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Emission pathways and mitigation options for achieving consumption-based climate targets in Sweden

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National emission reduction targets under the Paris Agreement have a territorial focus, incentivizing mitigation actions domestically. Here we examine the theoretical basis for adopting complementary consumption-based net-zero emission targets and assess the consequences of adopting such proposed targets for Sweden. We apply scenario analyses based on a prospective lifecycle assessment framework. The framework is a hybrid of bottom-up simulations for passenger travel, construction and housing, and food, and top-down analyses for remaining consumption. In this work, we show how consumption-based climate targets may accentuate the need for new demand-side climate policies that contribute to reducing emissions along supply chains of products and services. Our scenario analysis suggests that combining advanced mitigation technologies with behavioral changes could reduce emissions from 9.8 tons of carbon dioxide equivalents per capita in 2019 to between 2.7 and 4.8 tons by 2045 for Swedish residents, depending on global decarbonization pathways.

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Climate policies tend to focus on measures that affect territorial greenhouse gas (GHG) emissions—i.e., the accounting framework established by the United Nations Framework Convention on Climate Change (UNFCCC)[1]. The influence of these policies on emissions abroad is therefore often overlooked[2]. Carbon pricing is considered the most efficient policy to reduce GHG emissions[3], but pricing initiatives enforced so far have been insufficient to drive deep decarbonization[4,5] and are far from achieving a global, uniform price signal. Differences in climate policy commitments between countries and regions also risk inducing carbon leakage[6–10], where emissions increase elsewhere due to domestic climate policy. The mere risk of carbon leakage has also played a key role historically by discouraging politicians in the United States[11] and the European Union (EU)[12] from enforcing adequate climate policies.

Sweden has relatively low territorial GHG emissions—5 tons of carbon dioxide equivalents per capita (tCO_2e_{pc}) in 2019[13] (excl. land use, land use change, and forestry—LULUCF)—and has adopted a net-zero target for 2045 to address these emissions[14]. Swedish consumption-based GHG emissions were 9.8 tCO_2e_{pc} in 2019[15] (incl. emissions of GHGs and indirect non-CO_2 forcers of aviation, and excl. LULUCF), showing a large discrepancy between the accounting frameworks. Further, 42% of Swedish consumption-based emissions in 2018 occurred in countries where climate policies are considered weak[16].

Consumption-based emission accounting could potentially incentivize abatement along the whole supply chain and reduce carbon leakage risks[1,9]. Emissions are here attributed to end-use products and services[8]. However, a complete shift to consumption-based accounting would require an international framework to deal with how countries can be held accountable for emissions outside of their jurisdiction, which risks infringing on national sovereignty[6]. A shift to consumption-based emission accounting would also likely suffer from blind spots related to exports, which could create its own carbon leakage risks[9]. In 2022, a Swedish parliamentarian committee unanimously proposed a compromise—adopting a consumption-based net-zero GHG emission target alongside the territorial net-zero target[13]. Consumption-based accounting is not new from a scientific perspective[1,6,9]. However, the proposal signifies a new policy approach to be implemented in practice, and the theoretical basis for adopting consumption-based targets alongside territorial commitments to the UNFCCC has not yet been explored in the scientific literature.

Moreover, assessing the ambition level of the proposed targets in relation to other policy targets, potentials for emission reductions, and global climate policy development, can deepen the understanding of the added value of the targets. Scenario analysis is an important tool in this context, especially for assessing the impact of both supply- and demand-side mitigation measures[17,18]. Explorative scenarios are used to assess long-term developments depending on different changes to current systems, in contrast to normative scenarios that aim to assess what would be needed to reach a specific goal and predictive scenarios that aim to assess the most likely future[19]. Future Swedish consumption-based GHG emissions have been analyzed using backcasting[20], a normative scenario analysis approach aiming to achieve a certain emission level in 2050, and using explorative scenarios[16] for a subset of consumption categories based on prospective lifecycle assessment.

Prospective lifecycle assessment is a methodological framework that can be used for scenario analysis and considers two sets of systems in transition (so-called foreground systems and background systems)[21], where the adoption of new products and services by the end-user, incl. demand changes, is considered in the foreground systems and the supply chains involved in supplying those products and services are considered in the background systems. Studies applying a prospective lifecycle assessment framework generally either mapp integrated assessment modeling results for future decarbonization scenarios to lifecycle inventory databases[22,23], or combine results from integrated assessment models (IAMs) with lifecycle inventories and additional analytical tools to understand the deployment of new technologies, such as Morfeldt et al.[24] for electric cars or Pehl et al.[25] for power systems.

Other national or regional case studies that use similar approaches for explorative scenarios include India[26], Denmark[27], and the EU[28]. These studies all consider the transition of foreground and background systems using different types of hybrid modeling that combines top-down, e.g., multi-regional input-output analysis, with bottom-up simulation models for demand, and IAM results to understand how background systems may evolve in the future. However, at the time of writing, scenario analyses in the context of consumption-based climate policy targets, covering all national consumption, have not yet been explored.

In this work, we examine the theory justifying the adoption of consumption-based emission accounting alongside the UNFCCC's territorial framework. We also assess the consequences of adopting the proposed consumption-based targets for Sweden by comparing them to different emission pathways. We use explorative scenario analysis for domestic mitigation options, both technological and behavioral, which complements previously used methods by covering all consumption categories in a hybrid bottom-up and top-down modeling framework based on prospective lifecycle assessment. The framework considers the inertia of the transition towards a low-carbon society—in Sweden as well as abroad. In addition, policies that could promote the implementation of advanced technology and behavioral measures are discussed in the context of the scenarios. The scenario analysis results show that combining advanced mitigation technologies with behavioral changes could achieve the lowest emissions per capita—between 2.7 and 4.8 tCO_2e_{pc} by 2045—for Swedish residents, depending on global decarbonization pathways. While the scenario results are relevant to the Swedish context, the discussions on the viability of consumption-based targets and potential policy options are applicable to other countries with similar emission levels embedded in imports of products and services. The scenario methodology is also applicable to other countries provided that the underlying data is available.

Results

Viability of complementary consumption-based targets. Here, we examine the theoretical basis for adopting a complementary consumption-based accounting framework in a national setting. For a complementary consumption-based target to be justified it should (i) be consistent with current international frameworks and agreements, (ii) have a sound policy design, and (iii) provide added value by addressing weaknesses in the territorial framework.

Consistency with UNFCCC. The transparency framework of the Paris Agreement[29] is built on territorial accounting of GHG emissions. It has the dual purpose of generating national GHG inventories that can be summed up to track global progress and track progress with the countries' nationally determined contribution (NDC).

The adoption of the Paris Agreement marked a shift within the UNFCCC, from negotiations on national emission reduction targets (following territorial accounting) to a framework where each country determines their contribution to the overall goal of

the agreement[30], in the form of nationally determined contributions (NDCs) for the short-term (Article 2.2[29]) and long-term low GHG emission development strategies (Article 2.19[29]). Note that the latter is not mandatory but has been recurringly encouraged in UNFCCC statements (Decisions 1/CMA.2[31] and 1/CMA.3[32]). The framework maintains the UNFCCC's demands for transparency—in terms of national, and territorial greenhouse gas inventories and reports describing each country's emission development and policy response—and extends them to also cover developing countries (Article 13[29]). The transparency framework has the dual purpose of generating accurate estimates of national emissions to be summed up for tracking global progress (Article 13[29]), and to track progress with NDCs and long-term mitigation strategies for each specific country (Article 13[29] and Decision 4/CMA.1[33]).

These decisions open for a country to determine its own accounting methodology if the NDC includes targets that are not consistent with IPCC guidelines (i.e., territorial accounting). These requirements, among other things, stipulate that "parties shall promote environmental integrity, transparency, accuracy, completeness, comparability, and consistency, and ensure the avoidance of double counting" (Article 4.13[29]). Consumption-based emissions can be estimated in a methodologically consistent way by using global multi-regional input-output (MRIO) tables with environmental extensions[1] and methods have been developed to improve the accuracy of these results[34]. However, such methods suffer from double counting if adopted alongside territorial accounting. Moreover, the transparency of the methods can be questioned given the assumptions needed when constructing complete MRIO tables and when translating economic trade data to embodied emission flows[6]. Consumption-based accounting based on MRIO tables is also inherently more complex in comparison to territorial accounting. Hence, consumption-based accounting may not qualify as a methodology for tracking progress with NDCs.

We see another potentially valuable contribution of national consumption-based accounting as a complement, adopted alongside the UNFCCC framework, that does not influence the integrity of the transparency framework. Each country is required to assess the fairness of its contribution and how its NDC contributes to achieving the overall goal of the Paris Agreement (Decision 4/CMA.1[33]). Here, complementary consumption-based targets could enhance the country's fair contribution to the goals of the agreement by counteracting carbon leakage and by unlocking additional mitigation potentials by targeting domestic activities where the emissions occur outside the country's territory.

Hence, complementary consumption-based targets, that are not explicitly included in the NDC for a country, can be designed to not necessarily interfere with the well-defined procedures for the transparency framework and NDC accounting of the Paris Agreement and still provide added value.

Policy design. In the realm of environmental policy-making, the 'polluter pays principle' takes center stage[1]. This principle advocates for policies to target the source of pollution to stimulate abatement while avoiding unnecessary distortions to the economy. Its basis aligns with the territorial accounting framework and implicitly questions the efficacy of policies that target proxies, such as inputs or consumption activities, to reduce pollution. Following this line of reasoning, an optimal strategy for meeting a global climate target would entail every country imposing economy-wide carbon prices on polluting sources[35]. However, the improbability of achieving a globally (near) uniform carbon price in the immediate future necessitates the exploration of additional policy measures to meet climate targets[8,35–38].

Policies explicitly targeting behavioral changes are believed to be politically sensitive but could indirectly reduce both 'upstream' and 'downstream' emissions[36]. Nevertheless, Schmutzler and Goulder[37] show that output taxes may be more cost-efficient than emission taxes in situations where (i) monitoring costs are high, (ii) abatement options are limited, uncertain, or unavailable in the short term, and (iii) where demand is elastic, or substitutions are possible. However, emission taxes consistently stimulate suppliers to seek ways to mitigate their costs. Hence, as noted by Schmutzler and Goulder[37], emission taxes potentially drive technological advancement in cleaner processes and solutions even when abatement opportunities in the short term are limited.

