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Low carbon strategies need to tackle the carbon footprint of materials production

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Low carbon strategies need to tackle the carbon footprint of materials production

Paper issued from the International Research Conference: **"Strong Sustainability: How sustainable are Net Zero trajectories?"**

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Contributions
Antoine Teixeira conduct the study, build the calibration and parametrization databases, designed, developed and programmed the model, performed the simulations and the analyses, contributed to the interpretation of the results, created the plots, and wrote the paper. Julien Lefèvre contributed to design the study, participated in the interpretation of the results, and revised the whole paper.

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Abstract
Like Net-Zero GHG emissions (NZE) country goals which have recently multiplied, national low carbon strategies currently focus on reducing direct territorial emissions across sectors, such as domestic energy, transport, buildings and industry sectors. Doing so they do not tackle emissions embodied in imports and insufficiently emissions related to base carbon-intensive materials production which are used across sectors including for capital formation. However the carbon footprint of materials production (CFM) represents a high share of global emissions and is mostly embodied in imports in many rich countries. Here we develop a novel framework to assess and map the carbon footprint of materials at the country level in the present situation and in future scenarios. Replicable for other countries, our framework is applied to the case of France. We find that although territorial emissions from materials supply only stand for 53 MtCO2eq in 2015, the CFM amounts to 228 MtCO2eq, i.e. 3.4 tCO2e/cap with a high share of imported emissions. Furthermore, we show that current NZE strategy only reduces the carbon footprint by 46% by 2050 compared to 2015 as it barely abates the CFM. All final goods and services contribute meaningfully to the current and future CFM, in particular final services. Mapping the French CFM across supply chains and trade flows allows to identify key policy interventions towards more sustainable NZE strategies.

Keywords
Carbon footprint, materials production, low carbon strategies, scenarios analysis, input-output modeling, industrial ecology

JEL codes
Q56, Q58

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Résumé
Au même titre que les objectifs nationaux de neutralité carbone qui se sont récemment multipliés, les stratégies nationales bas carbone se concentrent actuellement sur la réduction des émissions directes territoriales des secteurs de production d'énergie, des transports, du bâtiment et de l'industrie. De cette manière, elles ne traitent pas des émissions indirectes associées aux importations et pas suffisamment de celles liées à la production de matériaux à forte intensité carbone et utilisés dans tous les secteurs, y compris pour la formation de capital.
Cependant, l'empreinte carbone de la production de matériaux (ECM) représente une part importante des émissions mondiales et est principalement incorporée dans les importations de nombreux pays riches. Ici, nous développons un nouveau cadre de modélisation permettant d'analyser et cartographier l'empreinte carbone des matériaux au niveau national de nos jours et pour de futurs scénarios.
Réplicable pour différents pays, celui-ci est appliqué au cas de la France. Malgré que les émissions territoriales dues à la production de matériaux ne représentent que 53 MtCO2eq en 2015, nous constatons que l'ECM s'élève à 228 MtCO2eq, soit 3,4 tCO2e/cap, avec une part importante d'émissions importées. En outre, nous montrons que la stratégie de neutralité carbone de la France ne réduit l'empreinte carbone que de 46 % d'ici 2050 par rapport à 2015, laissant l'ECM presque inchangée.
Tous les biens et services finaux contribuent de manière significative à l'ECM actuelle et future, en particulier les services finaux. La cartographie de l'ECM française à travers les chaînes d'approvisionnement et les flux commerciaux permet d'identifier les principales interventions politiques en faveur de stratégies de neutralité carbone plus durables.

Mots-clés
Empreinte carbone, production de matériaux, stratégie nationale bas-carbone, analyse de scénarios, modélisation entrée-sortie, écologie industrielle, émissions importées, CDN

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Codes JEL
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Introduction

In line with the Paris climate agreement[1], many countries have now adopted Net-Zero GHG Emissions (NZE) targets (https://eciu.net/netzerotracker) and national long-term strategies are being developed to reach carbon neutrality at the territorial level by around mid-century[2–4]. These strategies include sectoral roadmaps describing the measures to decarbonize the different sectors of the economy (energy supply, transport, buildings, industry and agriculture). However, existing strategies suffer several weaknesses. First, national NZE strategies are often restricted to territorial emissions from domestic producers. In this case they do not include specific ambitions to reduce emissions embodied in imports, putting aside the full impact of domestic consumption on climate change[5]. A carbon footprint approach following a life-cycle perspective is essential to account for imported emissions[6–8], especially when they stand for a big share of the carbon footprint such as for European countries[9]. Second, low carbon strategies (and most mitigation analysis) focus on direct emissions at the sectoral level without a life-cycle perspective on the carbon-intensive materials needed to build capital stocks in all sectors[10]. However, materials production (steel & iron, aluminum, cement, glass, chemicals & petrochemicals, and pulp & paper) currently accounts for almost one-quarter of global GHG emissions[8] and this share is expected to increase as global material demand could double by mid-century following economic trends[11–13]. This would extend the recent increase of the carbon footprint of materials production driven by the growth of capital stocks and all types of final consumption (including services)[8]. Deploying low-carbon infrastructure and technologies as foreseen by decarbonization plans could increase material demand even more than already expected[14–16], which is currently not fully taken into account in existing strategies and analysis[10,17]. All the more so as the potential for a fast transition to zero-carbon industrial processes and materials is still uncertain[18,19]. Recent studies provide a better understanding of the carbon footprint of materials (CFM) production across supply chains at the global level[8]. However, to our knowledge CFM analysis tailored to national contexts is currently lacking and is needed to improve country-driven climate and sustainability policies.

Here we develop a novel framework based on the CFM approach at the national level allowing to map country specific CFM across supply chains and trade in the present situation but also in future transition scenarios. Our framework involves a Hybrid Input-Output (HIO) model called MatMat that we developed[20] extending existing works[7,8,21–23] and following key modeling principles of the Industrial Ecology community[24,25]. It has been designed to study the determinants of current GHG footprints by disentangling the link between GHG emissions, capital formation, and materials production along the supply chains from abroad and domestic producers to the final demand. In particular, it includes an endogenization of capital formation in the computation of the carbon footprint and the CFM is assessed reproducing the Hypothetical Extraction Method (HEM) describes by Hertwich (2021)[8]. It also offers a parametrization interface to integrate exogenous shocks from various sets of expertise about low-carbon scenarios to assess future scenarios and climate policies. The framework, replicable for other countries, is applied here to France as a representative case study of many western economies.

