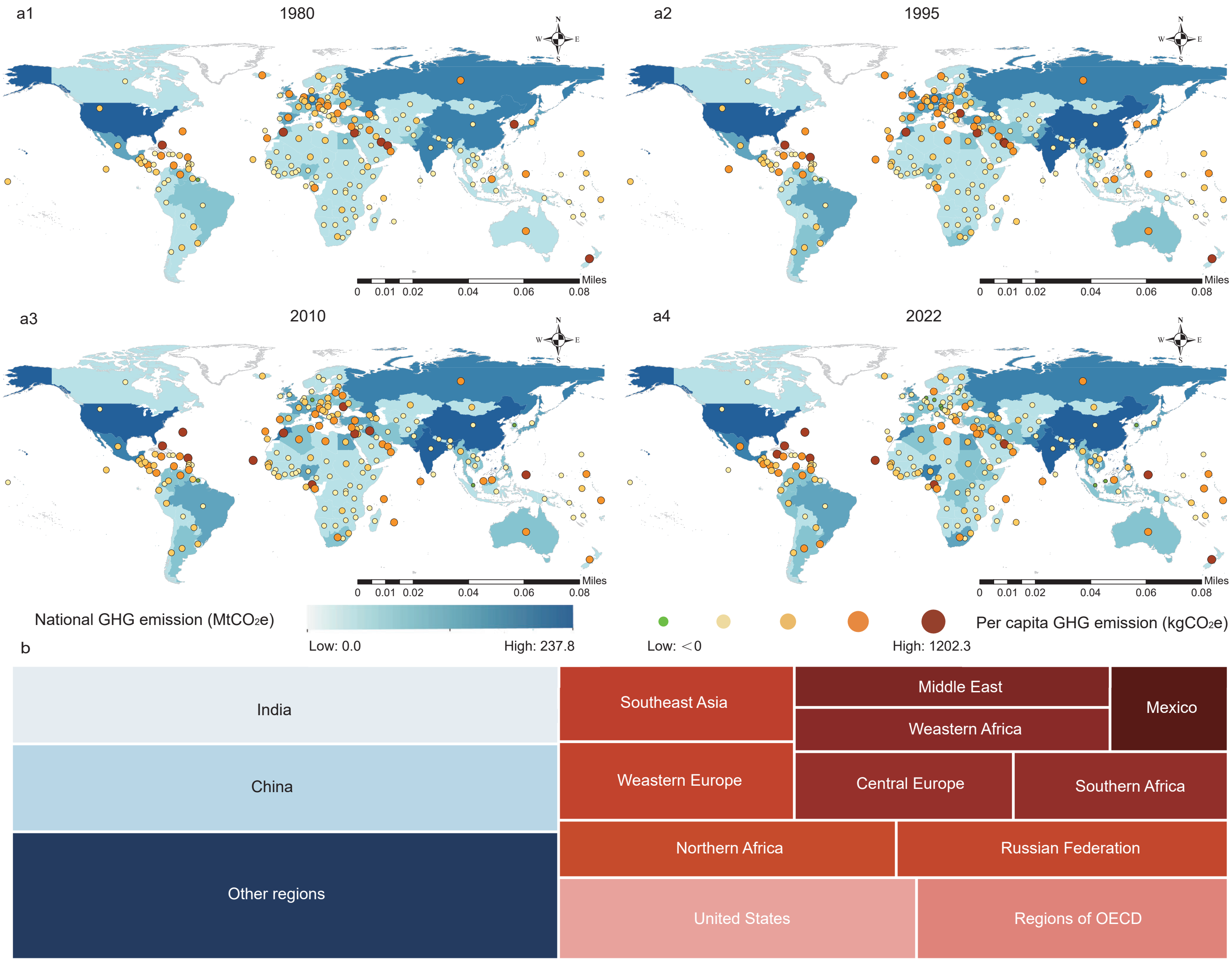
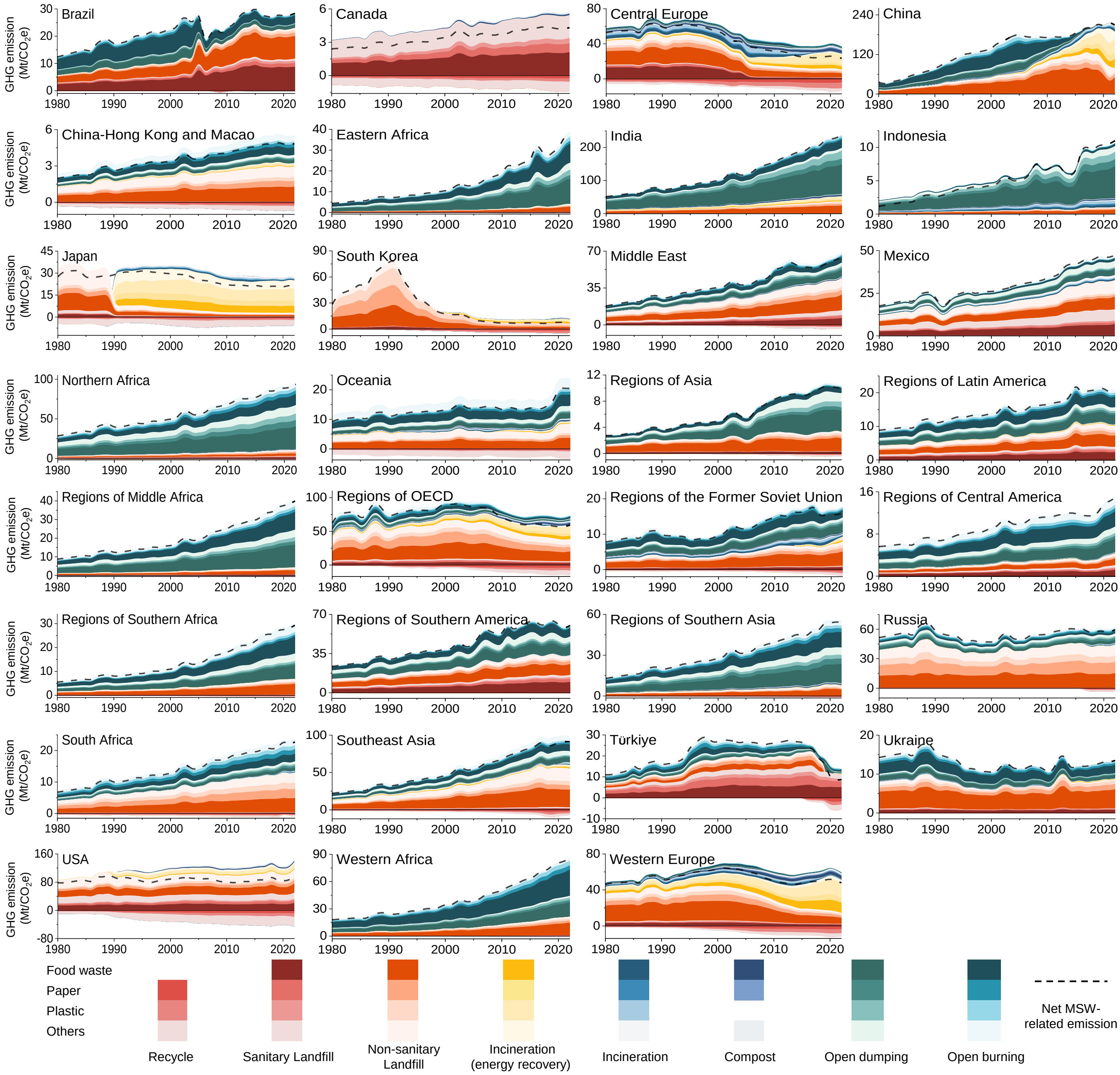
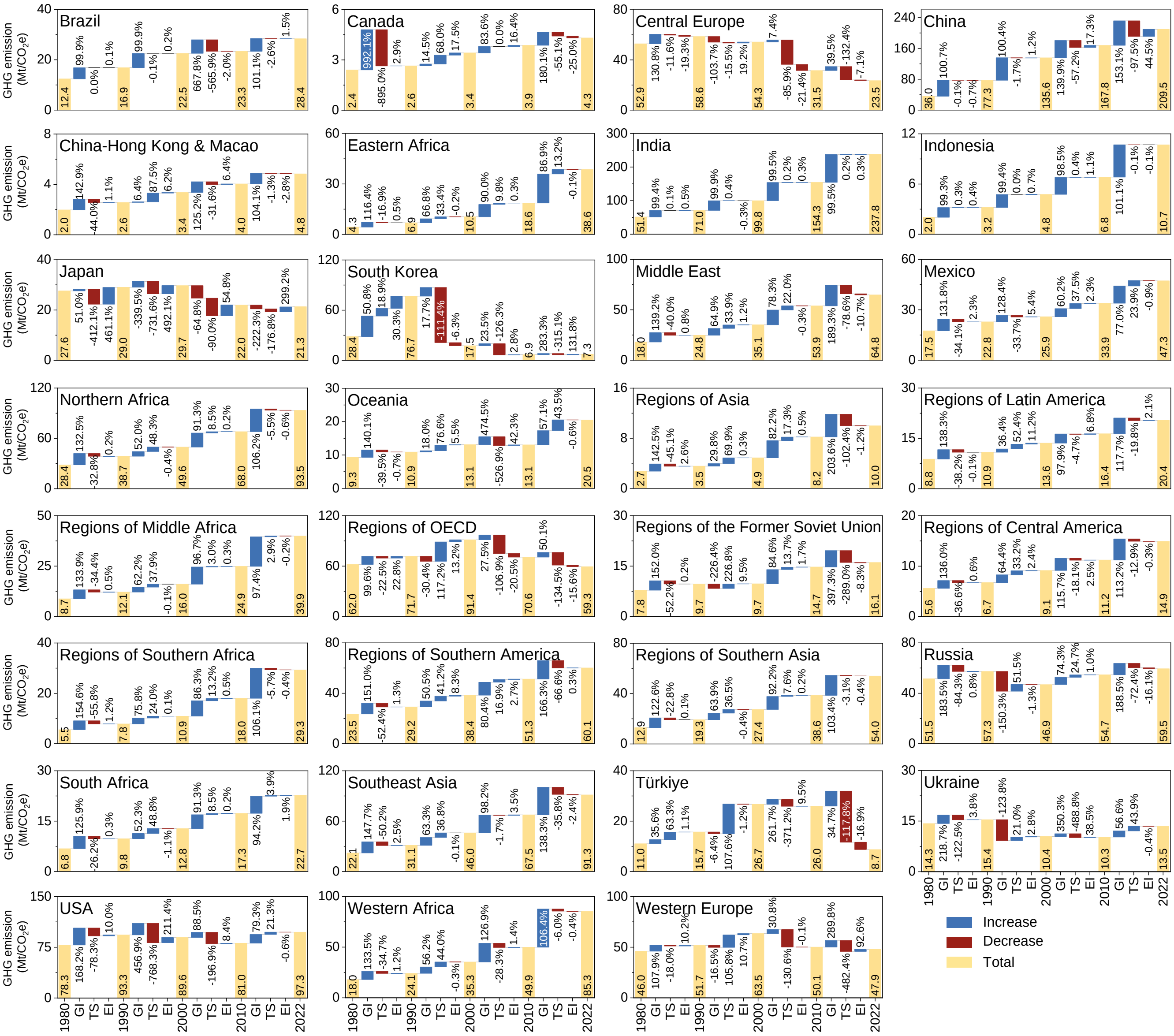


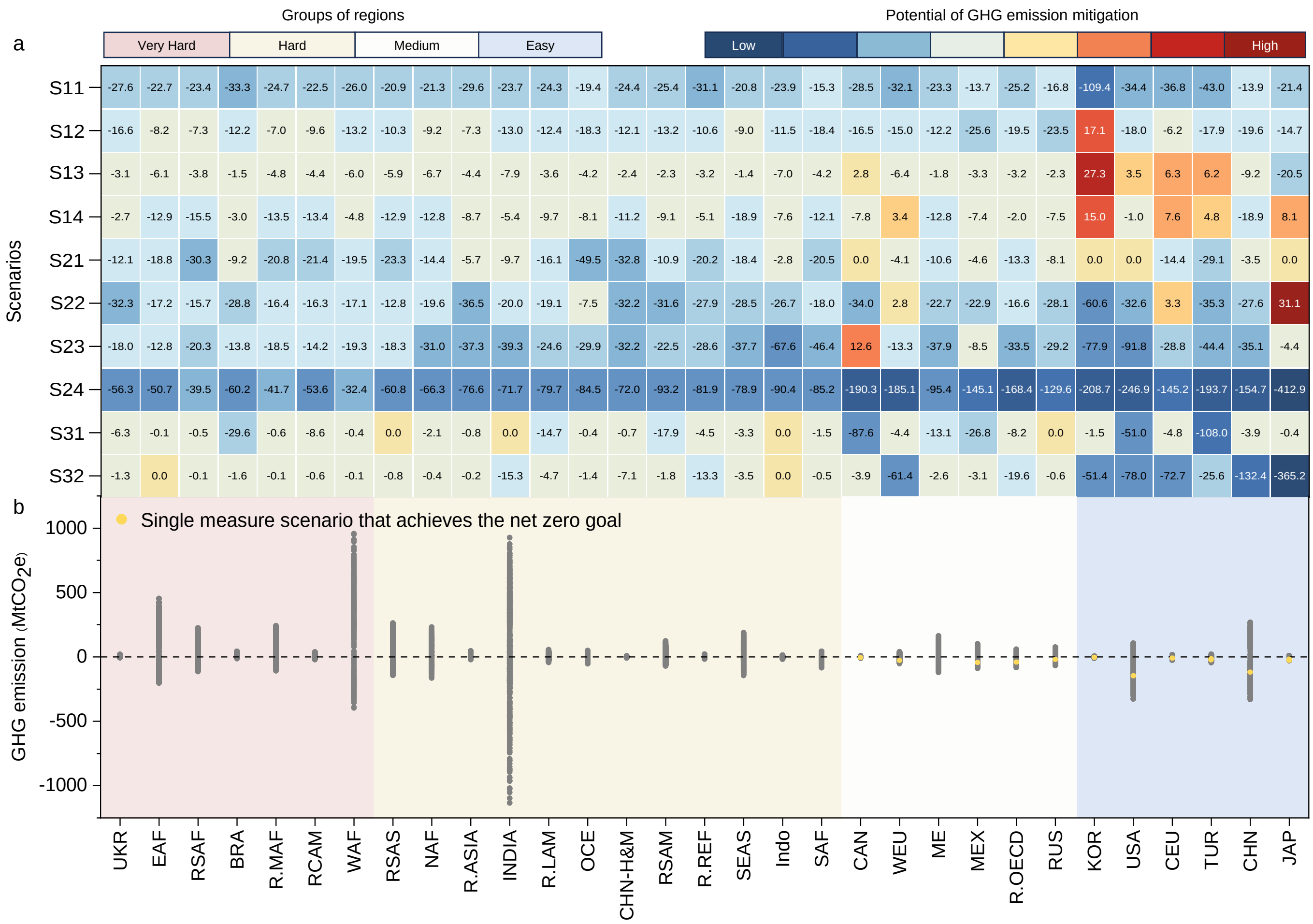
a1
1980
a2
1995
a3
2010
a4
2022
Miles
0 0.01 0.02 0.04 0.06 0.08
National GHG emission (MtCO2e)
Low: 0.0
High: 237.8
Low: <0
High: 1202.3
Per capita GHG emission (kgCO2e)
b
India
China
Other regions
Southeast Asia
Middle East
Weastern Africa
Mexico
Weastern Europe
Central Europe
Southern Africa
Northern Africa
Russian Federation
United States
Regions of OECD



Brazil
Canada
Central Europe
China
China-Hong Kong and Macao
Eastern Africa
India
Indonesia
Japan
South Korea
Middle East
Mexico
Northern Africa
Oceania
Regions of Asia
Regions of Latin America
Regions of Middle Africa
Regions of OECD
Regions of the Former Soviet Union
Regions of Central America
Regions of Southern Africa
Regions of Southern America
Regions of Southern Asia
Russia
South Africa
Southeast Asia
Türkiye
Ukraine
USA
Western Africa
Western Europe
GHG emission (Mt/CO_2e)
Food waste
Paper
Plastic
Others
Recycle
Sanitary Landfill
Non-sanitary Landfill
Incineration (energy recovery)
Incineration
Compost
Open dumping
Open burning
Net MSW-related emission



GHG emission (Mt/CO2e)
Brazil
Canada
Central Europe
China
China-Hong Kong & Macao
Eastern Africa
India
Indonesia
Japan
South Korea
Middle East
Mexico
Northern Africa
Oceania
Regions of Asia
Regions of Latin America
Regions of Middle Africa
Regions of OECD
Regions of the Former Soviet Union
Regions of Central America