Stimulating technological development on the supply side could however also be achieved by introducing a differentiated output tax that credits emission-saving technologies. Such a domestic policy has the potential advantage of catalyzing technological progress not just among local producers but also among foreign ones, thereby increasing cost efficiency. Alternatively, as shown by Fullerton and Mohr[38] an output tax combined with a technology subsidy geared towards emission reductions, can be as efficient as an emissions tax.

In summary, the complexity of environmental policy-making necessitates a nuanced approach beyond the 'polluter pays principle'. Domestic consumption-focused policies and technology subsidies are promising strategies that could complement traditional emission pricing at their source.

Addressing weaknesses. Consumption-based targets could address carbon leakage risks and incentivize additional mitigation measures by targeting domestic consumption activities where emissions occur outside the country's territory. In addition, consumption-based targets adopted alongside territorial targets could introduce a consumer perspective[1], incentivizing both demand- and supply-side emission reductions irrespective of where the emissions occur. Demand-side measures are instrumental in some scenarios[39] that strive to limit the global mean temperature increase to 1.5 °C without large dependency on carbon dioxide removal. These scenarios often foresee substitution away from carbon-intensive products and services to low-carbon options—e.g., car-free mobility solutions, plant-based diets—or absolute reductions in demand—e.g., air travel, space heating/cooling—that could be incentivized by consumption-based policies.

Examples of such policies are differentiated consumption taxes on basic material or animal-based food. For basic materials (e.g., cement, steel, and petrochemicals), abatement cost per unit tends to be high while the downstream consumer (e.g., a car buyer) typically would see little of the carbon cost[40]. Differentiated consumption charges have been proposed for these sectors to both reduce the risk of carbon leakage[41] and reinstate the demand-side carbon price signal[42]. In the case of animal-based food, high monitoring costs are paired with comparatively low technological potentials for reducing ruminant methane emissions and nitrous oxide emissions from fertilizers. Hence, consumption charges could be a cost-effective policy for mitigating agricultural GHG emissions[37,43–46]. Emerging plant-based protein sources and the increasing share of vegetarians and flexitarians in the EU[47] also indicate an ongoing substitution.

Ambition level of proposed Swedish consumption-based targets. As shown in the previous section, complementary consumption-based targets and policies can be supported theoretically. Here, we compare the net-zero target trajectories for consumption-based emissions proposed by the Swedish parliamentarian committee[13] with four different scenarios, see Fig. 1.

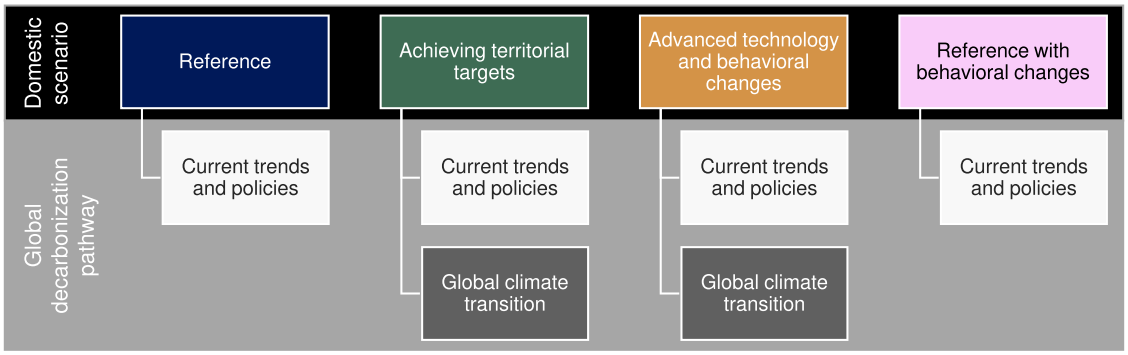

Fig. 1 Scenario overview. Scenarios for domestic action and their connections to each respective global decarbonization pathway. Each domestic scenario is combined with a global decarbonization pathway that follows current trends and policies. Future consumption-based emissions are strongly influenced by technology developments worldwide, such as the global adoption rate of renewable energy, sustainable aviation fuels, and fossil-free materials production. Hence, the two scenarios that assume climate action domestically—achieving territorial targets (green) and advanced technology and behavioral changes (yellow)—are also combined with a global climate transition following the Paris Agreement. The latter pathway is equivalent to limiting the global mean temperature increase to 1.8 °C above preindustrial levels (or 1.5 °C if substantial negative emissions are realized). The results are presented as ranges when both global decarbonization pathways are used.

The proposal[13] consists of absolute emission reduction targets for consumption-based emissions (i.e., emissions for the total population and excluding non-CO_2 climate impacts of aviation), expressed relative to a base year (i.e., 2010). The targets are referred to as two alternative trajectories (i.e., linearly interpolated): (i) the main trajectory with reductions of 26% by 2030, 57% by 2040, and 66% by 2045, and (ii) the alternative trajectory with reductions of 47% by 2030, 69% by 2040, and 77% by 2045. Remaining emissions above net-zero (in 2045) are to be offset using carbon dioxide removal, and verified emission reductions abroad through Swedish investments, and/or climate benefits related to Swedish exports[13]. Emission estimates relevant to compare with the target trajectories are presented in Table 1 together with emissions per capita estimates that are also visualized in Figs. 2 and 3. Note that our main results presented in Figs. 2 and 3 include non-CO_2 climate impacts of aviation while those are not included in the proposed targets.

The scenario analysis is based on a hybrid approach. Bottom-up simulation models are used for estimating future emissions for passenger travel, construction and housing, and food consumption. Emissions related to remaining consumption categories are estimated using a top-down approach based on an expanded Kaya identity[48] and data from Exiobase[15], see Methods.

Reference scenario. Consumption-based emissions decreased by 9% from 2019 to 2020, see Fig. 2, due to reduced air travel in response to the Covid-19 pandemic. Air travel emissions recover by 2025 and reach 0.9 tCO_2e_{pc}, close to pre-pandemic levels of 1.0 tCO_2e_{pc}, see details for each consumption category in Supplementary Fig. 2. Changes in other consumption categories counteract the trend, especially emissions from passenger cars that decrease by 23% compared to 2019 due to electrification. While air travel emissions increase after 2025, reaching 1.2 tCO_2e_{pc} in 2045, emissions decrease in all other consumption categories. Passenger car travel stands out with a reduction of 60% compared to 2019 due to the electrification of the fleet. Emission reductions in other consumption categories are related to current efficiency trends. Subsequently, the carbon intensity of Swedish electricity generation and district heating is assumed to reach zero by 2058, when the EU Emission Trading System's (EU ETS) CO_2 cap reaches zero[49] (i.e., not including recent provisional decisions related to the Fit-for-55-proposal). Consumption-based emissions reach 7.5 tCO_2e_{pc} in 2045. This is equivalent to a reduction of 24% compared to 2010 (referring to emissions for the total population and excluding non-CO_2 climate impacts of aviation, both in line with the proposal). The reduction can be compared to the proposed Swedish consumption-based targets of 66–77% for the main or alternative trajectories, respectively.

Achieving territorial targets scenario. If Sweden's territorial targets are met and global industries develop in line with current trends and policies, consumption-based emissions could decrease to 6.3 tCO_2e_{pc} by 2045 (cf. 7.5 tCO_2e_{pc} in the reference scenario). The major differences between this scenario and the reference depend on assumptions for the construction sector (i.e., 54% emission reduction by 2045 compared to the reference scenario), mainly due to domestically produced fossil-free steel and asphalt, and cement production using carbon capture and storage; passenger car travel (i.e., 39% emission reduction in 2045 compared to the reference scenario) due to full fleet electrification and phase-out of fossil fuels; and food production (i.e., 24% reduction in 2045 compared to the reference scenario), due to domestic use of fossil-free fertilizers and feed additives that reduce methane occurrence in cattle[50]. The assumed measures are detailed in the first column of Table 2. A higher pace in the decarbonization of electricity and district heating (by 2045 instead of 2058) also contributes to reducing emissions. These reductions are offset by growth in air travel emissions due to an assumed doubling of flights per capita. Air travel emissions level out around 2035. The share of sustainable aviation fuels (SAFs) is assumed to approach 100% by 2045 for domestic flights[51] and EU-bound flights taking off from Sweden[13].

Global climate transition. Here, we assume global action, where other countries match the ambition of the Paris Agreement. This implies reaching global net-zero GHG emissions by 2070[52]. For the bottom-up simulated categories, faster global decarbonization mainly impacts Swedish air travel, where emissions start to decrease from 0.8 tCO_2e_{pc} in 2025 to 0.6 tCO_2e_{pc} in 2045 due to an increased share of SAFs for international air travel. Decarbonized global construction materials and vehicle manufacturing also contribute to lower emissions as well as fossil-free fertilizers and feed additives in global food production.

A global climate transition also has a notable impact on emissions related to the top-down modeled consumption categories, which decrease by 50% in 2045 compared to the reference scenario. However, the rate of energy efficiency (i.e., the energy use per unit of economic activity) and carbon intensity

Table 1 Scenario results in comparison to the base year.

	Absolute greenhouse gas emissions, incl. non-CO_2 effects [million tons CO_2e]	Greenhouse gas emissions per capita, incl. non-CO_2 effects [tons CO_2e]	Absolute greenhouse gas emissions, excl. non-CO_2 effects [million tons CO_2e]	Greenhouse gas emissions per capita, excl. non-CO_2 effects [tons CO_2e]
Base year (2010)	108.5	11.5	106.2	11.3
Scenarios (2045)				
Reference	86.8 (20%)	7.5 (35%)	80.9 (**24%**)	7.0 (38%)
Achieving territorial targets	43.0–72.9 (33–60%)	3.7–6.3 (45–68%)	39.8–67.6 (**36–63%**)	3.4–5.8 (48–70%)
Advanced technology and behavioral changes	31.1–55.3 (49–71%)	2.7–4.8 (59–77%)	29.9–53.3 (**50–72%**)	2.6–4.6 (59–77%)
Reference with behavioral changes	66.0 (39%)	5.7 (51%)	64.2 (**40%**)	5.5 (51%)

Absolute greenhouse gas emissions and greenhouse gas emissions per capita, with and without non-CO_2 effects of combustion at high altitudes, for the base year (2010) as well as for each scenario in the year 2045. The emission reductions in 2045 compared to 2010 are provided in parentheses. The emission reductions relevant to compare with the proposed targets are highlighted in bold. Note that the range indicated represents the uncertainty in the global climate transition, where the higher level represents current trends and policies, and the lower level represents a global climate transition in line with the Paris Agreement's goals.