We first compare territorial emissions in France with the carbon footprint of final consumption in 2015 detailing the contribution of materials supply to emissions, in particular the CFM across material types and final consumption. We highlight the high CFM compared to territorial emissions, else involved in all types of final consumption. Second, we project the French carbon footprint and the CFM by 2050 under the governmental NZE[26,27] scenario assuming that foreign countries meet their Nationally Determined Contribution (NDCs)[28,29]. It allows isolating the impacts of the national low carbon strategy and demonstrating how the current national plan relies on other countries to be sustainable from a footprint perspective, especially regarding the CFM. Third, we provide a detailed mapping of French GHG emissions from cradle to final consumption across scenarios which allows highlighting the main determinants of the CFM across supply chains and trade. Based on this mapping we finally discuss possible policy levers to tackle the CFM toward carbon footprint neutrality and a more sustainable national low carbon strategy.

1. Methods

Our study involved an hybrid Input-Output (IO) model called MatMat we developed[20] based on extending existing works[7,8,21–23] and following key modeling principles of the IE community[24,25] allowing flexibility, reproduction, and transposition to other case studies. It aims to fill existing gaps between Integrated Assessment Modelling (IAM) and Industrial Ecology (IE) communities[10,17] about global supply chains and the life-cycle perspective of future energy and materials systems at a national scale. In particular, it has been designed (i) to perform static analysis of the current economy but also prospective studies through the integration of exogenous scenarios from various sets of expertise about low-carbon scenarios, (ii) to disentangling the link between GHG emissions, investments demand and materials production along the supply chains from abroad and domestic producers to final domestic energy services. In particular, the consumption-based scheme includes an endogenization of capital and the carbon footprint of materials is assessed using the Hypothetical Extraction Method (HEM)[7,8].

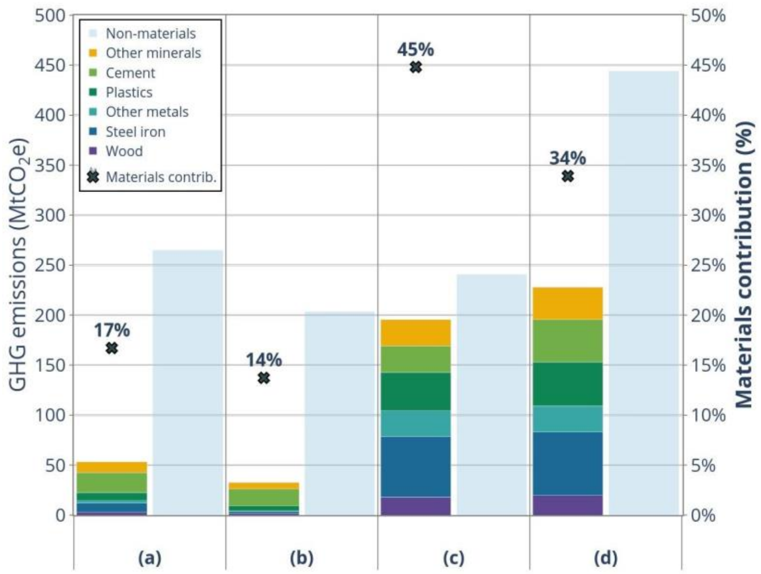
Departing from the Environmental Extended IO (EEIO) database Exiobase v3.7[23], we built a hybrid IO calibration database for our french case study based on a multi-layer approach[42]: energy fluxes are expressed in in k.tep, and GHG emissions in $MtCO_2e$. Note that we integrate the six main GHG about fossil fuels combustion and industrial processes. We exclude emissions from land-use change and agriculture as link between them and materials supply is not straightforward. We complete this dataset using KLEMS database to desegregate investment vector in a square matrix[7,43] and Eurostat databases to refine the quality of the physical fluxes, in particular about the energy balance.

Our model proposes an innovative method to build to prospective scenarios (e.g. the transition to Net-Zero emissions). It enables to integrate and reconcile at meso level various sets of expertise about the low-carbon transition from micro-scale (e.g. outcomes from energy models) to macro-scale (e.g. findings from macroeconomic models). In particular, MatMat provides a parametrization interface about (i) material, energy, carbon, and capital content of domestic production and imports, (ii) the evolution of final consumer and investment demands, and (iii) the change in trades. In the current study, the parametrization for prospective analysis by 2050 is built from bottom-up and macroeconomic expertises of the French governmental NZE scenario[26,26] and a global mitigation scenario[28,29]. The national scenario encompasses (i) macroeconomic drivers from ThreeME macroeconomic model[44], (ii) a complete description of energy efficiency gains in each economic sector from the energy model MedPro (https://www.enerdata.fr/research/), (iii) investment chronicles in low-carbon infrastructures and equipment (https://www.i4ce.org/theme_travail/investir-pour-le-climat-et-financer-la-transition/). The worldwide scenario includes a set of key parameters from the Imaclim-R World model[45] to describe indirect GHG emissions embodied in imports, i.e. energy efficiency gains and carbon content.

2. Results

2.1 Territorial emissions vs. carbon footprint of materials production

Figure 1. Overview of the contribution of materials to broad France's GHG emissions in 2015



Notes: (a) territorial emissions,
(b) territorial share of the carbon footprint
(c) imported share of the carbon footprint
(d) total carbon footprint

For each variable (x-axis), emissions are broken down to show the contribution of the production of each material (coloured left bars) from the rest (right light blue bars). This breakdown is given in MtCO2eq and represented by the bar plot (left y-axis), while the contribution of all materials is given in percentage by the black cross scatter plot (right y-axis).

In 2015, territorial GHG emissions accounted for 318 MtCO2eq in France (Fig. 1a), excluding GHG emissions from agriculture and land-use change. Materials supply contributed 'only' to 53 MtCO2eq of that amount (17%). Building materials stood for the major part: 20 MtCO2eq from cement, lime & plaster and 11 MtCO2eq from other minerals (stone, sand & clay, ceramics goods, baked clay products, and glass). Steel and iron participated in 9 MtCO2eq, rubber & plastics in 8 MtCO2eq, other metals (mainly aluminum) in 3 MtCO2eq, and woods and paper products in 3 MtCO2eq. Only part of territorial emissions from materials production was related to domestic final consumption, about 32 MtCO2eq (Fig. 1b), the rest being related to French exports. Most of it was from materials production required to build domestic infrastructures and buildings for final services and housing (Extended data Fig. 1b).