Regions of Southern Africa
Regions of Southern America
Regions of Southern Asia
Russia
South Africa
Southeast Asia
Türkiye
Ukraine
USA
Western Africa
Western Europe
1980
GI
TS
EI
1990
2000
2010
2022
Increase
Decrease
Total



Scenario	UKR	EAF	RSAF	BRA	R.MAF	RCAM	WAF	RSAS	NAF	R.ASIA	INDIA	R.LAM	OCE	CHN-H&M	RSAM	R.REF
S11	-27.6	-22.7	-23.4	-33.3	-24.7	-22.5	-26.0	-20.9	-21.3	-29.6	-23.7	-24.3	-19.4	-24.4	-25.4	-31.1
S12	-16.6	-8.2	-7.3	-12.2	-7.0	-9.6	-13.2	-10.3	-9.2	-7.3	-13.0	-12.4	-18.3	-12.1	-13.2	-10.6
S13	-3.1	-6.1	-3.8	-1.5	-4.8	-4.4	-6.0	-5.9	-6.7	-4.4	-7.9	-3.6	-4.2	-2.4	-2.3	-3.2
S14	-2.7	-12.9	-15.5	-3.0	-13.5	-13.4	-4.8	-12.9	-12.8	-8.7	-5.4	-9.7	-8.1	-11.2	-9.1	-5.1
S21	-12.1	-18.8	-30.3	-9.2	-20.8	-21.4	-19.5	-23.3	-14.4	-5.7	-9.7	-16.1	-49.5	-32.8	-10.9	-20.2
S22	-32.3	-17.2	-15.7	-28.8	-16.4	-16.3	-17.1	-12.8	-19.6	-36.5	-20.0	-19.1	-7.5	-32.2	-31.6	-27.9
S23	-18.0	-12.8	-20.3	-13.8	-18.5	-14.2	-19.3	-18.3	-31.0	-37.3	-39.3	-24.6	-29.9	-32.2	-22.5	-28.6
S24	-56.3	-50.7	-39.5	-60.2	-41.7	-53.6	-32.4	-60.8	-66.3	-76.6	-71.7	-79.7	-84.5	-72.0	-93.2	-81.9
S31	-6.3	-0.1	-0.5	-29.6	-0.6	-8.6	-0.4	0.0	-2.1	-0.8	0.0	-14.7	-0.4	-0.7	-17.9	-4.5
S32	-1.3	0.0	-0.1	-1.6	-0.1	-0.6	-0.1	-0.8	-0.4	-0.2	-15.3	-4.7	-1.4	-7.1	-1.8	-13.3

Scenario	SEAS	Indo	SAF	CAN	WEU	ME	MEX	R.OECD	RUS	KOR	USA	CEU	TUR	CHN	JAP
S11	-20.8	-23.9	-15.3	-28.5	-32.1	-23.3	-13.7	-25.2	-16.8	-109.4	-34.4	-36.8	-43.0	-13.9	-21.4
S12	-9.0	-11.5	-18.4	-16.5	-15.0	-12.2	-25.6	-19.5	-23.5	17.1	-18.0	-6.2	-17.9	-19.6	-14.7