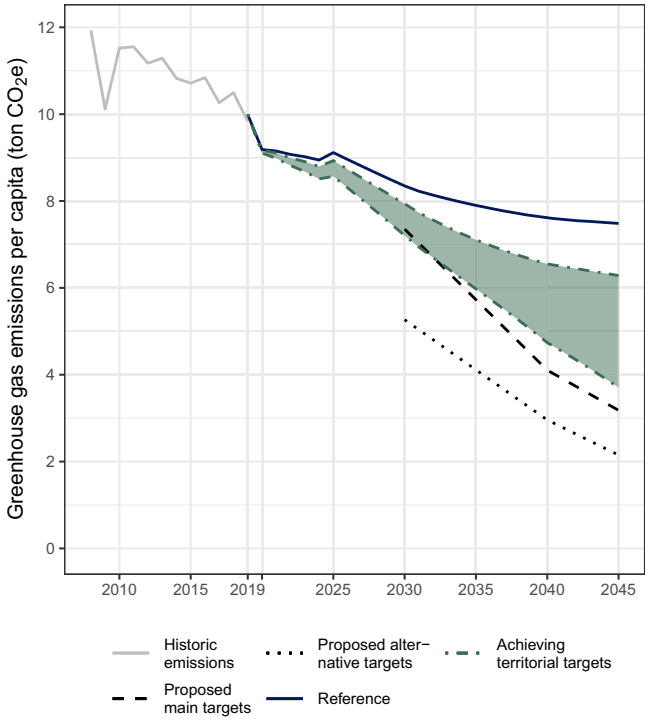

Fig. 2 Consumption-based emission pathways for the reference scenario and if territorial targets are met. Scenario analysis in comparison with proposed target trajectories (dashed: main trajectory, dotted: alternative trajectory). Historic emissions (solid-gray) for 2008–2019 and scenarios—reference (solid-black) and achieving territorial targets (dot-dashed)—for 2019–2045. Note that the range indicated for achieving territorial targets (dot-dashed) represents the uncertainty in the global climate transition, where the higher level represents current trends and policies, and the lower level represents a global climate transition in line with the Paris Agreement's goals. Historic emissions are based on data from Exiobase[15] with the addition of non-CO_2 effects of combustion at high altitudes based on energy use data for aviation from Exiobase[15], following the method outlined in Supplementary Note 1. Results for total Swedish consumption-based emissions with or without non-CO_2 effects of combustion at high altitudes are available in Supplementary Fig. 1.

improvements assumed in the top-down methodology are highly uncertain, see Supplementary Figs. 3 and 4. On the one hand, the energy efficiency assumption used—the historic trend at the global level[53]—may overestimate the improvement potential given that the energy efficiency of Swedish economic activities is already relatively high[54]. On the other hand, behavioral changes could enable higher rates of energy efficiency improvements through, e.g., pushing towards buying high-quality products with longer lifetimes or increasing the degree of servitization—where users pay for a service instead of buying equipment[55].

Swedish consumption-based emissions reach 3.7 tCO_2e_{pc} by 2045 if territorial targets are achieved in combination with a global climate transition. Hence, achieving the territorial emission reduction targets would reduce consumption-based emissions by 36–63% in 2045 compared to 2010 (referring to emissions for the total population and excluding non-CO_2 climate impacts of aviation, both in line with the proposal), depending on the development in the rest of the world.

The emission impact of demand-side mitigation measures. Here, we explore how demand-side measures impact Swedish consumption-based emissions and compare those impacts with the net-zero target trajectories proposed by the Swedish

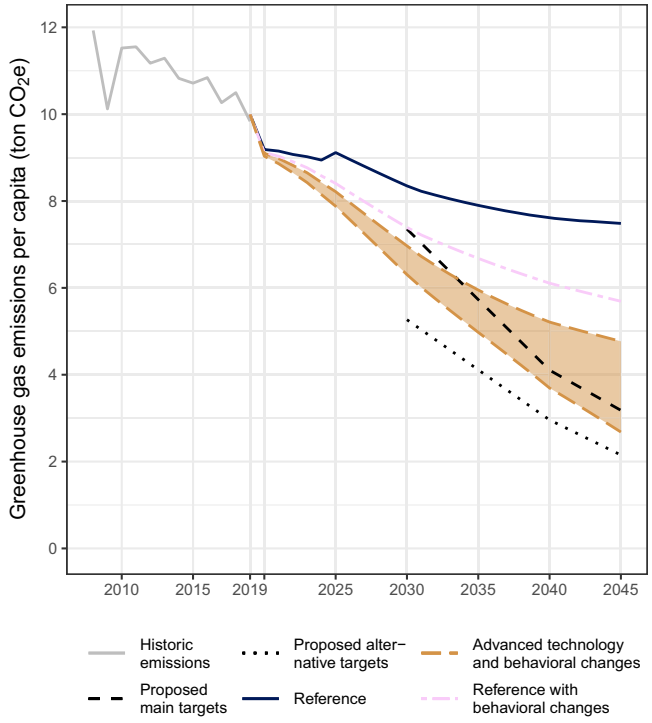

Fig. 3 Consumption-based emission pathways for scenarios including behavioral changes. Scenario analysis in comparison with the proposed target trajectories (dashed: main trajectory, and dotted: alternative trajectory). Historic emissions (solid-gray) for 2008–2019 and scenarios—reference (solid-black), reference with behavioral changes (two-dashed), and advanced technology and behavioral changes (long dash)—for 2019–2045. Note that the range indicated for the advanced technology and behavioral changes scenario (long dash) represents the uncertainty in the global climate transition, where the higher level represents current trends and policies, and the lower level represents a global climate transition in line with the Paris Agreement's goals. Historic emissions are based on data from Exiobase[15] with the addition of non-CO_2 effects of combustion at high altitudes based on energy use data for aviation from Exiobase[15], following the method outlined in Supplementary Note 1. Results for total Swedish consumption-base emissions with or without non-CO_2 effects of combustion at high altitudes are available in Supplementary Fig. 1.

parliamentarian committee[13]. Two scenarios are analyzed: (i) a scenario combining technologies assumed to be implemented in response to the territorial targets, additional advanced technologies, and behavioral changes that shift or fully avoid consumption, see categorization along the avoid-shift-improve spectrum[18,56] in Table 2, and (ii) a reference scenario combined with only avoid or shift measures that highlight the effect of behavioral changes alone. The latter scenario also highlights how far sufficiency actions[16,17,55] can take us in reducing the emissions. Note that the sufficiency actions considered in this study are incremental in the sense that they are consistent with a growing economy, whereas sufficiency actions in response to societal development towards degrowth could go further.

The advanced technology transition includes self-driving cars that enable car sharing in cities and to some extent ride sharing. We assume that policy measures minimize any induced travel demand[57] implied by these technologies. The behavioral changes include assumptions of reduced driving by 20% per capita compared to 2019 by increased cycling and use of public transport as well as reductions in travel. Total air travel per capita is halved, and domestic flights are reduced even more. Increased rail travel is assumed to compensate for some flights, both

Table 2 Categorization of mitigation actions.

Consumption category	Achieving territorial targets	Advanced technology and behavioral changes		
	Improve	*Avoid*	*Shift*	*Improve (additional)*
International air travel	Increased use of sustainable aviation fuels, measures to reduce non-CO_2 effects, electrification	Sharp reduction in air travel per capita	Increased train and bus trips to continental Europe	
Domestic air travel	Increased use of sustainable aviation fuels, measures to reduce non-CO_2 effects, electrification	Sharp reduction in air travel per capita	Increased domestic train and bus trips	
Passenger car travel	Electrification following phase-out of internal combustion engines in new car sales by 2030, and phase-out of fossil fuels by 2040	Less commuting	Increased cycling and public transport for commuting as well as leisure trips	Self-driving cars enabling car sharing in cities
Construction, space heating, and household energy use	More energy-efficient buildings and reduced emissions in electricity generation and district heating production, decarbonized domestic building materials	Reduced housing and commercial space per capita	Commercial and office space converted to housing; renovations instead of new construction	Increased materials efficiency in construction
Food	Fossil-free fertilizers and feed additives		Plant-based protein-rich products replace animal products	

Actions implemented in the mitigation scenarios according to the avoid-shift-improve framework. Note that the scenario of Achieving territorial targets only covers measures in the improved category. Quantifications of these assumptions and additional details are provided in Methods as well as Supplementary Notes 1–7.

domestic and—to a lesser extent—international. Trips to continental Europe make use of the potential for shifting to night trains[58]. Construction of new buildings and infrastructure are assumed to decrease by increased maintenance and renovation, and by converting offices and commercial space into housing. The average living space is assumed to fall by 10% compared to 2019. Additional material efficiency measures in construction and renovations contribute to further reducing emissions[59]. A shift towards consumption of plant-based protein-rich products enables a decrease in beef, lamb, and liquid dairy products by 75% compared to 2019 and cheese consumption is halved. Demand changes are detailed in Supplementary Table 1 and the rationale is discussed in the respective Supplementary Notes 1–7.

Reference scenario with behavioral changes. Notable emission reductions in 2045 compared to the reference scenario in response to behavioral changes alone are seen in air travel (73%), food consumption (35%), passenger car travel (36%), and construction (31%). The scenario reaches an emission level of 5.7 tCO_2e_{pc} in 2045, see Fig. 3. Total emissions are reduced by 40% in 2045 compared to 2010 (referring to emissions for the total population and excluding non-CO_2 climate impacts of aviation, both in line with the proposal). However, the emission level is higher than the proposed targets, indicating that behavioral measures alone are not enough to achieve the targets.

Advanced technology and behavioral scenario. Further emission reductions are expected compared to the reference scenario in 2045 for air travel (74–86%), food consumption (61–66%), passenger car travel (68–83%), and construction (75–83%), where ranges depend on the global decarbonization pathway. Compared to the scenario achieving territorial targets, the effect is largest for air travel emissions (0.2–0.3 tCO_2e_{pc} in 2045 compared to 0.6–1.0 tCO_2e_{pc}, where ranges depend on the global decarbonization pathway) and food consumption (0.5 tCO_2e_{pc} in 2045 compared to 1.0 tCO_2e_{pc}—the difference between the global decarbonization pathways is smaller than 0.1 tCO_2e_{pc}). These effects can be explained by both categories lacking options for close-to-zero decarbonization technologies in the near term. For passenger car travel, construction, space heating, and household electricity use, behavioral shifts in combination with technological advances result in earlier emission reductions, but only have minor effects on the level of emissions by 2045, see Supplementary Fig. 2. The scenario combining advanced technologies with behavioral changes could reach 2.7–4.8 tCO_2e_{pc} by 2045, see Fig. 3, reducing consumption-based emissions by 50–72% in 2045 compared to 2010 (referring to emissions for the total population and excluding non-CO_2 climate impacts of aviation, both in line with the proposal).