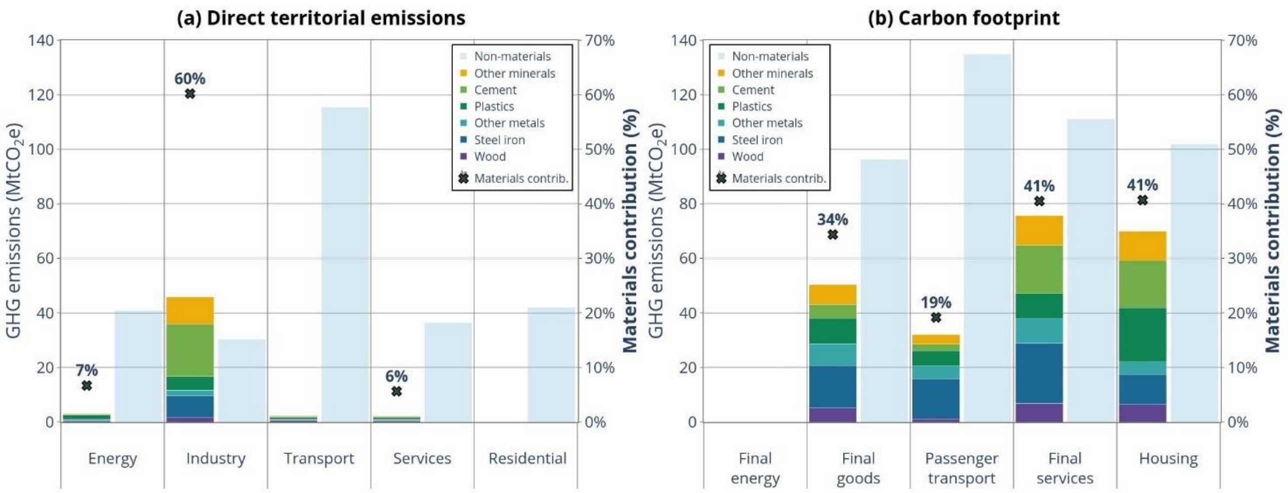
The carbon footprint extends the territorial producer-oriented perspective of GHG emissions accounting to a more inclusive approach of the full carbon impacts of domestic consumption. It covers total direct and indirect emissions involved to fulfill final domestic consumption, excluding GHG emissions embodied in exports. In 2015 the total French carbon footprint included 236 MtCO2eq of territorial emissions (Fig. 1b), and 436 MtCO2eq of imported emissions (Fig. 1c). In total, it reached up to 672 MtCO2eq (Fig. 1d), more than twice territorial emissions. The CFM contributed up to 228 MtCO2eq of that amount (34% of the total carbon footprint), four times territorial GHG emissions from domestic materials production. Steel & iron were responsible for 64 MtCO2eq of the carbon footprint of materials, rubber & plastics for 44 MtCO2eq, cement, lime & plaster for 43 MtCO2eq, other minerals for 32 MtCO2eq, other metals (mainly aluminum) for 26 MtCO2eq and wood and paper products for 20 MtCO2eq (Fig. 1d). 86% of the CFM were imported emissions (196 MtCO2eq). Emissions from metals and rubber & plastics were almost entirely imported, following the French low endowment in metallic and fossil resources[30]. For instance, only 12% of metals involved to satisfy final domestic consumption, were produced domestically (Table 1a). Emissions from building materials production are also part of imported emissions while those materials are mostly not contained in any imported goods. Those materials were involved in the production of the foreign capital formation needed to produce French imports. From the final consumer perspective, the carbon footprint of materials is quite distributed among all final goods and services: (i) final public, business, and trade services account for 33% of the CFM, (ii) housing (construction and maintenance of residential buildings plus heating/cooling systems and energy use) for 31%, final consumption goods (durable goods, e.g. furniture, electric appliances, and non-durable goods, e.g. food, clothing and chemicals) for 22%, and passenger transport (energy use and transport equipment and infrastructures related to public and private transportation) for 14% (Fig. 2b). Main differences across sectors stem from the carbon footprint of building materials, which is concentrated in final services and housing. Final services contribute the most to the CFM, breaking the myth of the dematerialized carbon-free service economy, as they rely indirectly on an important amount of materials production.

From all appearances, GHG emissions from materials production look a second order concern when focusing on the territorial emissions of a service-based economy like France which has experienced a strong and continuous deterioration of its trade balance and its production apparatus over the last 40 years[31]. It stands only for 17% of territorial emissions (Fig. 1a), well behind transport and buildings which amount respectively up to 37% and 25% in 2015 (Fig. 2a). The carbon footprint of materials production provides a very different perspective. It reflects a high share of materials in the total carbon footprint of domestic consumption (34%), an absolute high value (3.4tCO2eq/cap, more than twice the average total carbon footprint in India) and it is spread out in all final goods and services and types of materials. It thus should be a priority for climate policy making (Fig. 1d).

Table 1. Worldwide materials production required to satisfy France's final demand in 2015 and by 2050 following the NZE strategy

	Wood	Steel iron	Other metals	Plastics	Cement	Other minerals
Total materials demand in 2015 (G€)	41.7	44.6	28.2	97	20.6	22.5
(a) Production location in 2015 (%)						
Domestic	47.1	13.1	10.6	57.6	85.1	35.5
Abroad	52.9	86.9	89.4	42.4	14.9	64.5
(b) Final destination of total production in 2015 (%)						
Housing	35.43	18.66	19.36	51.44	50	35.11
Passenger transport	5.14	22.55	16.01	10.31	2.49	10.06
Final goods	23.12	23.9	30.21	18.53	6.12	20.81
Final services	36.31	34.89	34.41	19.72	41.39	34.02
(c) Growth of materials production from 2015 to 2050 in CP scenario (%)						
Domestic	75.01	47.31	63.35	31.4	64.12	75.38
Abroad	76.32	60.89	63.08	68	65.95	73.68
Total	75.7	59.1	63.11	46.92	64.39	74.28
(d) Additional growth of materials production from 2015 to 2050 from AP of the NZE strategy (%)						
Domestic	0.25	0.7	0.32	-1.25	2.48	-4.57
Abroad	-1.28	-2.57	-2.36	-2.47	-1.67	-2.46
Total	-0.56	-2.18	-2.08	-1.84	1.86	-3.21

