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Reducing material requirements while decarbonising the Spanish economy: from a green growth to a postgrowth paradigm

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Supplementary material for this article is available online

Abstract

The transition to a low-carbon economy is expected to increase material requirements, as low-carbon technologies (LCTs) typically require more materials than fossil fuel-based energy systems. Here, we extend the MEDEAS-Spain Integrated Assessment Model (IAM) to improve the representation of material requirements, stocks, and flows. Key novelties are: (i) the use of sectoral material demand intensities for each economic sector, (ii) the consistent representation of material stocks and flows, (iii) for an exhaustive list of 43 mineral materials covered. We perform an impact analysis on the material requirements and associated environmental impacts (final energy consumption, greenhouse gas (GHG) emissions, and material footprint) of a baseline and three decarbonisation scenarios (reaching a 100% renewable electricity mix) to 2050. First, the PNIEC-LTDS scenario represents the national energy and climate plan (consistent with a green growth paradigm). Second, the CappedEcon scenario presents a final demand capped to its 2025 level (moderate demand-side measures). Third, the Sufficiency scenario is parametrised by downscaling monetary final demand across sectors to a level sufficient to provide decent living standards for the entire Spanish population; a novel approach within IAMs that aligns well with a postgrowth paradigm.

The results show that the material requirements of LCTs deployment are substantial. For the PNIEC-LTDS scenario, LCTs are responsible for more than 30% of total cumulative (2025–2050) requirements for copper (36%), chromium (70%), cobalt (84%), graphite (81%), lithium (66%), and nickel (82%). The material footprint increases by 47% between 2025 and 2050 for the PNIEC-LTDS scenario. However, material requirements are mostly driven by final consumption for the rest of economic activities (74% of the cumulative material footprint for the PNIEC-LTDS scenario). In contrast, the Sufficiency scenario achieves a large reduction in GHG emissions (fossil-fuel emissions are reduced by 93% compared to 2025) and in material footprint compared to the other scenarios (and reduced by 55% compared to 2025). The robustness of the results is ensured through a range of uncertainty analyses. Our results therefore suggest that reducing the level of final demand (with sector-specific reductions), in line with the transition to a postgrowth

paradigm, could be crucial to reconcile a rapid and large deployment of LCTs with a reduction in material footprint.

1. Introduction

1.1. Background and context

The 'Fit for 55' package of legislation defines a set of climate change mitigation targets at the European Union (EU) level. Targets are set to reduce greenhouse gas (GHG) emissions by 55% by 2030 compared to 1990, and to supply 42.5% of final energy demand with renewable energy by 2030 [1]. The international context has also fostered a set of measures at the EU level to support the energy transition. The attempt to build a common response and stimulus to the pandemic has resulted in the EU Next Generation funds, directed amongst other purposes to green investments [2]. The REPowerEU plan, adopted in the wake of the war in Ukraine, seeks to reduce the reliance on Russian oil and gas through a set of measures, including the development renewable energy systems [3][8]. Spain is a major country in terms of renewable energy generation and installed capacity[9], and is attracting considerable investments in alternative energy systems [6]. The targets to 2050, which are set out in the Long Term Decarbonisation Strategy (LTDS) [7], are ambitious. Targets include a 90% GHG emissions reduction (compared to 1990), a fully renewable power system, and a 97% share of final energy demand covered by renewable energy. The National Integrated Plan for Energy and Climate (PNIEC) defines short-term objectives to 2030, and sets a target of 32% GHG emissions reduction compared to 1990 (55% compared to 2005), and 81% of electricity generation and 48% of final energy demand covered by renewable energy, respectively [6].

Figure 1(a) shows that the share of electricity covered by renewable energy has strongly increased in Spain, from 15.6% in 2000 to 50.1% in 2023. Such an increase has been allowed by the substantial deployment of solar and wind power technologies, which generation share has increased from 2.1% in 2000 to 40.5% in 2023. Despite the quick deployment of renewable energy in recent years, particularly for solar PV, figure 1(b) shows that the capacity in service in 2023 is still much lower than the 2030 targets for solar PV (76 GW) and for wind power (62 GW) — wind and solar deployment targets are not available to 2050. However, we note that according to the Spanish Electric Grid [8] the capacity of solar PV and wind power approved but not yet connected to the grid is approximately 72 GW and 28 GW, respectively, thus sufficient to exceed the PNIEC targets in terms of solar PV (values obtained in December 2024). The effects of nearly a lost decade in investment in renewable energy deployment, which resulted from the reversal of incentives for renewable energy deployment in the aftermath of the 2008 economic crisis (see e.g. [9, 10]) can be clearly visualised. Despite their level of ambition regarding the deployment of low-carbon technologies (LCTs), neither the PNIEC nor the LTDS address in detail their material implications.