S13	-1.4	-7.0	-4.2	2.8	-6.4	-1.8	-3.3	-3.2	-2.3	27.3	3.5	6.3	6.2	-9.2	-20.5
S14	-18.9	-7.6	-12.1	-7.8	3.4	-12.8	-7.4	-2.0	-7.5	15.0	-1.0	7.6	4.8	-18.9	8.1
S21	-18.4	-2.8	-20.5	0.0	-4.1	-10.6	-4.6	-13.3	-8.1	0.0	0.0	-14.4	-29.1	-3.5	0.0
S22	-28.5	-26.7	-18.0	-34.0	2.8	-22.7	-22.9	-16.6	-28.1	-60.6	-32.6	3.3	-35.3	-27.6	31.1
S23	-37.7	-67.6	-46.4	12.6	-13.3	-37.9	-8.5	-33.5	-29.2	-77.9	-91.8	-28.8	-44.4	-35.1	-4.4
S24	-78.9	-90.4	-85.2	-190.3	-185.1	-95.4	-145.1	-168.4	-129.6	-208.7	-246.9	-145.2	-193.7	-154.7	-412.9
S31	-3.3	0.0	-1.5	-87.6	-4.4	-13.1	-26.8	-8.2	0.0	-1.5	-51.0	-4.8	-108.0	-3.9	-0.4
S32	-3.5	0.0	-0.5	-3.9	-61.4	-2.6	-3.1	-19.6	-0.6	-51.4	-78.0	-72.7	-25.6	-132.4	-365.2

S11: halve food waste S12: halve paper waste S13: halve plastic waste S14: halve the generation of other waste S21: increase MSW collection rate
S22: implement organic waste composting S23: promote incineration for electricity generation S24: enhance material recycling of non-organic waste
S31: increase the methane capture efficiency of landfills S32: enhance the conversion efficiency of electric heating in resource incineration and landfills

Groups of regions			
Very Hard	Hard	Medium	Easy

Contribution rate (%)			
16.3 - 20.5	8.6 -16.4	3.6 – 8.5	0- 3.7

Degree of difficulty			
Very Hard	Hard	Medium	Easy

Regions	Net-zero time in 1.5 ℃ path of CMIP6	Achieve net zero with the simplest scenario				Achieve net zero with the earliest time			