Figure 2. Sectoral breakdown of French direct territorial emissions and carbon footprint in 2015 and contribution of materials production



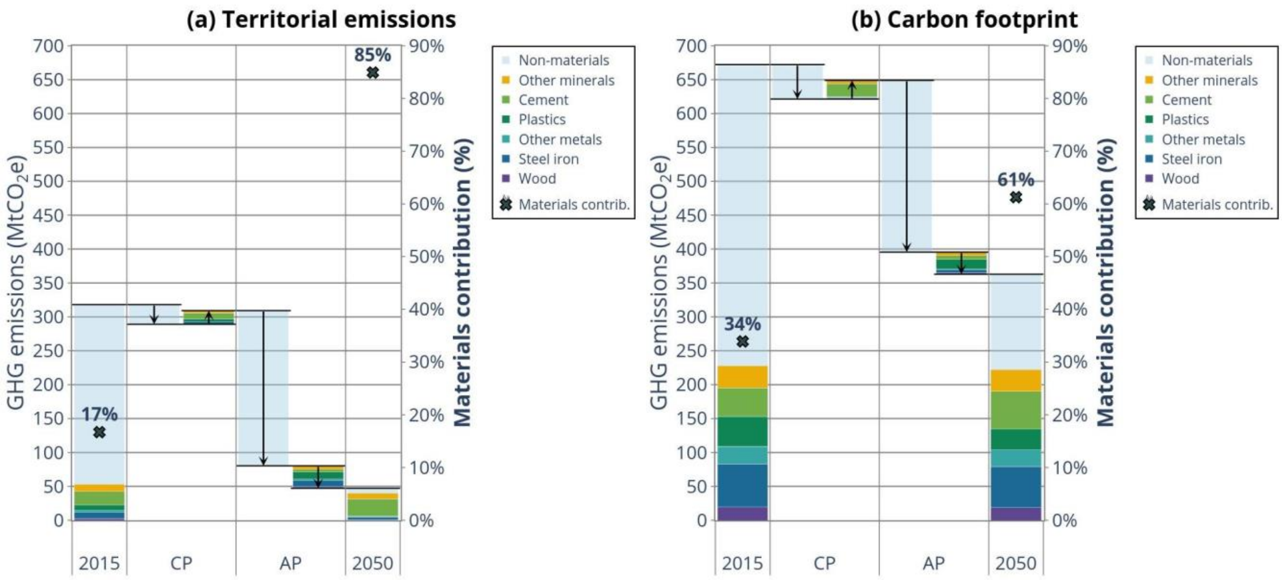
Note: For each sector (x-axis), the description of the bar and scatter plots is identical than Fig. 1.

2.2 A blind spot of current NZE strategies

Here, we investigate the impact of the French NZE strategy on the CFM by 2050. We analyze the reference scenarios of the most recent NZE strategy officially released[26,26]: (i) the Current Policies (CP) scenario based on trend economic growth and climate policies enacted prior 2016[32], and (ii) the Additional Policies (AP) scenario including ambitious measures and policies towards Net-Zero territorial emission by 2050. We assume that foreign countries follow their National Determined Contribution following existing worldwide climate mitigation scenarios[28,29]. More stringent global scenarios have not been implemented to properly isolate the specific impacts of French climate policies.

Current Policies (CP) do not abate territorial GHG emissions by 2050. Trend energy efficiency gains in buildings contribute to reducing them by 46 MtCO2eq compared to 2015 (Fig. 3a). However, energy efficiency gains are almost offset by the increase of territorial emissions from energy and materials supply (37 MtCO2eq) driven by economic growth (including an increase in exports) and the increase of materials demand. In the CP scenario, the emissions from domestic materials supply rise to 24% of total territorial emissions (Extended data Fig. 2a). Additional policies in the AP scenario allow to reach carbon neutrality by 2050 in almost every sector of the economy: transport, buildings, energy supply, and to a lesser extent industry. The remaining territorial emissions from industry and domestic materials production are planned to be compensated through forest management and the development of Carbon Capture and Storage (CCS) technologies[33]. We confirm that the NZE strategy could keep its promises of carbon neutrality with a caveat. By strictly applying the sectoral measures of the NZE strategy, we find 47 MtCO2eq remaining GHG emissions by 2050 to produce domestic materials (Fig. 3a), twice the official amount. The reason is that official scenarios assume stable levels of domestic materials production from 2010 to 2050, independent from trend economic growth and the demand for low-carbon infrastructure and equipment. Endogenizing materials production, we find that domestic materials production will increase between 30 to 75% in the CP scenario (Table 1c). Low carbon investments and the change in the dynamics of capital formation (deployment of renewable energy, buildings refurbishment, development of soft mobility and public transport, etc.) add another 5% of material production in the AP scenario (Table 1d). These results underline the importance of adopting a life-cycle perspective on materials demand in energy scenarios.

Figure 3. Variation of France's direct territorial emissions and carbon footprint from 2015 to 2050 following the NZE strategy



Notes: Impacts are decomposed between the contribution to GHG emission variations within the Current Policies (CP) and the one of Additional Policies (AP) by itself encompassed furthermore in NZE strategy.