Results for top-down modeled categories. Consumption-based emissions for the top-down modeled categories are in our analysis not affected by any explicit behavioral changes. Demand-side measures for consumer products could potentially reduce emissions further[60]. Figure 4 shows that these consumption categories make up a notable share of remaining emissions in 2045, especially if the global pathway develops according to current trends and policies. The sensitivity analysis of the rate of change in the energy efficiency of economic activities, see Supplementary Figs. 3, 4, suggests that decreasing energy use per economic unit could result in additional emission reductions. Such changes could include shifts towards more expensive, high-quality products and shifts from products to services. However, more detailed studies are needed on how the manufacturing of consumer products may change, what the potentials are for shifts in consumption, and how increased circularity as well as rebound effects could affect those trends.

Potential policies for achieving technology and behavioral changes. The ambitious Fit-for-55 policy package in the EU includes a range of policies that can be expected to deliver major emission reductions[61]. These are primarily focused on reducing emissions at their source and may also affect consumption patterns. If fully implemented, the emission intensity of products and services will be reduced and relative prices in the economy will shift and affect consumption choices.

Supply chain decarbonization. Emissions from the production and use of products and services—e.g., electricity, new cars, new buildings, and air travel services—will be reduced due to both emission trading schemes and more specific sectoral policies. Furthermore, emission reduction targets from an end-user perspective are already implemented in corporate emission accounting through, for example, the Greenhouse Gas Protocol and Science Based Targets initiative, which supports companies in setting mitigation targets throughout their products' value chains[62]. These voluntary targets have loopholes[63,64]. If these targets work as intended and are sufficiently ambitious (i.e., contribute to speeding up mitigation along the companies' supply chains), they would contribute to reducing the emission intensities of the companies' products and services.

Nevertheless, additional policies are likely needed to affect the emission intensities along the supply chains of products and services, especially if the rest of the world does not fully implement the advanced technologies assumed in our scenario. One such policy instrument is the maximum lifecycle carbon footprint threshold for electric vehicle batteries, as laid out in the proposed EU battery regulation[65]. Potential additional instruments include regulations in the agricultural sector that require nitrification inhibitors to abate nitrous oxide emissions from fertilizer use and methane inhibitors for ruminant animals to reduce the methane intensity of meat and dairy production[66]. To avoid risks of carbon leakage and trade distortions, these instruments could be combined with carbon border adjustment mechanisms (CBAM), potentially together with climate club constructions[67]. Pushing towards an expansion of CBAM beyond the scope included in Fit-for-55, or realizing a climate club[68] on a global scale with member countries from several continents, could reduce the emission intensities along the supply chains regardless of country of origin.

Driving behavioral change. The scenarios with behavioral changes encompass various demand-side changes. These behavioral changes are larger than the shifts in consumption patterns expected through changes in relative prices in response to Fit-for-55. Hence, the behavioral changes cannot be expected to occur spontaneously even though they are aligned with current trends. For example, increased remote working can reduce commuting and the need for office space, but policies are necessary to drive these behavioral changes and to avoid rebound effects that may increase supply chain GHG emissions (e.g., increased commuting distances, increased housing area)[69,70]. Consumption taxes are potential strategies[71] to achieve the large changes in consumption patterns that are stipulated in our scenario. Implementing tax shifts, which involve the introduction or increase of taxes on carbon-intensive products and services alongside reductions in other taxes, is a policy design that has the potential to garner greater public acceptance, despite the generally low acceptance of new taxes[70]. The potential policies discussed below are related to the key behavioral changes highlighted in the scenario analyses

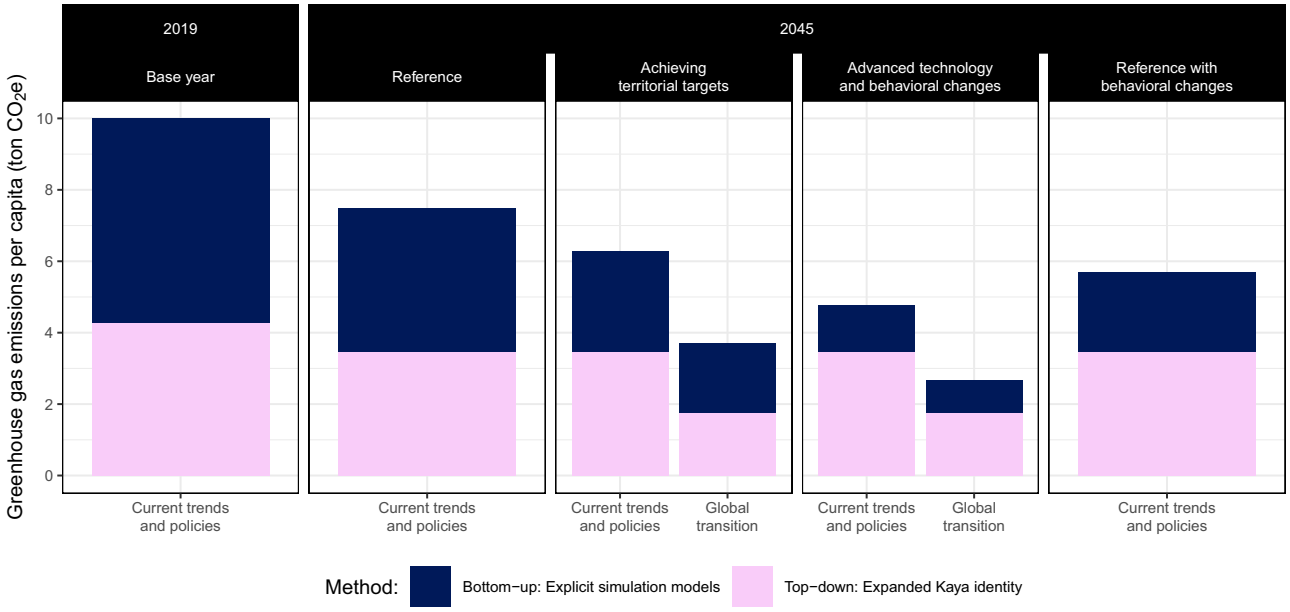

Fig. 4 Consumption-based emissions in 2045. Results for 2045 for the different scenarios (panes), depending on development in the rest of the world (columns) and type of estimation method—bottom-up: explicit simulation models (blue) and top-down: expanded Kaya identity (pink). Results are also given for the base year (2019) in the first pane.

for achieving lower total carbon footprints. These include a decrease in air and car travel, reduced housing and commercial space, and a shift from animal-based to plant-based protein sources.

Regarding air travel, ticket prices are likely to increase since airlines will have to purchase emission allowances for EU flights as well as fulfill an SAF quota. With no new allowances issued after 2040, airlines will be compelled to adopt more expensive alternatives to reduce emissions[72,73], such as biofuels, green electrofuels, and all-electric aircrafts. Consequently, this will likely reduce the demand for air travel and promote a shift towards alternative modes of transportation, such as international train travel. Choice modeling studies have demonstrated that improved train alternatives and altered relative prices can result in notable shifts from air travel to long-distance night trains[74]. However, since intercontinental flights constitute over half of the air travel emissions of Swedish residents, stronger EU or national policy measures will be necessary in the absence of a robust global policy. Many countries, such as Germany, the UK, France, and Sweden, have implemented distance-based taxes on air travel tickets[75], which could be gradually increased to achieve targeted reductions (similar to taxes on tobacco, alcohol, and fossil fuels in certain countries).

We also assume reductions in car travel and a shift to active transport (i.e., cycling and walking), public transport, and, potentially, ride-sharing with autonomous taxis. Existing mobility policies primarily focus on shifting from vehicles using fossil fuels to electric vehicles. However, additional policies for limiting the use of remaining vehicles with internal combustion engines are likely to be important to meet Swedish climate policy targets, together with limiting the carbon footprint of battery supply chains. Local policies for increased service quality and accessibility will likely be important for public transport[76] and promoting active transport, e.g., safe and convenient biking and walking lanes, can further contribute to emission reductions[77]. Various taxation instruments may also be critical to handle other aspects of the transition that may spill over to reducing emissions, such as taxes on new electric vehicle purchases that mainly would limit battery material demand and kilometer-based taxes that could compensate for the loss in tax revenue when fossil fuels are phased out. From an emissions perspective, these instruments could keep car ownership and usage low, and limit emissions in electricity generation and vehicle manufacturing. Plausible pricing instruments can also be differentiated based on public transport accessibility to avoid problems with perceived unfairness[78] between the urban and rural populations.

Concerning housing, current targets and policies aim to increase construction levels to address housing shortages and stimulate the economy. Reversing this trend and designing policies that promote reduced housing area per capita, as well as commercial space, is a relatively unexplored area[79]. Taxes on real estate based on square meters (in addition to monetary value) could serve as a potential key policy instrument to incentivize individuals to downsize their homes and organizations to reduce commercial space. To achieve this, it is also crucial to minimize taxes and other expenses associated with such relocations. Subsidies could be introduced to encourage the conversion of office space into housing, reconstruction of large private villas into several smaller units, and establishment of various forms of co-living arrangements with low space usage per capita.

Food consumption habits are influenced by factors such as prevailing trends, product availability, and advertising. Currently, there is a noticeable inclination[80] towards healthy foods with a lower climate impact, especially chicken, and the market is rapidly evolving[81] with the introduction of new and cheaper plant-based protein options. Nevertheless, policy intervention will be necessary to bring about the needed shifts in dietary patterns. One potential approach involves implementing a tax shift within the food sector[43], where excise duties based on the weight of foods with high climate impacts, such as meat and dairy products, would be implemented on top of the value-added tax while lowering the value-added tax on other food items.

Discussion

Complementary consumption-based targets may motivate policy instruments incentivizing substitution in consumption and reducing demand for carbon-intensive products and services. Due

to differing emission reduction ambitions among countries, implementing policies solely aimed at producers can pose challenges such as carbon leakage and domestic job loss. As a solution to this problem, policies that target consumption, treating domestic activities and imports equally, can be employed. However, to achieve an effective approach, it is crucial to also prioritize the incentivization of low-carbon technologies and encourage producers to undertake abatement efforts.