		The earliest net-zero time with the simplest scenarios	Simplest scenarios	Contribution of mitigation	The difficulty of achieving scenarios	The earliest net-zero time of all scenarios	The simplest scenarios used in the earliest net-zero time	Contribution of mitigation	The difficu of achievi scenario
Ukraine	2050	2046 (2035 - 2058)	S21+S22+S24	0.7%	**	2042 (2038 - 2049)	S11+S21+S22+S23+S24+S31+S32	0.8%	****
Eastern Africa	2100	2096 (2075-2100+)	S21+S24	4.5%	**	2078 (2042-2100+)	S11+S21+S22+S23+S24+S32	6.8%	****
Regions of Southern Africa	2090	2086 (2066-2100+)	S21+S24	3.2%	**	2069 (2054 - 2087)	S11+S21+S22+S23+S24+S32	4.6%	****
Brazil	2090	2086 (2067-2100+) 2086 (2083-2100+)	S21+S22+S24 S21+S23+S24	0.8%	**	2074 (2051 - 2094)	S11+S21+S23+S24+S31+S32	1.0%	****
Regions of Middle Africa	2080	2079 (2067-2100+)	S21+S24	4.5%	**	2063 (2050 - 2079)	S11+S21+S22+S23+S24+S32	6.5%	****
Regions of Central America	2070	2066 (2051 - 2095)	S21+S24	0.6%	**	2054 (2033 - 2068)	S11+S21+S22+S23+S24+S32	1.3%	****
Western Africa	2090	2081 (2057-2100+)	S21+S22+S24	14.1%	**	2072 (2066 - 2095)	S11+S21+S22+S23+S24+S32	16.3%	****
Regions of Southern Asia	2090	2074 (2048-2100+)	S21+S23+S24	5.4%	**	2067 (2054 - 2085)	S11+S12+S21+S23+S24+S32	6.0%	****
Northern Africa	2080	2077 (2059-2100+)	S21+S24	4.7%	**	2057 (2039 - 2071)	S11+S21+S22+S23+S24+S31+S32	6.9%	****
Regions of Asia	2070	2066 (2061 - 2090) 2066 (2061 - 2082)	S22+S24 S23+S24	1.1% 1.4%	**	2051 (2035 - 2058)	S11+S21+S23+S24+S32	1.7%	****
India	2100	2079 (2057 - 2089)	S23+S32	20.5%	***	2066 (2063 - 2079)	S11+S21+S23+S24+S32	19.2%	****