1.2. The material challenges of an ambitious energy transition

LCTs (renewable energy systems, electric vehicles, batteries) require large amounts of non-renewable materials, typically much more than traditional fossil fuel-based energy systems (both in terms of quantities, and in terms of range of materials) [11, 12]. As such, the demand for specific materials (for instance, for lithium, cobalt, or rare earth elements) is expected to surge dramatically [13–15], particularly in the power (renewable energy systems, grids and batteries) [16, 17] and transportation (electric vehicles engines and batteries) [18, 19] sectors. Considering the criticality of materials for the energy transition, but also the considerable environmental impacts of raw material extraction and processing [20, 21], an increasing number of studies attempts to capture the material requirements of the energy transition and to identify critical materials and levers to mitigate environmental impacts and supply risks [22]. Numerous studies have raised concerns regarding the fact that material requirements are extremely high and may exceed currently known reserves (or even resources) for some materials under current transition plans [23–25][10]. While reserves are likely to keep increasing as a result of technological and economic factors [26–28], such results highlight the material challenge of the energy transition.

[8] Note however that REPowerEU funds are also partly directed to developing new fossil fuel infrastructure, leading to a serious risk of carbon lock-in [4].

[9] The International Renewable Energy Agency for instance ranks Spain as 5th and 7th country in terms of wind power and solar energy installed capacity, respectively [5]. Data for the year 2023.

[10] Reserves refer to currently known mineral deposits for which the extraction is currently both technologically feasible and economically profitable, while resources refer to currently known deposits that could potentially be one day recovered.

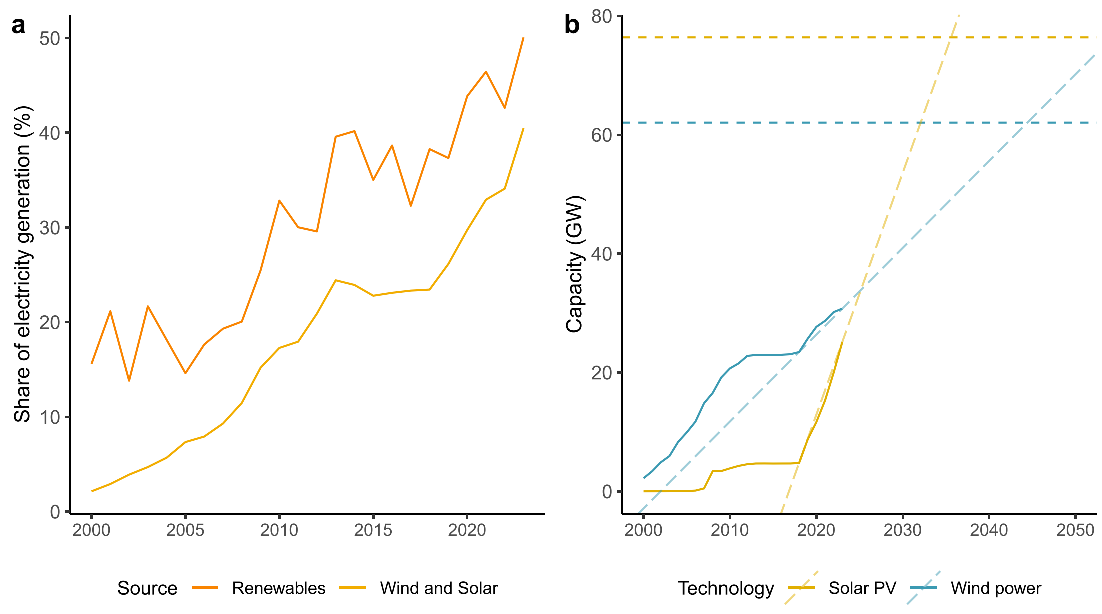

Figure 1. (a) Historical renewable energy and variable renewable energy (solar and wind power) electricity generation shares, and (b) historical deployment capacity of wind power and solar photovoltaic (PV) alongside trends and national targets to 2030 (dotted horizontal lines).

Recent works have quantified the material requirements for Spain in the context of the energy transition. First, García-Gusano *et al* [29] analyses the future critical material requirements of the power sector in Spain using an optimisation model (with a cost optimisation procedure), and finds that criticality indicators may considerably worsen as a result of the decarbonisation. Second, Lallana *et al* [30] analyses the material requirements of the Spanish energy and digital transition, and finds that the material requirements of the Spanish energy transition will be considerable (although they can be reduced with demand-side and circular economy policies), with a very large contribution of the automotive sector. However neither study captures the material requirements of the rest of economic activities.

Despite the growing interest and research on the material requirements of the energy transition (including on low energy demand and material modelling, see [31]), recent work shows that most Integrated Assessment Models (IAMs) still lack a comprehensive representation of material cycles and of their associated energy requirements [32–34]. Indeed, most models considering material cycles only do so for very limited materials (mostly steel and cement). It is worth noting, however, that recent developments in some IAMs, for instance IMAGE (see e.g. [13, 16, 35]), MESSAGE (see [36]), or MEDEAS (see [19]) seek to expand and improve material representation. Specifically, the MEDEAS set of models have so far combined a bottom-up approach for LCTs with an empirical linear relationship between material demand and GDP [37], which has however been criticised as a questionable approach (for example, the approach conflicts with empirical data in higher-income countries) [38]. More recently, the approach was expanded to explicitly represent stocks and flows of materials in the transportation sector [19]. Here, we further extend the representation of materials by (i) using sectoral material demand intensities to account for the effects of economic structure on material demand, and (ii) explicitly representing economy-wide stocks and flows of materials.