There are also accounting problems when focusing only on the consumption perspective. Methods for monitoring consumption-based emissions are inherently more complex than for territorial emissions, requiring additional assumptions and simplifications. Hence, solely relying on consumption-based accounting is not consistent with the transparency principle set out in UNFCCC decisions, and including consumption-based targets as part of countries' NDCs risk resulting in double counting of emissions. However, if the targets are implemented as complements to the territorial targets, as proposed for Sweden, they could enhance the fairness of the NDC by counteracting carbon leakage and unlocking additional mitigation potentials for emissions occurring outside the country's territory.

Our scenario analysis indicates that the Swedish proposed targets on consumption-based emissions can only be achieved by combining advanced technology with behavioral changes, provided that other countries—from which Sweden imports products –achieve equivalent emission reductions. In such a case, the main trajectory targets can be achieved, but not the more ambitious alternative trajectory. Achieving these emission reductions implies more extensive societal transformations that potentially could be achieved by exploring further behavioral changes not considered in this study, e.g., regarding consumer product categories such as textiles and home electronics, and by promoting a faster transition in producing countries, e.g., through the formation of climate clubs.

Further, some scholars[82,83] argue that planned degrowth pathways—challenging the economic growth regime—can enable faster emission reductions globally without extensive use of carbon dioxide removal through a reduction in total energy demand. Analyzing degrowth pathways, for example, by applying a general work-time reduction, would be interesting and possible using the methodology developed in this study. However, such pathways are outside of the scope of this study. Our scenarios instead assume continued economic growth combined with drastic technological changes and incremental, but far-reaching, shifts from consumption of high- to low-carbon-intensive products and services.

Finally, there are many open questions regarding the appropriateness of consumption-based targets, the political acceptability of such targets and the policy instruments needed to achieve the targets, the cost-effectiveness of consumption-focused policy instruments, and how to track the progress and fulfillment of such targets. These questions are relevant directions for future research.

Methods

Decarbonization scenarios and their rationale. A set of decarbonization scenarios explore combinations of advanced low-carbon technology in Sweden and abroad with behavioral changes in Sweden, see Fig. 1. The methodological approach used for the scenario construction is based on designing a few selected pathways that represent highly divergent, yet plausible futures—similar to the approach used for the emission scenarios for the shared socioeconomic pathways[84]. The scenarios are developed to analyze the implications of consumption-based targets proposed by a cross-party committee of the Swedish parliament[13]. Each scenario is based on a simple rationale for domestic development combined with different decarbonization pathways for emissions occurring abroad. The different measures foreseen are classified on the avoid-shift-improve spectrum[18,56] in Table 2.

In a reference scenario, the future unfolds in line with current trends and policies (as of mid-2019). Global and national incentives to reduce emissions continue to be weak and fail at disrupting the fossil-fueled society. The demand for products and services continues to increase, while some reductions in average carbon footprint per product or service are achieved by increased efficiency and adopted CO_2 emission regulations. This trend is in line with historic developments[54]—Swedish consumption-based emissions have been relatively stable since the early 1990s, but demand for products and services has increased while the emissions intensity has decreased. Nevertheless, decisions already made will be honored, which for example means that emissions from electricity generation will decrease and the use of renewable fuels for both road and air transport will increase.

The reference scenario and the reference scenario with only behavioral changes assume that current trends and policies prevail for all countries, while the other domestic scenarios are analyzed for two global decarbonization pathways: current trends and policies, and global climate transition. The latter assumes a decarbonization pathway in line with the Paris Agreement's goals of holding global mean temperature increase well below 2 °C and striving towards 1.5 °C compared to preindustrial levels. The pathways used are based on the International Energy Agency[52] and their decarbonization pathway aims to hold the global mean temperature increase below 1.8 °C compared to preindustrial levels at a probability of 66%. This pathway is equivalent to global net-zero carbon dioxide emissions by 2070.

In the scenario that achieves territorial targets, Sweden implements the policy instruments needed to achieve the net-zero target for territorial GHG emissions by 2045, interpreted using further indications by the Swedish government[85] (e.g., transport and energy-related emissions within Sweden are assumed to reach close to zero by 2045). Emission reductions are mainly achieved through a domestic technology change, such as electrification of the passenger car fleet and increased use of biofuels in line with a governmental assessment[86] together with fossil-free steel production and cement production with the capture of carbon dioxide[87]. Decarbonization of domestic building material production, combined with regulatory requirements and public procurement targets on embedded emissions in buildings and infrastructures. Fossil-free fertilizers and feed additives contribute to emission reductions in agriculture. Demand for products and services is assumed to follow the same trends as in the reference scenario. The level of consumption-based emissions in this scenario also depends on developments in the rest of the world. The upper emission level shows the result of the rest of the world following current trends and policies. The lower emission level means that a global climate transition has started in line with the Paris Agreement, where the technology changes are also implemented abroad but at a slower pace than domestically.

In the scenario for advanced technology and behavioral changes, the effects of large-scale behavioral changes on future emissions are illustrated in combination with advanced technology development beyond what is expected to be achieved if complying only with the territorial targets. Behavioral changes include cycling and public transport replacing some car use and remote work expands to allow for less commuting. There is a sharp increase in domestic rail travel, and trips to continental Europe are also sometimes done by train. Trips to the Mediterranean by flight are less frequent, and intercontinental travel becomes a once- or twice-in-a-lifetime event. An emphasis

on maintenance and renovation, conversion of offices and other commercial space into housing, and reductions in living space result in lower demand for new construction. Plant-based protein-rich products replace animal products. For advanced technological changes, self-driving cars enable car sharing in cities to reduce the number of cars and to some extent enable ride-sharing, and increased material efficiency to reduce emissions further in both new construction and renovations.

In the reference scenario with behavioral changes, the avoid and shift categories of behavioral changes (Table 2) are implemented but without combining them with technological change in Sweden or abroad. Neither the technological changes motivated by the territorial targets nor advanced technologies are implemented in this scenario. The technological development is in line with current trends and policies, which means that Sweden's territorial climate targets are not met.

Prospective lifecycle assessment and harmonized assumptions. This study uses a prospective lifecycle assessment framework to estimate the carbon footprint (i.e., GHG emissions using global warming potentials over a 100-year time horizon) for Sweden over the period 2019–2045 for the decarbonization scenarios. Statistics[13] show that Swedish consumption-based emissions in 2019 are attributed to transport services (20%), food consumption (16%), housing (13%), and other products and services (11%) by households, public consumption (11%), and public and private investments (29%).

In this study, we have developed explicit, bottom-up simulation models for passenger transportation, food consumption, construction of buildings and transport infrastructure, and heating of buildings and commercial spaces, see Fig. 5. The remaining emissions are related to the consumption of other products and services as well as private investments in machinery, electronic equipment, etc. Scenarios for the remaining emissions are estimated using a top-down approach based on data from the environmentally extended multi-regional input-output model Exiobase[88] (version 3.8.2[15]) and an expanded Kaya identity. Each simulation model, described in greater detail in the following sections and Supplementary Notes 1–7, is harmonized with assumptions in line with the prospective lifecycle assessment framework. We model the introduction of new technologies by an S-curve (a so-called logistic function), if not otherwise stated, based on the theory of diffusion of innovations[89,90]. The results as well as several of the scenario assumptions are given per capita based on a population projection provided by Statistics Sweden[91].

Assumptions on the carbon intensity of energy use are harmonized between the bottom-up simulation models to achieve consistent background systems. The carbon intensity of energy use covers both direct emissions from the combustion of fossil fuels and emissions that occur in the extraction, production, and refining of the respective energy carriers. End-use energy carriers explicitly modeled are electricity, and liquid fuels (equivalent to gasoline/diesel and jet fuel for aviation) based on fossil sources or biomass.

We differentiate between electricity used in Sweden, Europe, and globally. For each geographical region, the projected mixes of electricity generation technologies used are based on analyses of the Swedish Energy Agency[92], the European Commission[93], and the International Energy Agency[52]. For Sweden, direct emissions are assumed to reach zero in 2045 or 2058 (guided by when the EU ETS reaches zero overall under the current EU directive[49]) depending on the scenario. The carbon intensities used for electricity represent averages for each respective geographic area following the attributional nature of the chosen prospective lifecycle assessment framework[21,94]. Adjustments have been made to account for transmission and distribution losses. Upstream emissions from maintenance in power generation plants and fuel production are estimated for each technology based on global averages for each of the two global decarbonization pathways[25].

Specific carbon intensities from the combustion of liquid fossil fuels are assumed for gasoline/diesel[24] and jet fuel[95] for aviation. Their upstream emissions are estimated based on global averages for oil extraction and refining[96] and an emission reduction potential equivalent to halving refining emissions[97]. The carbon intensity of liquid biofuels used in gasoline/diesel vehicles is based on the fuel sales in Sweden in 2019[98]. The mitigation potential for upstream emissions represents gradually switching to hydrogenated vegetable oil from cellulose[24], reaching full market penetration by 2070. The carbon intensity of liquid sustainable alternative fuels (SAFs) for aviation varies with the feedstock. For 2019, the average carbon intensity for non-palm oil feedstocks is assumed[99], which gradually shifts to a level equivalent to hydrogenated vegetable oil from cellulose[24], reaching full market penetration by 2070.

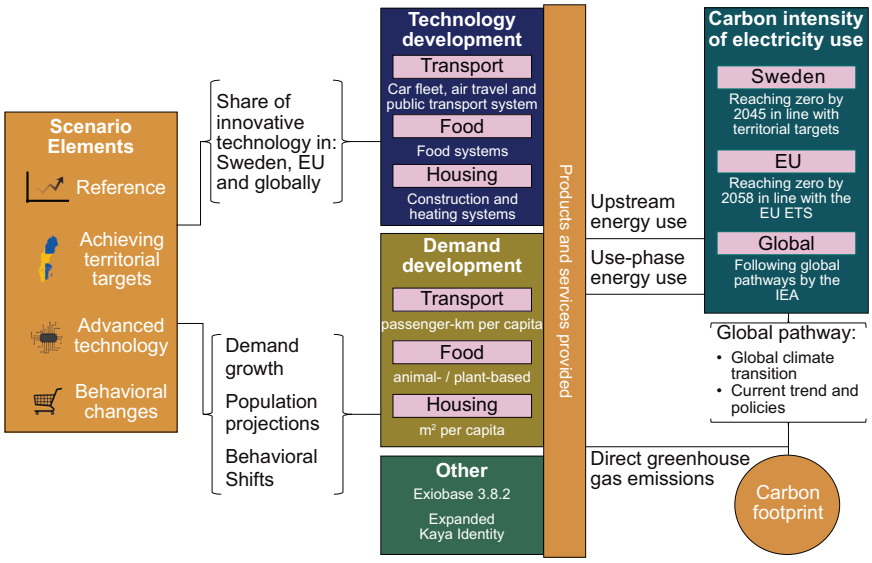

Fig. 5 Prospective lifecycle assessment framework. The figure shows how carbon footprints are estimated based on different scenario elements.