Regions of Latin America	2080	2072 (2055-2100+)	S21+S24	1.2%	**	2053 (2033 - 2063)	S11+S21+S22+S23+S24+S31+S32	1.8%	****
Oceania	2080	2060 (2045 - 2083)	S21+S24	1.5%	**	2049 (2033 - 2061)	S11+S12+S21+S23+S24+S32	1.8%	****
Hong Kong and Macao of China	2060	2053 (2041 - 2075)	S21+S24	0.2%	**	2041 (2030 - 2048)	S11+S21+S22+S23+S24+S32	0.3%	****
Regions of Southern America	2080	2070 (2055-2100+)	S22+S24	3.0%	**	2054 (2048 - 2072)	S11+S12+S21+S22+S23+S24+S31+S32	3.9%	****
Regions of Former Soviet Union	2050	2047 (2040 - 2063)	S21+S24	0.7%	**	2037 (2028 - 2043)	S11+S21+S22+S23+S24+S32	1.0%	****
Southeast Asia	2070	2065 (2051 - 2096)	S21+S24	5.0%	**	2048 (2041 - 2059)	S11+S21+S22+S23+S24+S32	7.3%	****
Indonesia	2070	2052 (2040 - 2058)	S23+S32	0.6%	***	2046 (2032 - 2053)	S11+S21+S23+S24+S32	0.4%	****
South Africa	2090	2070 (2050 - 2082)	S23+S32	1.1%	***	2053 (2043 - 2067)	S11+S12+S21+S23+S24+S32	1.4%	****
Canada	2050	2038 (2033 - 2049)	S24	0.3%	*	2032 (2031 - 2036)	S11+S24+S31	0.5%	***
Western Europe	2060	2046 (2039 - 2064)	S24	1.7%	*	2038 (2028 - 2048)	S11+S21+S23+S24+S32	2.2%	****
Middle East	2070	2062 (2044 - 2068)	S23+S24	4.7%	**	2047 (2033 - 2055)	S11+S21+S23+S24+S31+S32	6.8%	****
Mexico	2090	2071 (2056-2100+)	S24	2.4%	*	2056 (2050 - 2070)	S11+S21+S23+S24+S32	3.2%	****
Regions of OECD	2060	2046 (2039 - 2065)	S24	2.5%	*	2037 (2027 - 2043)	S11+S21+S23+S24+S32	3.6%	****
Russian	2050	2045 (2038 - 2062)	S24	2.8%	*	2035 (2033 - 2039)	S11+S21+S22+S23+S24+S32	4.1%	****