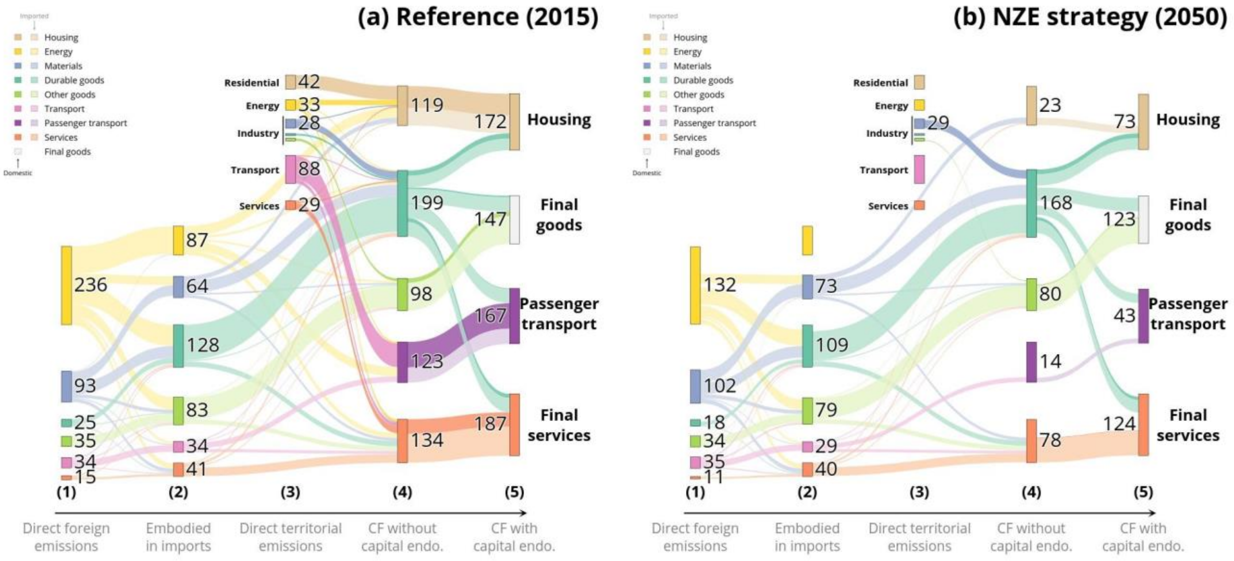
Like for territorial emissions, the carbon footprint hardly decreases in the CP scenario. Moderate energy efficiency gains and decarbonization under CP in France and NDC globally lead to a slight reduction of 3.5% of the carbon footprint by 2050 (Fig. 3b). However this trend is half offset by higher emissions from domestic and foreign material production needed to supply for the growing demand in France. Materials production abroad increases by 60 to 75% depending on the material considered (Table 1c). It is driven by the final consumption of all goods and services, but less by passenger transport for which a lower growth of the capital stock than the average of the economy is expected (Extended data Table 1a). Material demand of passenger transportation is concentrated in metals (20% of total production) and plastics (10% of total production) (Table 1b). Measures and policies in the AP scenario lead to a decline of 46% of the total carbon footprint compared to 2015 (Fig. 3b). 65% of the total drop comes from the decrease in territorial emissions, while only 35% is due to a reduction of imported emissions. Overall, most reductions concern non-materials-related emissions in both cases. In fact, the NZE strategy barely changes the CFM. It remains close to its 2015 level, about 222 MtCO2eq and represents 61% of the remaining carbon footprint. AP by itself only offsets the additional growth of the CFM observed in the CP scenario. Effects are concentrated in final services and housing which benefit from the decarbonization of domestic materials production, contrary to final goods and passenger transport which rely more on imported metals (Extended data Fig. 3). We conclude that the CFM is a blind spot of current French climate policy and additional policies are needed to tackle it.

2.3 Mapping the carbon footprint across supply chains and trade

Figure 4 represents Sankey diagrams mapping direct and indirect GHG emissions at different stages of supply chains. By tracking GHG emissions from their cradle at foreign and domestic suppliers to final domestic consumers, we explicit the link between GHG emissions, materials supply, and investment demand. Comparing 2015 situation to 2050 in the AP scenario, we highlight the key determinants of unabated GHG emissions at different stages of supply chains with a focus on material-related emissions.

Level (1) on Figure 4 describes the cradle of imported GHG emissions as direct emissions from foreign producers: in 2015 only 93 MtCO2eq were direct emissions from materials production, less than half the imported share of the CFM. The other half was mostly indirect emissions from upstream energy supply. This contrasts with the domestic share of the CFM mainly made of 85% of direct territorial emissions from materials producers (Fig. 2a) as domestic energy supply is less carbon intensive in France. The NZE strategy in the AP scenario leads to an increase of 102 MtCO2eq of emissions from foreign materials producers, offset by a slight reduction of emissions from energy supply for material production. Overall, global energy efficiency gains (NDC assumptions) allow compensating for the 60-75% growth of foreign materials production (Table 1c). Canceling the carbon footprint of materials at the source would imply more ambitious global decarbonization measures in trade partners industrial processes and of energy supply for materials production.

Figure 4. Formation of the French carbon footprint in 2015 by 2050 following the NZE strategy



Note: This Sankey diagram describes the distribution of GHG emissions in MtCO2eq along domestic and foreign value chains, from abroad and domestic producers to domestic final consumers: (1) Direct foreign emissions ; (2) Emissions embodied in imported goods and services ; (3) Direct territorial emissions ; Carbon footprint by final goods and services (4) without and (5) with the endogenization of capital goods. Fluxes lower than 2 MtCO2eq have not been drawn to lighten the figure. The nodes are sized based on 2015 values to explicit which fluxes are disappearing by 2050.

Level (2) describes GHG emissions embodied in imported goods. Energy products stand for 20% of imported emissions. The NZE strategy cancels those emissions by almost eliminating imports of fossil energy and achieving energy independence by 2050. However it leaves unabated emissions linked to imports of industrial and manufacturing products. Materials, non-durable and durable goods amount to 276 MtCO2eq in 2015 (63% of imported emissions) and 260 MtCO2eq in 2050 under AP scenario, half of it being from imports of durable goods. Also, most of these goods are directly destined to the final consumer, up to one-quarter of the total carbon footprint. Therefore, a change in the sourcing of manufactured goods, in particular durable, is a key option to reduce the carbon content of imports. It implies a transformation of production and consumption practices which is as much in the hands of consumers as in those of industry and government through the provision of public services.

Levels (4) and (5) describe the carbon footprint by final goods and services with and without capital endogenization. Comparing both levels for each type of final consumption outside final goods (housing, passenger transport, and final services) bring to the fore the load of the domestic capital formation on the carbon footprint of final services. Providing these services actually involves energy and GHG emissions to use the capital stock (e.g. fuel combustion for transportation and space heating) but also to build the capital stock[34]. In 2015, the latter accounted for 25-30% of the carbon footprint of the different final services, and mostly remain unabated emissions by 2050 in the AP scenario. The NZE strategy in fact focuses on canceling GHG emissions from capital use by renewing and extending existing capital stock, but without sufficient decarbonization of the production of capital stocks. Actions are needed to reduce jointly both types of emissions as recommended by the Industrial Ecology community[10].