The carbon intensity of district heating is based on key environmental indicators provided by one of the Swedish district heating companies[100]. We assume that the indicators are representative of average Swedish district heating as the company's fuel mix[100] is broadly in line with the Swedish average[101].

Bottom-up: Explicit simulation models. Each simulation model is based on statistics and projections on activity data for transportation (i.e., passenger-km traveled for different modes), space heating and construction (i.e., m^2 of living space, tons of materials, level of construction activity), and food consumption (i.e., kg of consumed foods). Demand assumptions are summarized in Supplementary Table 1. The resulting levels of demand are presented in total and per capita in Supplementary Table 2 for passenger travel services, Supplementary Table 3 for space heating, Supplementary Table 4 for construction, and Supplementary Table 5 for food consumption. The methods used in each simulation model are presented below and additional details are provided in the respective supplementary notes.

The simulation model for Swedish air travel is based on the method developed by Åkerman et al.[72] and builds on carbon footprint studies[102,103] using Swedavia Airports' traveler surveys, covering domestic, intra-EU and extra-EU air travel for Swedish residents. The carbon footprint estimates cover emissions for the entire trip and non-CO_2 effects of combustion at high altitude[104] in addition to the direct and upstream impact of fuel combustion for air travel. Additional details on the air travel simulation model are provided in Supplementary Note 1.

Long-distance public transport (above 100 km, excl. air travel) simulations are based on estimates for energy use per passenger km for different modes. Additional details on the long-distance public transport simulation model are provided in Supplementary Note 2.

Short-distance public transport (below 100 km) simulations combine activity data for bus, rail, and ferry (passenger-km) with estimations for energy use per vehicle km and occupancy rates. Energy use per vehicle-km and battery-electric bus diffusion is estimated with a fleet turnover model for buses and fixed annual efficiency increases for rail and ferry. Emissions from the manufacturing and disposal of vehicles are also included, except for ferries. Additional details on the short-distance public transport simulation model are provided in Supplementary Note 3.

The scenario analysis of Swedish passenger car travel is based on the method developed by Morfeldt et al.[24], which has been extended to account for self-driving cars and shared mobility. The method builds on a stock-flow model of the vehicle fleet turnover combined with prospective lifecycle assessment. Additional details on the passenger car travel simulation model are provided in Supplementary Note 4.

The bottom-up simulation model used to explore emissions from buildings and infrastructure construction builds on work by Karlsson et al.[59]. Here the model has been further developed to better describe sourcing of construction materials (i.e., domestic production relative imports), changes in overall construction activity, changes in the rate of new construction and the rate of renovations and reinvestments. Additional details on the construction simulation model are provided in Supplementary Note 5.

Heating of housing and commercial spaces, and household electricity use are modeled based on energy use statistics for buildings[105] and demographic statistics on living arrangements[106,107]. The model estimates how the share in energy carriers for heating different types of buildings will change in the different scenarios, see Supplementary Fig. 1 for the base year. Assumptions are made in response to the scenarios' technology and behavioral change narratives for how the energy use per area of space and the living area per person changes over time. Additional details on the heating and electricity simulation model are provided in Supplementary Note 6.

The carbon footprint related to food consumption is estimated based on systems analyses[50,66] of agricultural and agro-industrial processes, estimating emissions from farm to store shelf. Emissions related to the private transportation of foods and storing/cooking are included in the housing and transport simulation models. Additional details on the food simulation model are provided in Supplementary Note 7.

Top-down: expanded kaya identity–linking with exiobase. The bottom-up simulations are complemented with the environmentally extended multi-regional input-output model Exiobase[88] (version 3.8.2[15]) to provide estimates of the consumption categories not covered by the bottom-up models and, hence, estimate the total Swedish consumption-based GHG emissions. Exiobase provides a consistent time series for 1995-2022 for consumption-based impacts, e.g., emissions of GHGs, and stressors, e.g., energy use, for different countries, including Sweden. The data is provided in either symmetric Product-by-Product input-output tables following the industry technology assumption or symmetric Industry-by-Industry input-output tables following the fixed product sales assumption[88]. We use the Industry-by-Industry tables since their definition, which implies estimates of impacts related to each industry's products regardless of where in the economy they are used[108], is closest to how our bottom-up-simulation models are structured. A concordance table, see Supplementary Table 6, is used to allocate the 163 industries modeled in Exiobase to distinguish between consumption categories explicitly modeled using bottom-up simulations and categories modeled using the top-down approach explained below. The boundary between the bottom-up and top-down methods is straightforward to set for consumption categories closely related to the simulation models (e.g., supply of food items, supply of transportation services, and construction activities). In addition, allocations have been made based on country-specific parameters for the manufacturing of vehicles, chemicals, wood products, energy carriers, membership organizations, and services, see details in Supplementary Table 6.

Scenarios for the remaining industries, see results of the allocation in Supplementary Fig. 3, are designed based on the following method.

We formalize the scenario assumptions by simplifying an expanded Kaya identity[48]:

$$C = P \cdot \frac{GNP}{P} \cdot \frac{FE}{GNP} \cdot \frac{PE}{FE} \cdot \frac{PE_{FF}}{PE} \cdot \frac{TFC}{PE_{FF}} \cdot \frac{NFC}{TFC} = C_{bottom} + P \cdot \frac{GNP_{top}}{P} \cdot \frac{FE_{top}}{GNP_{top}} \cdot \frac{TFC_{top}}{FE_{top}}, \quad (1)$$

where C is total GHG emissions, P is population, GNP is the gross national product, FE is final energy use, PE is the primary energy use, PE_{FF} is primary fossil fuel energy use, TFC is the total fossil CO_2-equivalent emissions, and NFC is the CO_2-equivalent net-emissions after accounting for carbon dioxide removal. We simplify the expression since we do not explicitly consider carbon dioxide removal, and we base the emission factor on final energy use, rather than primary energy use, see right side of Eq. (1). The subscripts *bottom* and *top* denote the consumption category coverage by the bottom-up simulation models and the top-down approach, respectively.

The model assumes that population growth follows Swedish official projections[91] and economic growth per capita (i.e.,

increase in *GNP*/*P*) is assumed to be 1.4% per year (based on the average during 2022–2030 according to a Swedish official prognosis[109]). The energy intensity of economic activity (*FE*/*GNP*) is assumed to follow historic global trends for 1995–2014 of 1.83% per year reduction, as estimated by Koomey et al.[53], in the scenarios presented in the main paper. Two extreme cases (presented in Supplementary Figs. 3, 4) are used to test the sensitivity of this assumption—assuming no reduction or 4.5% per year reduction, which is in line with the energy efficiency improvements assumed in global low energy demand scenarios[110] for achieving the 1.5-degree ambition of the Paris Agreement. The economic growth per capita (*GNP*/*P*) and energy intensity of economic activity (*FE*/*GNP*) for the consumption categories simulated using the top-down approach are assumed to develop in line with the economy at large.

The carbon footprints for the consumption categories not covered by the bottom-up models are estimated by using energy use data from Exiobase[15] for the base year for aviation, maritime and road transport, and non-transport energy use activities in the supply chain of those consumption categories. The total fossil CO_2-equivalent emissions per final energy use (*TFC*/*FE*) are estimated based on the assumption that these consumption categories mainly cause emissions abroad and that carbon intensities develop in line with average global industries. We assume that aviation and maritime transport activities correspond to international trips outside the EU. The assumptions on aviation activities follow those described for international trips in Supplementary Note 1 except for increased energy efficiency since this factor is covered by the energy intensity of economic activity (*FE*/*GNP*) parameter described above. Road transport activities are assumed to mainly occur within the EU and are assumed to be made using conventional trucks in the global pathway in line with current trends and policies. In the global climate transition pathways, we assume that 50% of the fleet will be fully electric by 2045, in line with scenarios for fast-paced electrification of transport[93], following an S-curve that reaches 100% by 2070. Non-transport energy use activities are assumed to consist of mainly heat and steam production used in global manufacturing industries. The base year energy use is assumed to be 28% electricity use and 72% fossil fuels based on the share of energy carriers in global industry energy use[111], and the industrial energy use is assumed to follow an S-curve that fully shifts to electrified processes by 2070 in the global climate transition pathway.

Data availability

Data for all figures and the concordance table (Supplementary Table 6) are available at Zenodo (https://doi.org/10.5281/zenodo.8305754).

Code availability

The computer code used to generate the results reported in this study is available from the corresponding author upon request. Exiobase[88] (version 3.8.2[15]) was downloaded and analyzed using the pymrio[112] tool (version 0.4.7).