South Korea	2060	2045 (2039 - 2058)	S24	0.2%	*	2034 (2028 - 2038)	S11+S22+S23+S24	0.3%	***
United States	2060	2038 (2034 - 2051)	S24	6.9%	*	2031 (2027 - 2033)	S23+S24+S31+S32	11.9%	***
Central Europe	2070	2044 (2038 - 2059)	S24	0.9%	*	2034 (2030 - 2037)	S11+S21+S22+S23+S24+S32	1.4%	****
Türkiye	2060	2050 (2041 - 2071)	S24	0.8%	*	2037 (2031 - 2043)	S21+S23+S24+S31+S32	1.5%	***
China	2060	2048 (2042 - 2068)	S24	8.6%	*	2034 (2026 - 2045)	S11+S22+S23+S24+S32	11.0%	****
Japan	2050	2029 (2028 - 2032)	S24	0.7%	*	2025 (2024 - 2025)	S11+S24+S32	0.8%	***

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Groups of regions: Very Hard | Hard | Medium | Easy

Contribution rate (%): 16.3 - 20.5 | 8.6 -16.4 | 3.6 – 8.5 | 0- 3.7

Degree of difficulty: Very Hard | Hard | Medium | Easy

Regions	Net-zero time in 1.5 ℃ path of CMIP6	Achieve net zero with the simplest scenario: The earliest net-zero time with the simplest scenarios	Simplest scenarios	Contribution of mitigation	The difficulty of achieving scenarios	Achieve net zero with the earliest time: The earliest net-zero time of all scenarios	The simplest scenarios used in the earliest net-zero time	Contribution of mitigation	The difficulty of achieving scenarios
Ukraine	2050	2046 (2035 - 2058)	S21+S22+S24	0.7%	**	2042 (2038 - 2049)	S11+S21+S22+S23+S24+S31+S32	0.8%	****
Eastern Africa	2100	2096 (2075-2100+)	S21+S24	4.5%	**	2078 (2042-2100+)	S11+S21+S22+S23+S24+S32	6.8%	****
Regions of Southern Africa	2090	2086 (2066-2100+)	S21+S24	3.2%	**	2069 (2054 - 2087)	S11+S21+S22+S23+S24+S32	4.6%	****