3. Discussion

3.1 Towards more sustainable low carbon strategies

We found that the CFM in France amounted to 3.4 tCO2e/cap in 2015 (34% of total carbon footprint) compared to only 0.8 tCO2e/cap (53 MtCO2eq) for territorial emissions from material supply. Therefore, the CFM should be a main focus of low carbon strategies and climate policy. The novel framework developed here allows to map the CFM across supply chains and trade, assess the impact of low carbon strategies on the CFM and identify levers for further reducing the CFM towards climate neutrality at national scale. We show on the case of France that although current national NZE strategy could massively reduce territorial emissions and almost halve total carbon footprint, it would leave the CFM basically untouched (both territorial and imported emissions) by 2050. In fact, the load of materials production on GHG emissions especially remains at the background of final services wrongly thought of being sustainable and dematerialized. We conclude that the CFM is a main blind spot of current national strategy and additional measures are needed to tackle the CFM towards more sustainable footprints. We have further provided a detailed mapping of the carbon footprint and main determinants of the unabated CFM across supply chains. Based on this analysis, we discuss here additional policies to tackle the CFM at three different levels: (i) border policies supporting imports of clean industrial products at the national level, (ii) relocating low-carbon industrial productions next to material efficiency and circular economy policies, (iii) fostering low-energy an low-material demand patterns.

We have assumed here moderate climate policies in foreign trade partners (NDCs) to isolate the effects of domestic policies, but many countries have enacted more ambitious goals and similar NZE commitments than France by mid-century[4]. Keeping a high import dependency, the issue at stake is the speed of decarbonization in countries where imported goods are produced. Even if trade partners follow a track towards NZE by mid-century, a transitional state will remain around 2030 and 2040 with a high carbon content of imports, even after the emission peak[28,29]. Canceling the CFM from the cradle implies full decarbonization of the production of materials and associated energy supply. However, the potential for a fast transition to zero-carbon industrial processes and materials as required is still uncertain, all the more in developing countries producing most materials[18,19]. In addition, these countries might prioritize decarbonization of their domestic energy services, over that of their materials production. Overall, coordination and cooperation between importing and exporting countries are required to ensure the feasibility of carbon footprint neutrality: (i) North-South monetary transfers to support faster decarbonization of abroad industrial apparatus ; (ii) The implementation of a carbon tax at the border to encourage imports of low carbon manufacturing goods ; (iii) The development of climate clubs to ensure the broader cooperation and collaboration between countries allowing the endogenization of whole supply chains within national climate policies[35]. However, those options are dependent on the willingness of trade partners to follow them collectively and recent experiences have demonstrated the difficulty to do so. Thereafter, we discuss complementary levers that can be activated domestically to cancel the CFM.

The CFM is composed of imported manufacturing goods for the most part. Extending energy self-sufficiency as planned by the NZE strategy to manufacturing goods might be an effective option to reduce imported emissions. However, it would require adequate low-carbon domestic production capacities to substitute domestic production from imports. In a linear economy following the “take-make-dispose” principle, it especially requires raw materials, which are missing in countries like France. However, shifting to a circular economy viewpoint opens up new opportunities for relocation and reindustrialization while decreasing the CFM. Western countries like France have developed based on imports of materials and durable goods from other countries during last decades[30]. They have accumulated a stock of capital generating enough waste that could be turned into the main resources for the next few decades[36]. More concretely, three main types of circular economy strategies[37–39] could contribute to decreasing the CFM and decouple economic activity from material extraction: closing supply chains (recycling, reuse, remanufacturing); product lifetime extension (more durable goods, repairing) and resource efficiency (process and design improvements, sharing, etc.). However, the world economy is still only 6% circular[40]. Moving towards circularity will imply deep structural changes and industrial reorganization around new innovative technology clusters and supply chains.

Eventually, reducing domestic final demand for materials and manufacturing is a needed complementary way to reach carbon footprint neutrality by mid-century. Low-energy demand (LED) policies have demonstrated their potential to provide equivalent energy services more efficiently while reducing the demand for energy and new infrastructures and equipment[39,41]. It enables a reduction in the demand for imported manufacturing goods while reducing imported GHG emissions. Deploying LED patterns allows to decrease the demand for energy next to capital goods, which can facilitate the transition to a local circular economy.

Using a case study on France allowed us to propose a fine analysis of value chains for the whole economy (Fig. 4), isolate key determinants of CFM, and draw up a list of recommendations for public policies. We believe these guidelines stand for many western countries with similar characteristics, i.e. high CFM, low direct territorial emissions from materials production, and high trade deficit regarding manufacturing goods. Our framework is applicable to any other countries and based on a modeling platform MatMat in the process of being put in open-source. Beyond the general policy conclusions that can be drawn from the case of France, country specific analysis is needed to differentiate policy recommendations and derive domestic policies tailored to the particular structure of the CFM across supply chains and trade.