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References

1. Tukker, A., Pollitt, H. & Henkemans, M. Consumption-based carbon accounting: sense and sensibility. *Clim. Policy* **20**, S1–S13 (2020).
2. Kander, A., Jiborn, M., Moran, D. D. & Wiedmann, T. O. National greenhouse-gas accounting for effective climate policy on international trade. *Nat. Clim. Chang.* **5**, 1–5 (2015).
3. Klenert, D. et al. Making carbon pricing work for citizens. *Nat. Clim. Chang.* **8**, 669–677 (2018).
4. Lilliestam, J., Patt, A. & Bersalli, G. The effect of carbon pricing on technological change for full energy decarbonization: a review of empirical ex-post evidence. *WIREs Clim. Change* **12**, e681 (2021).
5. Lilliestam, J., Patt, A. & Bersalli, G. On the quality of emission reductions: observed effects of carbon pricing on investments, innovation, and operational shifts. A response to van den Bergh and Savin (2021). *Environ. Resour. Econ.* **83**, 733–758 (2022).
6. Afionis, S., Sakai, M., Scott, K., Barrett, J. & Gouldson, A. Consumption-based carbon accounting: does it have a future? *Wiley Interdiscip. Rev. Clim. Change* **8**, 1–19 (2017).
7. Peters, G. P. From production-based to consumption-based national emission inventories. *Ecol. Econ.* **65**, 13–23 (2008).
8. Peters, G. P. & Hertwich, E. G. Post-Kyoto greenhouse gas inventories: production versus consumption. *Clim. Change* **86**, 51–66 (2008).
9. Steininger, K. W., Lininger, C., Meyer, L. H., Muñoz, P. & Schinko, T. Multiple carbon accounting to support just and effective climate policies. *Nat. Clim. Chang.* **6**, 35–41 (2016).
10. Grubb, M. et al. Carbon leakage, consumption, and trade. *Annu. Rev. Environ. Resour.* **47**, 1–43 (2022).
11. Lee, H., Cochran, V. A. & Roy, M. US domestic climate change policy. *Clim. Policy* **1**, 381–395 (2001).
12. Clò, S. Grandfathering fuctioning and carbon leakage: assessing the inconsistencies of the new ETS directive. *Energy Policy* **38**, 2420–2430 (2010).
13. Swedish Government. Sveriges globala klimatavtryck (Sweden's global carbon footprint) SOU 2022:15. https://www.regeringen.se/rattsliga-dokument/statens-offentliga-utredningar/2022/04/sou-202215/ (2022).
14. Swedish Government. Regeringens proposition 2016/17:146 Ett klimatpolitiskt ramverk för Sverige (Governmental bill 2016/17:146 A climate policy framework for Sweden). https://www.regeringen.se/rattsliga-dokument/proposition/2017/03/prop.-201617146 (2017).
15. Stadler, K. et al. Exiobase 3 (3.8.2) [Data set]. *Zenodo* https://doi.org/10.5281/zenodo.5589597 (2021).
16. Larsson, J. et al. Consumption-based Scenarios for Sweden—a basis for discussing new climate targets. https://research.chalmers.se/publication/529052 (2022) https://doi.org/10.13140/RG.2.2.23833.08801.
17. Nikas, A. et al. The desirability of transitions in demand: incorporating behavioural and societal transformations into energy modelling. *Energy Res. Soc. Sci.* **70**, 101780 (2020).
18. van den Berg, N. J. et al. Improved modelling of lifestyle changes in integrated assessment models: cross-disciplinary insights from methodologies and theories. *Energy Strategy Rev.* **26**, 100420 (2019).
19. Börjeson, L., Höjer, M., Dreborg, K.-H., Ekvall, T. & Finnveden, G. Scenario types and techniques: towards a user's guide. *Futures* **38**, 723–739 (2006).
20. Fauré, E., Finnveden, G. & Gunnarsson-Östling, U. Four low-carbon futures for a Swedish society beyond GDP growth. *J. Clean Prod.* **236**, 117595 (2019).
21. Arvidsson, R. et al. Environmental assessment of emerging technologies: recommendations for prospective LCA. *J. Ind. Ecol.* **22**, 1286–1294 (2018).
22. Sacchi, R. et al. PRospective EnvironMental Impact asSEment (premise): a streamlined approach to producing databases for prospective life cycle assessment using integrated assessment models. *Renew. Sust. Energ. Rev.* **160**, 112311 (2022).
23. Steubing, B. & de Koning, D. Making the use of scenarios in LCA easier: the superstructure approach. *Int. J. Life Cycle Assess.* **26**, 2248–2262 (2021).
24. Morfeldt, J., Davidsson Kurland, S. & Johansson, D. J. A. Carbon footprint impacts of banning cars with internal combustion engines. *Transp. Res. D Transp. Environ.* **95**, 102807 (2021).
25. Pehl, M. et al. Understanding future emissions from low-carbon power systems by integration of life-cycle assessment and integrated energy modelling. *Nat. Energy* **2**, 939–945 (2017).
26. Mastrucci, A., Min, J., Usubiaga-Liaño, A. & Rao, N. D. A framework for modelling consumption-based energy demand and emission pathways. *Environ. Sci. Technol.* **54**, 1799–1807 (2020).
27. Bjørn, A. et al. Pursuing necessary reductions in embedded GHG emissions of developed nations: will efficiency improvements and changes in consumption get us there? *Glob. Environ. Change* **52**, 314–324 (2018).
28. Costa, L. et al. The decarbonisation of Europe powered by lifestyle changes. *Environ. Res. Lett.* **16**, 044057 (2021).
29. United Nations. Paris Agreement. https://unfccc.int/sites/default/files/english_paris_agreement.pdf (2015).
30. Pattberg, P. & Widerberg, O. The climate change regime. *In:* Oxford Research Encyclopedia of Climate Science https://doi.org/10.1093/acrefore/9780190228620.013.46 (Oxford University Press, 2017).
31. United Nations Framework Convention on Climate Change. Report of the Conference of the Parties serving as the meeting of the Parties to the Paris Agreement on its second session, held in Madrid from 2 to 15 December 2019

(CMA.2) - Decisions 1–9. https://unfccc.int/sites/default/files/resource/cma2019_06a01E.pdf (2019).
32. United Nations Framework Convention on Climate Change. Report of the Conference of the Parties serving as the meeting of the Parties to the Paris Agreement on its third session, held in Glasgow from 31 October to 13 November 2021 (CMA.3) - Decisions 1–4. https://unfccc.int/sites/default/files/resource/cma2021_10a01E.pdf (2021).
33. United Nations Framework Convention on Climate Change. Report of the Conference of the Parties serving as the meeting of the Parties to the Paris Agreement on the third part of its first session, held in Katowice from 2 to 15 December 2018 (CMA.1) - Decisions 3–12. https://unfccc.int/sites/default/files/resource/cma2018_03a01E.pdf (2018).
34. Wood, R., Moran, D. D., Rodrigues, J. F. D. & Stadler, K. Variation in trends of consumption based carbon accounts. *Sci. Data* **6**, 1–9 (2019).
35. Nordhaus, W. D. To tax or not to tax: alternative approaches to slowing global warming. *Rev. Environ. Econ. Policy* **1**, 26–44 (2007).
36. Grubb, M. et al. Consumption-oriented policy instruments for fostering greenhouse gas mitigation. *Clim. Policy* **20**, S58–S73 (2020).
37. Schmutzler, A. & Goulder, L. H. The choice between emission taxes and output taxes under imperfect monitoring. *J. Environ. Econ. Manage* **32**, 51–64 (1997).
38. Fullerton, D. & Mohr, R. D. Suggested subsidies are sub-optimal unless combined with an output tax. *Contrib. Econ. Analysis Policy* **2**, 1–20 (2003).
39. Creutzig, F. et al. Chapter 5: Demand, services and social aspects of mitigation. *In:* Climate Change 2022: mitigation of climate Change (eds. Shukla, P. R. et al.) https://doi.org/10.1017/9781009157926.007 (Cambridge University Press, 2022).
40. Rootzén, J. & Johnsson, F. Paying the full price of steel—perspectives on the cost of reducing carbon dioxide emissions from the steel industry. *Energy Policy* **98**, 459–469 (2016).
41. Stede, J., Pauliuk, S., Hardadi, G. & Neuhoff, K. Carbon pricing of basic materials: Incentives and risks for the value chain and consumers. *Ecol. Econ.* **189**, 107168 (2021).
42. Pollitt, H., Neuhoff, K. & Lin, X. The impact of implementing a consumption charge on carbon-intensive materials in Europe. *Clim. Policy* **20**, S74–S89 (2019).
43. Springmann, M. et al. Mitigation potential and global health impacts from emissions pricing of food commodities. *Nat. Clim. Change* **7**, 69–74 (2016).
44. Funke, F. et al. Toward optimal meat pricing: is it time to tax meat consumption? *Rev. Environ. Econ. Policy* **16**, 219–240 (2022).
45. Säll, S. & Gren, I. M. Effects of an environmental tax on meat and dairy consumption in Sweden. *Food Policy* **55**, 41–53 (2015).
46. Wirsenius, S., Hedenus, F. & Mohlin, K. Greenhouse gas taxes on animal food products: rationale, tax scheme and climate mitigation effects. *Clim. Change* **108**, 159–184 (2010).
47. Bechtold, K.-B. et al. What consumers want: a survey on European consumer attitudes towards plant-based foods. https://smartproteinproject.eu/market-research/ (2021).
48. Koomey, J., Schmidt, Z., Hummel, H. & Weyant, J. Inside the black box: understanding key drivers of global emission scenarios. *Environ. Model. Softw.* **111**, 268–281 (2019).
49. Zetterberg, L. & Elkerbout, M. Policy brief: the future of the EU emissions trading system - responding to the EU green deal proposals. https://www.mistracarbonexit.com/s/Policy-Brief_MCE_dec2019_3.pdf (2019).
50. Searchinger, T. et al. A pathway to carbon neutral agriculture in Denmark. (2021) https://doi.org/10.46830/wrirpt.20.00006.
51. Swedish Government. Biojet för flyget (Bio-jet for aviation)–SOU 2019:11. https://www.regeringen.se/4ac534/contentassets/6d591e58fd9b4cad8171af2cd7e59f6f/biojet-for-flyget-sou-201911 (2019).
52. International Energy Agency. World energy outlook. https://www.iea.org/reports/world-energy-outlook-2020 (2020).
53. Koomey, J., Schmidt, Z., Hausker, K. & Lashof, D. Exploring the black box: applying macro decomposition tools for scenario comparisons. *Environ. Model. Softw.* **155**, 105426 (2022).
54. Larsson, J. & Nässén, J. Konsumtionens klimatpåverkan - trender, mål och styrmedel (The climate impact of consumption - trends, targets and policy instruments). In: Konsumtionsrapporten 2019 (The consumption report 2019) (ed. Roos, J. M.) (University of Gothenburg, School of Business, Economics and Law, 2019).
55. Geissdoerfer, M., Pieroni, M. P. P., Pigosso, D. C. A. & Soufani, K. Circular business models: a review. *J. Clean Prod.* **277**, 123741 (2020).
56. Creutzig, F. et al. Towards demand-side solutions for mitigating climate change. *Nat. Clim. Chang.* **8**, 260–263 (2018).
57. Wadud, Z., MacKenzie, D. & Leiby, P. Help or hindrance? The travel, energy and carbon impacts of highly automated vehicles. *Transp. Res. Part A Policy Pract.* **86**, 1–18 (2016).
58. Morfeldt, J., Curtale, R., Kamb, A., Larsson, J. & Nässén, J. Carbon footprint effects of shifting from flights to night trains for Swedish tourism. *J. Clean. Prod.* **420**, 138321 (2023).
59. Karlsson, I. et al. Roadmap for decarbonization of the building and construction industry—a supply chain analysis including primary production of steel and cement. *Energies (Basel)* **13**, 4136 (2020).
60. Schmidt, S. et al. Understanding GHG emissions from Swedish consumption - current challenges in reaching the generational goal. *J. Clean Prod.* **212**, 428–437 (2019).
61. European Council. Fit for 55 - The EU's plan for a green transition. https://www.consilium.europa.eu/en/policies/green-deal/fit-for-55-the-eu-plan-for-a-green-transition/.
62. Bjorn, A., Lloyd, S. & Matthews, D. From the Paris Agreement to corporate climate commitments: evaluation of seven methods for setting 'science-based' emission targets. *Environ. Res. Lett.* **16**, 054019 (2021).
63. Bjørn, A., Lloyd, S. M., Brander, M. & Matthews, H. D. Renewable energy certificates threaten the integrity of corporate science-based targets. *Nat. Clim. Chang.* **12**, 539–546 (2022).
64. Ruiz Manuel, I. & Blok, K. Quantitative evaluation of large corporate climate action initiatives shows mixed progress in their first half-decade. *Nat. Commun.* **14**, 1–15 (2023).
65. European Commission. Proposal for a regulation of the European Parliament and of the Council concerning batteries and waste batteries, repealing Directive 2006/66/EC and amending Regulation (EU) No 2019/1020. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex%3A52020PC0798 (2020).
66. Wirsenius, S. et al. Comparing the life cycle greenhouse gas emissions land-use carbon opportunity costs. https://doi.org/10.46830/wrirpt.20.00006 (2020).
67. Szulecki, K., Overland, I. & Smith, I. D. The European Union's CBAM as a de facto climate club: the governance challenges. *Front. Clim.* **4**, 942583 (2022).
68. Nordhaus, W. Dynamic climate clubs: on the effectiveness of incentives in global climate agreements. *Proc. Natl. Acad. Sci. USA* **118**, e2109988118 (2021).
69. Santos, G. & Azhari, R. Can we save GHG emissions by working from home? *Environ. Res. Commun.* **4**, 035007 (2022).
70. Cerqueira, E. D. V., Motte-Baumvol, B., Chevallier, L. B. & Bonin, O. Does working from home reduce CO2 emissions? An analysis of travel patterns as dictated by workplaces. *Transp. Res. D Transp. Environ.* **83**, 102338 (2020).
71. Albrecht, J. The use of consumption taxes to re-launch green tax reforms. *Int. Rev. Law Econ.* **26**, 88–103 (2006).
72. Åkerman, J., Kamb, A., Larsson, J. & Nässén, J. Low-carbon scenarios for long-distance travel 2060. *Transp. Res. D Transp. Environ.* **99**, 103010 (2021).
73. Brynolf, S. et al. Review of electrofuel feasibility—prospects for road, ocean, and air transport. *Prog. Energy* **4**, 042007 (2022).
74. Curtale, R., Larsson, J. & Nässén, J. Understanding preferences for night trains and their potential to replace flights in Europe. The case of Sweden. *Tour Manag. Perspect.* **47**, 101115 (2023).
75. CE Delft. Taxes in the Field of Aviation and their impact. https://cedelft.eu/wp-content/uploads/sites/2/2021/03/CE_Delft_7M16_taxes_in_the_field_of_aviation_and_their_impact.pdf (2019).
76. Friman, M., Lättman, K. & Olsson, L. E. Public transport quality, safety, and perceived accessibility. *Sustainability* **12**, 3563 (2020).
77. Ek, K., Wårell, L. & Andersson, L. Motives for walking and cycling when commuting—differences in local contexts and attitudes. *Eur. Transport Res. Rev.* **13**, 1–12 (2021).
78. Eliasson, J., Pyddoke, R. & Swärdh, J. E. Distributional effects of taxes on car fuel, use, ownership and purchases. *Econ. Transp.* **15**, 1–15 (2018).
79. Zu Ermgassen, S. O. S. E. et al. A home for all within planetary boundaries: pathways for meeting England's housing needs without transgressing national climate and biodiversity goals. *Ecol. Econ.* **201**, 107562 (2022).
80. The Swedish Board of Agriculture. Köttkonsumtion av kött (Consumption of Meat). https://jordbruksverket.se/mat-och-drycker/hallbar-produktion-och-konsumtion-av-mat/konsumtion-av-kott (2023).
81. Global Food Institute Europe. Market insights on European plant-based sales 2020-2022 - Sweden. https://gfieurope.org/market-insights-on-european-plant-based-sales-2020-2022/#sweden (2023).
82. Keyßer, L. T. & Lenzen, M. 1.5 °C degrowth scenarios suggest the need for new mitigation pathways. *Nat. Commun.* **12**, 1–16 (2021).
83. Hickel, J. et al. Urgent need for post-growth climate mitigation scenarios. *Nat. Energy* **6**, 766–768 (2021).
84. Pedersen, J. T. S. et al. IPCC emission scenarios: how did critiques affect their quality and relevance 1990–2022? *Glob. Environ. Change* **75**, 102538 (2022).
85. Swedish Government. Regeringens proposition 2019/20:65 En samlad politik för klimatet—klimatpolitisk handlingsplan (Governmental bill 2019/20:65 Joint policy for climate change - climate policy action plan). https://www.regeringen.se/rattsliga-dokument/proposition/2019/12/prop.-20192065/ (2020).
86. Swedish Government. I en värld som ställer om - Sverige utan fossila drivmedel 2040 (In a transitioning world - Sweden without fossil fuels 2040) SOU 2021:48. https://www.regeringen.se/rattsliga-dokument/statens-offentliga-utredningar/2021/06/sou-202148/ (2021).
87. Pei, M., Petäjäniemi, M., Regnell, A. & Wijk, O. Toward a fossil free future with HYBRIT: development of iron and steelmaking technology in Sweden and Finland. *Metals* **10**, 972 (2020).