Brazil	2090	2086 (2067-2100+) 2086 (2083-2100+)	S21+S22+S24 S21+S23+S24	0.8%	**	2074 (2051 - 2094)	S11+S21+S23+S24+S31+S32	1.0%	****
Regions of Middle Africa	2080	2079 (2067-2100+)	S21+S24	4.5%	**	2063 (2050 - 2079)	S11+S21+S22+S23+S24+S32	6.5%	****
Regions of Central America	2070	2066 (2051 - 2095)	S21+S24	0.6%	**	2054 (2033 - 2068)	S11+S21+S22+S23+S24+S32	1.3%	****
Western Africa	2090	2081 (2057-2100+)	S21+S22+S24	14.1%	**	2072 (2066 - 2095)	S11+S21+S22+S23+S24+S32	16.3%	****
Regions of Southern Asia	2090	2074 (2048-2100+)	S21+S23+S24	5.4%	**	2067 (2054 - 2085)	S11+S12+S21+S23+S24+S32	6.0%	****
Northern Africa	2080	2077 (2059-2100+)	S21+S24	4.7%	**	2057 (2039 - 2071)	S11+S21+S22+S23+S24+S31+S32	6.9%	****
Regions of Asia	2070	2066 (2061 - 2090) 2066 (2061 - 2082)	S22+S24 S23+S24	1.1% 1.4%	**	2051 (2035 - 2058)	S11+S21+S23+S24+S32	1.7%	****
India	2100	2079 (2057 - 2089)	S23+S32	20.5%	***	2066 (2063 - 2079)	S11+S21+S23+S24+S32	19.2%	****
Regions of Latin America	2080	2072 (2055-2100+)	S21+S24	1.2%	**	2053 (2033 - 2063)	S11+S21+S22+S23+S24+S31+S32	1.8%	****
Oceania	2080	2060 (2045 - 2083)	S21+S24	1.5%	**	2049 (2033 - 2061)	S11+S12+S21+S23+S24+S32	1.8%	****
Hong Kong and Macao of China	2060	2053 (2041 - 2075)	S21+S24	0.2%	**	2041 (2030 - 2048)	S11+S21+S22+S23+S24+S32	0.3%	****
Regions of Southern America	2080	2070 (2055-2100+)	S22+S24	3.0%	**	2054 (2048 - 2072)	S11+S12+S21+S22+S23+S24+S31+S32	3.9%	****