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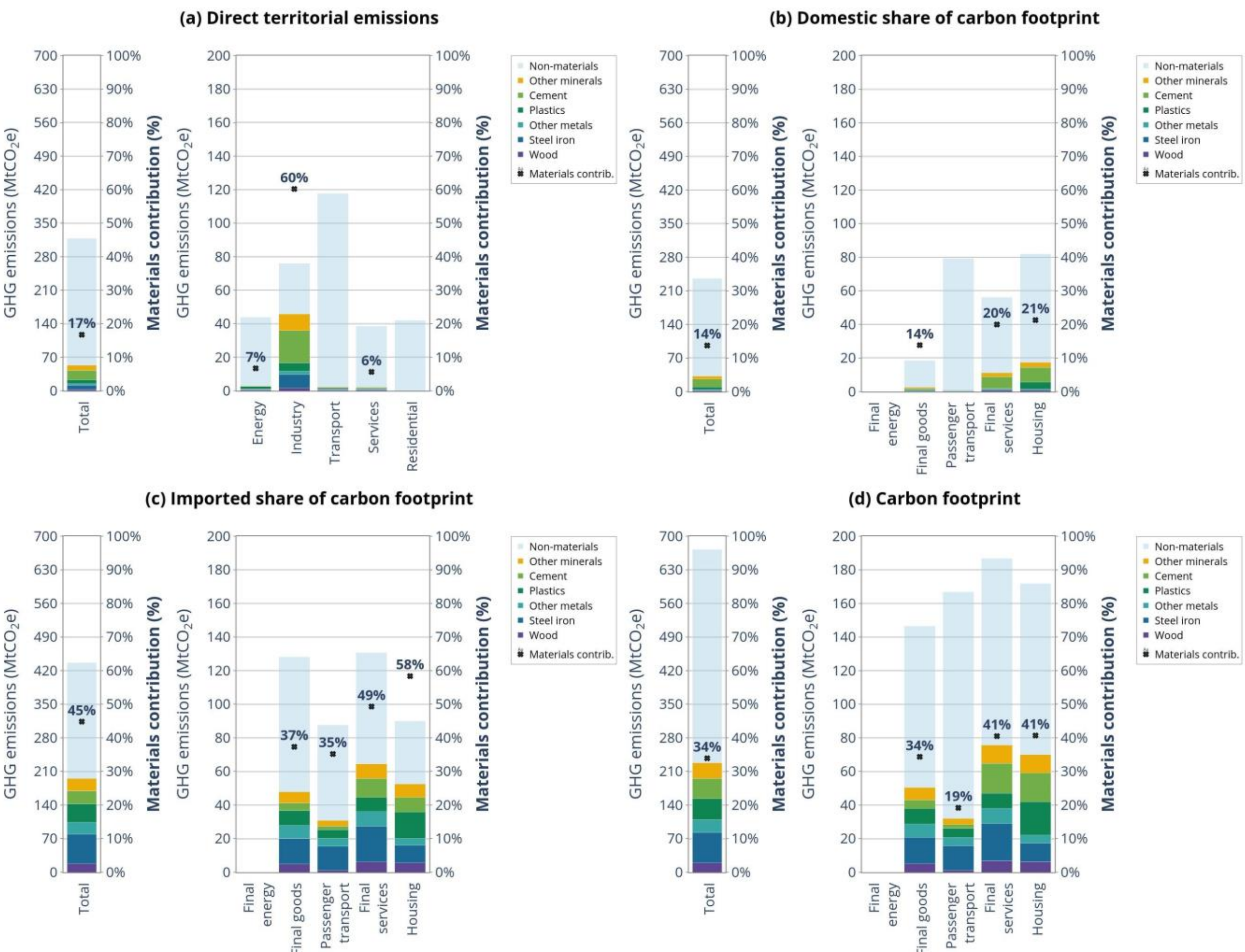
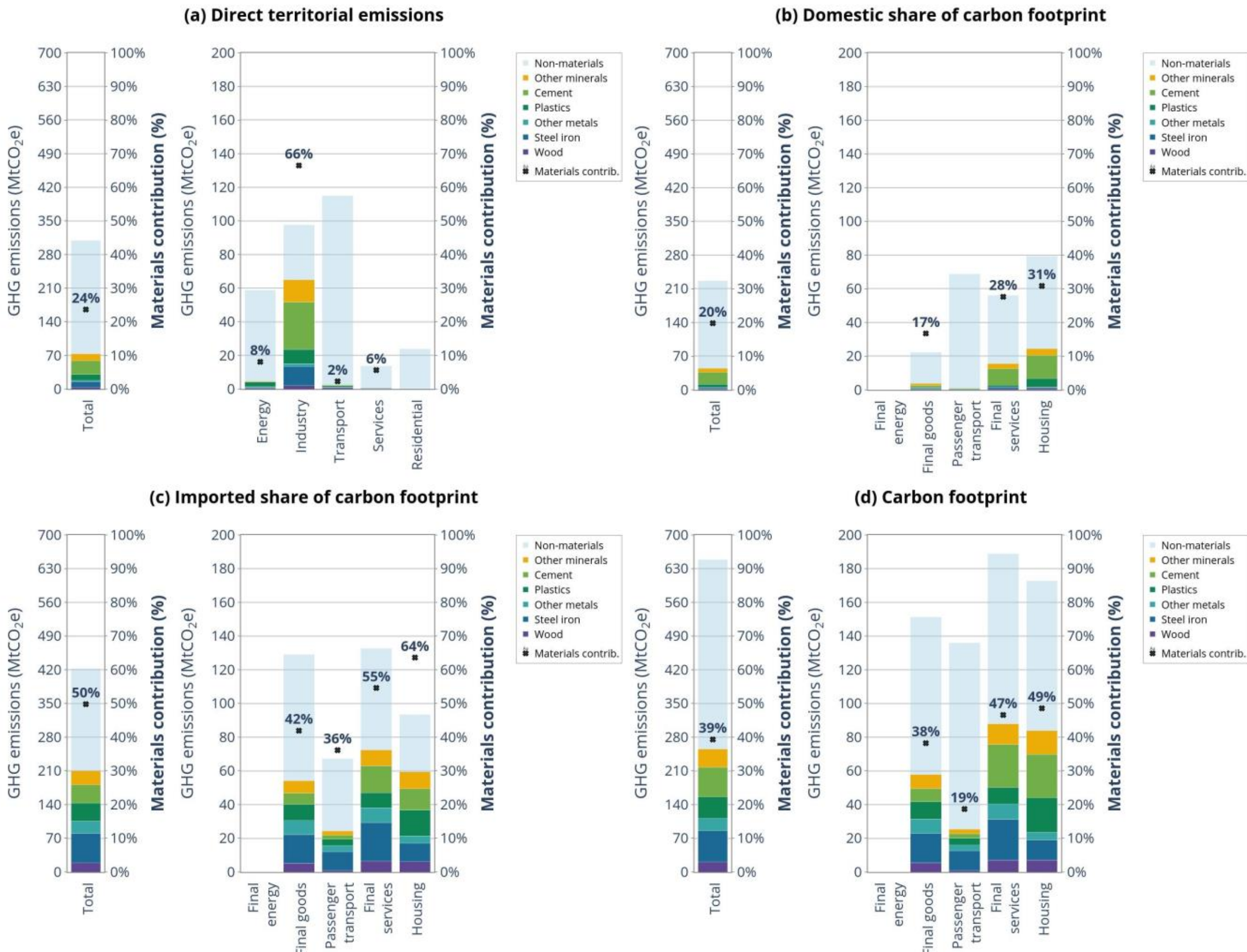
Extended data