88. Stadler, K. et al. EXIOBASE 3: developing a time series of detailed environmentally extended multi-regional input-output tables. *J. Ind. Ecol.* **22**, 502–515 (2018).
89. Wilson, C. Meta-analysis of unit and industry level scaling dynamics in energy technologies and climate change mitigation scenarios. *IIASA Interim Report* (2009).
90. Grübler, A. Technology and global change. https://doi.org/10.1017/CBO9781316036471 (Cambridge University Press, 1998).
91. Statistics Sweden. Sveriges framtida befolkning 2022-2070 (The future population of Sweden 2022–2070)–demographic reports. https://www.scb.se/publikation/45769 (2022).
92. Swedish Energy Agency. Scenarier över Sveriges energisystem 2018 - ER 2019:07 (Scenarios for the Swedish energy system 2018). https://energimyndigheten.a-w2m.se/Home.mvc?resourceId=133529 (2019).
93. European Commission. In-depth analysis in support of the Commission communication COM(2018) 773 - a clean planet for all - A European long-term strategic vision for a prosperous, modern, competitive and climate neutral economy. https://ec.europa.eu/clima/policies/strategies/2050_en (2018).
94. Yang, Y. Two sides of the same coin: consequential life cycle assessment based on the attributional framework. *J. Clean Prod.* **127**, 274–281 (2016).
95. Schäfer, A. W., Evans, A. D., Reynolds, T. G. & Dray, L. Costs of mitigating CO2 emissions from passenger aircraft. *Nat. Clim. Chang.* **6**, 412–417 (2016).
96. Masnadi, M. S. et al. Global carbon intensity of crude oil production. *Science* **361**, 851–853 (2018).
97. Jing, L. et al. Carbon intensity of global crude oil refining and mitigation potential. *Nat. Clim. Chang.* **10**, 526–532 (2020).
98. Swedish Energy Agency. Drivmedel 2019 (Fuels 2019) - ER 2020:26. https://www.energimyndigheten.se/fornybart/hallbarhetskriterier/drivmedelslagen/vaxthusgasutslapp/ (2020).
99. O'Connell, A., Kousoulidou, M., Lonza, L. & Weindorf, W. Considerations on GHG emissions and energy balances of promising aviation biofuel pathways. *Renew. Sust. Energ. Rev.* **101**, 504–515 (2019).
100. Stockholm Exergi. Miljönyckeltal Stockholm Exergi 2019 (Key environmental figures Stockholm Exergi 2019). https://www.stockholmexergi.se/content/uploads/2020/01/Milj%C3%B6nyckeltal-2019_1.pdf (2020).
101. Swedish Energy Agency. Energiläget i siffror 2021 (Energy in Sweden in numbers 2021). https://www.energimyndigheten.se/statistik/energilaget/ (2021).
102. Larsson, J., Kamb, A., Nässén, J. & Åkerman, J. Measuring greenhouse gas emissions from international air travel of a country's residents methodological development and application for Sweden. *Environ. Impact Assess. Rev.* **72**, 137–144 (2018).
103. Kamb, A. & Larsson, J. Climate footprint from Swedish residents' air travel. www.flightemissionmap.org. (2019).
104. Dray, L. et al. Cost and emissions pathways towards net-zero climate impacts in aviation. *Nat. Clim. Chang.* **12**, 956–962 (2022).
105. Swedish Energy Agency. Energistatistik för småhus, flerbostadshus och lokaler (Energy statistics for small houses, multi-family housing and commercial spaces). https://www.energimyndigheten.se/statistik/den-officiella-statistiken/statistikprodukter/energistatistik-for-smahus-flerbostadshus-och-lokaler/ (2021).
106. Statistics Sweden. Genomsnittlig bostadsarea per person efter region, hushållstyp och boendeform (Average housing area per capita by region, household type and living arrangements). https://www.statistikdatabasen.scb.se/pxweb/sv/ssd/START__HE__HE0111/HushallT23/ (2021).
107. Statistics Sweden. Antal personer efter boendeform, ålder och kön (Number of people by living arrangement, age and gender). https://www.statistikdatabasen.scb.se/pxweb/sv/ssd/START__HE__HE0111/HushallT31/ (2021).
108. Eurostat. Eurostat manual of supply, use and input-output tables 2008 edition. https://ec.europa.eu/eurostat/web/products-manuals-and-guidelines/-/ks-ra-07-013 (2008).
109. National Institute of Economic Research. GDP per capita. Forecast database. (September 2022). http://prognos.konj.se/PxWeb/pxweb/en/TidigarePrognoser/TidigarePrognoser__20220928__f09_bnpkonsumtioninvesteringarochutrikeshandel/F0907.px/ (2022).
110. Grubler, A. et al. A low energy demand scenario for meeting the 1.5 °C target and sustainable development goals without negative emission technologies. *Nat. Energy* **3**, 515–527 (2018).
111. International Energy Agency. World energy balances. https://www.iea.org/data-and-statistics/data-product/world-energy-balances (2021).
112. Stadler, K. Pymrio—A python based multi-regional input-output analysis toolbox. *J. Open Res. Softw.* **9**, 8 (2021).

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