Regions of Former Soviet Union	2050	2047 (2040 - 2063)	S21+S24	0.7%	**	2037 (2028 - 2043)	S11+S21+S22+S23+S24+S32	1.0%	****
Southeast Asia	2070	2065 (2051 - 2096)	S21+S24	5.0%	**	2048 (2041 - 2059)	S11+S21+S22+S23+S24+S32	7.3%	****
Indonesia	2070	2052 (2040 - 2058)	S23+S32	0.6%	***	2046 (2032 - 2053)	S11+S21+S23+S24+S32	0.4%	****
South Africa	2090	2070 (2050 - 2082)	S23+S32	1.1%	***	2053 (2043 - 2067)	S11+S12+S21+S23+S24+S32	1.4%	****
Canada	2050	2038 (2033 - 2049)	S24	0.3%	*	2032 (2031 - 2036)	S11+S24+S31	0.5%	***
Western Europe	2060	2046 (2039 - 2064)	S24	1.7%	*	2038 (2028 - 2048)	S11+S21+S23+S24+S32	2.2%	****
Middle East	2070	2062 (2044 - 2068)	S23+S24	4.7%	**	2047 (2033 - 2055)	S11+S21+S23+S24+S31+S32	6.8%	****
Mexico	2090	2071 (2056-2100+)	S24	2.4%	*	2056 (2050 - 2070)	S11+S21+S23+S24+S32	3.2%	****
Regions of OECD	2060	2046 (2039 - 2065)	S24	2.5%	*	2037 (2027 - 2043)	S11+S21+S23+S24+S32	3.6%	****
Russian	2050	2045 (2038 - 2062)	S24	2.8%	*	2035 (2033 - 2039)	S11+S21+S22+S23+S24+S32	4.1%	****
South Korea	2060	2045 (2039 - 2058)	S24	0.2%	*	2034 (2028 - 2038)	S11+S22+S23+S24	0.3%	***
United States	2060	2038 (2034 - 2051)	S24	6.9%	*	2031 (2027 - 2033)	S23+S24+S31+S32	11.9%	***
Central Europe	2070	2044 (2038 - 2059)	S24	0.9%	*	2034 (2030 - 2037)	S11+S21+S22+S23+S24+S32	1.4%	****
Türkiye	2060	2050 (2041 - 2071)	S24	0.8%	*	2037 (2031 - 2043)	S21+S23+S24+S31+S32	1.5%	***
China	2060	2048 (2042 - 2068)	S24	8.6%	*	2034 (2026 - 2045)	S11+S22+S23+S24+S32	11.0%	****
Japan	2050	2029 (2028 - 2032)	S24	0.7%	*	2025 (2024 - 2025)	S11+S24+S32	0.8%	***