Fig. 1 Contribution of materials supply in the French GHG emissions in 2015



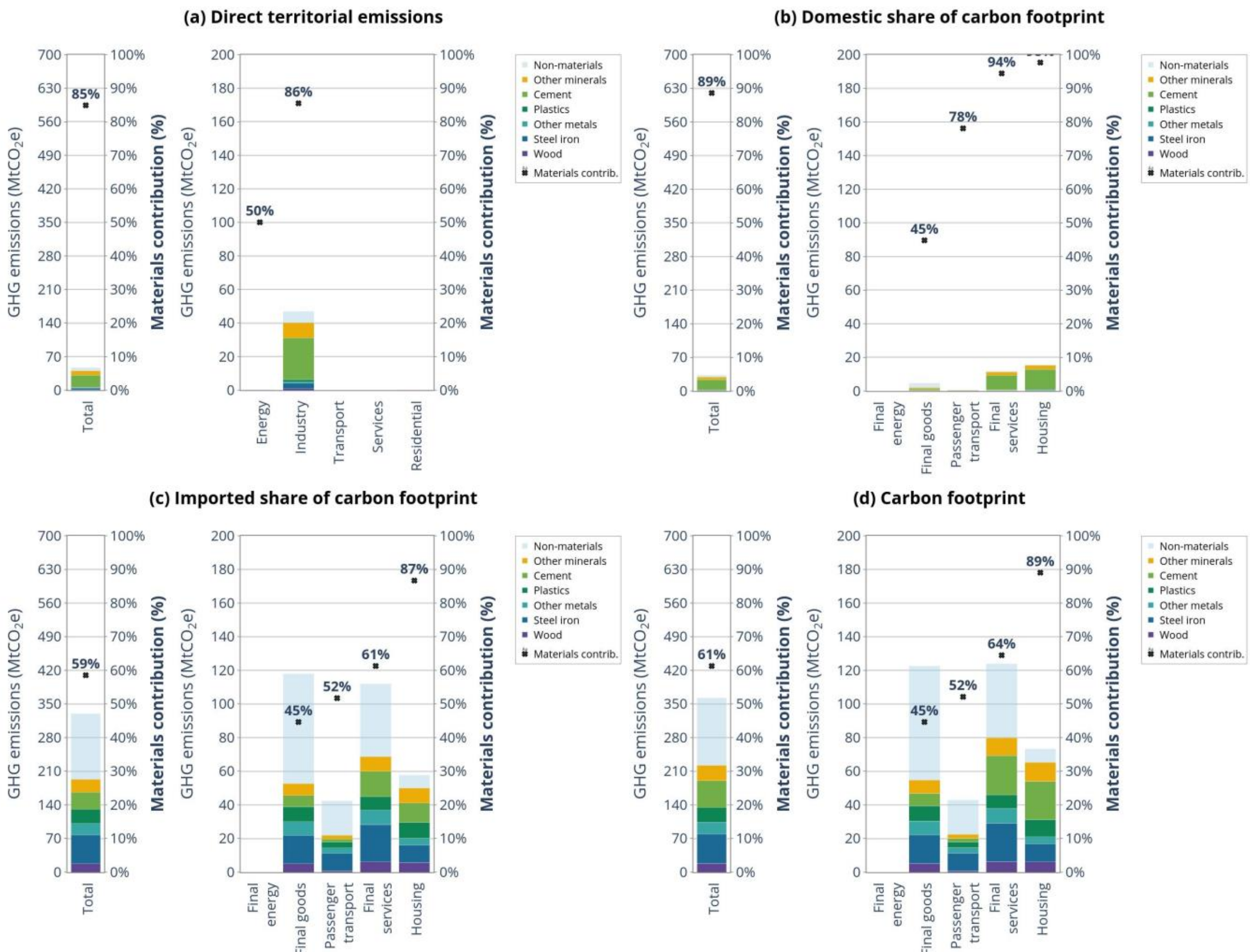
Note: Emissions are given for each variable by total (left) and sectoral breakdown (right). Beyond, emissions are broken down to show the contribution of the production of each material. This breakdown is given in MtCO2es and represented by the bar plot (left y-axis), while the contribution of all materials is given in percentage by the black cross scatter plot (right y-axis).

Fig. 2 Contribution of materials supply in the French GHG emissions by 2050 following current policies



Note: Emissions are given for each variable by total (left) and sectoral breakdown (right). Beyond, emissions are broken down to show the contribution of the production of each material. This breakdown is given in MtCO2eq and represented by the bar plot (left y-axis), while the contribution of all materials is given in percentage by the black cross scatter plot (right y-axis).

Fig. 3 Contribution of materials supply in the French GHG emissions by 2050 following the NZE strategy



Note: Emissions are given for each variable by total (left) and sectoral breakdown (right). Beyond, emissions are broken down to show the contribution of the production of each material. This breakdown is given in MtCO2eq and represented by the bar plot (left y-axis), while the contribution of all materials is given in percentage by the black cross scatter plot (right y-axis).

Table 1. Driver of Materials production growth from 2015 to 2050 following the NZE strategy

		Wood	Steel iron	Other metals	Plastics	Cement	Other minerals
Growth of total materials demand (%)		75.14	56.92	61.03	45.08	66.25	71.07
(a) Growth from trend economic growth and Current Policies (%)							
Domestic	Housing	15.42	2.14	2.15	7.77	31.51	15.89
	Passenger transport	0.11	−0.05	0.09	−0.01	0.49	0.19
	Final goods	6.27	1.45	1.77	4.96	2.3	2.27
	Final services	13.57	2.67	2.71	5.36	20.27	8.38
Abroad	Housing	13.82	9.74	10.16	8.78	3.25	16.12
	Passenger transport	0.86	5.17	3.69	1.72	0.33	1.98
	Final goods	12.62	16.93	21.67	9.97	2.07	13.86
	Final services	13.04	21.04	20.87	8.36	4.18	15.58
(b) Growth from Additional Policies (%)							
Domestic	Housing	0.13	0.06	0.04	−0.31	1.37	−0.85
	Passenger transport	−0.06	−0.01	−0.02	−0.1	−0.06	−0.17
	Final goods	0	0.01	0	−0.05	0.02	−0.13
	Final services	0.04	0.03	0	−0.19	0.78	−0.49
Abroad	Housing	−0.16	−0.46	−0.5	−0.42	0.01	−0.41
	Passenger transport	−0.27	−1.05	−0.83	−0.36	−0.16	−0.62
	Final goods	−0.05	−0.16	−0.15	−0.09	−0.04	−0.12
	Final services	−0.2	−0.59	−0.63	−0.33	−0.06	−0.43

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