1.3. The need for alternative, postgrowth economic scenarios

There is increasing evidence and recognition of the critical role of demand-side measures for climate change mitigation [39]. Reducing demand for energy services and materials can considerably facilitate meeting climate targets by reducing the required deployment of LCTs and associated impacts [40]. Recent studies quantifying the energy and material requirements for good living standards have for instance shown that energy and material consumption could be significantly reduced while still delivering good living standards for the whole population [41–45].

At the macroeconomic level, researchers have asserted the urgent need to develop alternative, postgrowth mitigation scenarios in IAMs [46–48]. Such scenarios may be regarded as describing the macroeconomic counterpart of large scale and ambitious demand-side measures to reduce energy and material requirements in the Global North. In brief, the evidence for absolute decoupling between environmental impacts and economic output is, to date, limited [49][11]. When such absolute decoupling may be observed, it does not meet the pace required to remain within acceptable limits, as shown for instance for CO_2 emissions in high-income countries [53]. By reducing energy and material demand, postgrowth scenarios therefore offer alternative mitigation pathways that reduce the reliance on risky and speculative (because so far, unproven at a large scale) negative emission technologies (see e.g. [54–56]).

Attempts to explore postgrowth scenarios in IAMs have been so far limited, although the literature is rapidly expanding [57–59]. Recent (non-exhaustive) examples include studies using the MEDEAS, EUROGREEN, LowGrow, and MESSAGE models. Using MEDEAS, authors have represented postgrowth scenarios with a decreasing level of aggregate economic activity alongside policies (e.g. working time reduction, increasing pro-labour income distributions, declining productivity growth, and structural changes in the productive sector) [60]. With the EUROGREEN model, a degrowth scenario has been represented for France implementing voluntary cuts in consumption and exports alongside a wealth tax and two policies for social equity: a working time reduction and a job guarantee [61]. Third, with the LowGrow stock-flow-consistent model in the case of Canada, and using a scenario combining a fast decarbonisation, reductions in income inequality, and reduction in working hours, authors show that increasing environmental and social outcomes are compatible with economic growth rates decreasing towards zero [62]. Fourth, recent studies have explored postgrowth scenarios with the MESSAGE IAM for Australia [63, 64], representing postgrowth scenarios using a non-monotonic utility function (for which utility peaks at a given consumption level), calibrated to peak at different GDP per capita levels. However, none of these studies apply a selective, literature-based downscale in the sectoral level of final demand. In the present work, we apply a novel methodology to study dynamically the material and environmental impacts of a sufficiency scenario consistent with the postgrowth principle of a selective downscaling of economic activities to a level sufficient to meet good living standards for all.

1.4. Contributions, research questions, and paper structure

Here, we present an impact analysis of the material requirements of three decarbonisation scenarios for Spain (alongside a baseline), including the Spanish national energy and climate plan. We use MEDEAS-Spain, the national development of the MEDEAS IAM (see [65]) for Spain. As the aim is to conduct an impact analysis of these decarbonisation scenarios (and not to judge their viability), the constraining feedback loops of the MEDEAS framework are deactivated. Specifically, the paper investigates the following questions for the case study of Spain:

- What are the material requirements of the energy transition, and how do these relate to the material requirements of the rest of economic activities?
- What are the environmental impacts associated with the energy transition, and how do these relate to those associated with the rest of the economy?
- To what extent can the transition to a postgrowth economic paradigm lower the material requirements and the associated environmental impacts?

Our contributions are threefold. First, in addition to the material requirements of LCTs, we also quantify the material requirements of the rest of economic activities using a novel method with sectoral material demand intensities, thereby contextualising the material implications of the energy transition within those of the broader economy. Second, we model the environmental impacts associated with material requirements in terms of material footprint, final energy consumption, and GHG emissions, distinguishing impacts entailed by the deployment of LCTs and by the rest of economic sectors. Furthermore, we quantify the material footprint avoided due to the reduction in fossil fuel extraction as result of the energy transition. Third, the use of an input output structure allows us to define and explore in a novel way the representation of a sufficiency scenario consistent with a postgrowth paradigm, whereby some economic sectors are downscaled while still meeting a sufficient level of economic activity to provide good living standards for all.

The paper is structured as follows. Section 2 introduces the key features of MEDEAS-Spain, and describes the materials module developed. Section 3 details the scenarios analysed, section 4 presents the results, and section 5 discusses the results, main limitations, and avenues for further work. Last, section 6 presents the key conclusions of the study.

[11] Even more so when considering that in many cases, Global North countries are outsourcing energy and emission-intensive industries to developing countries [50–52].

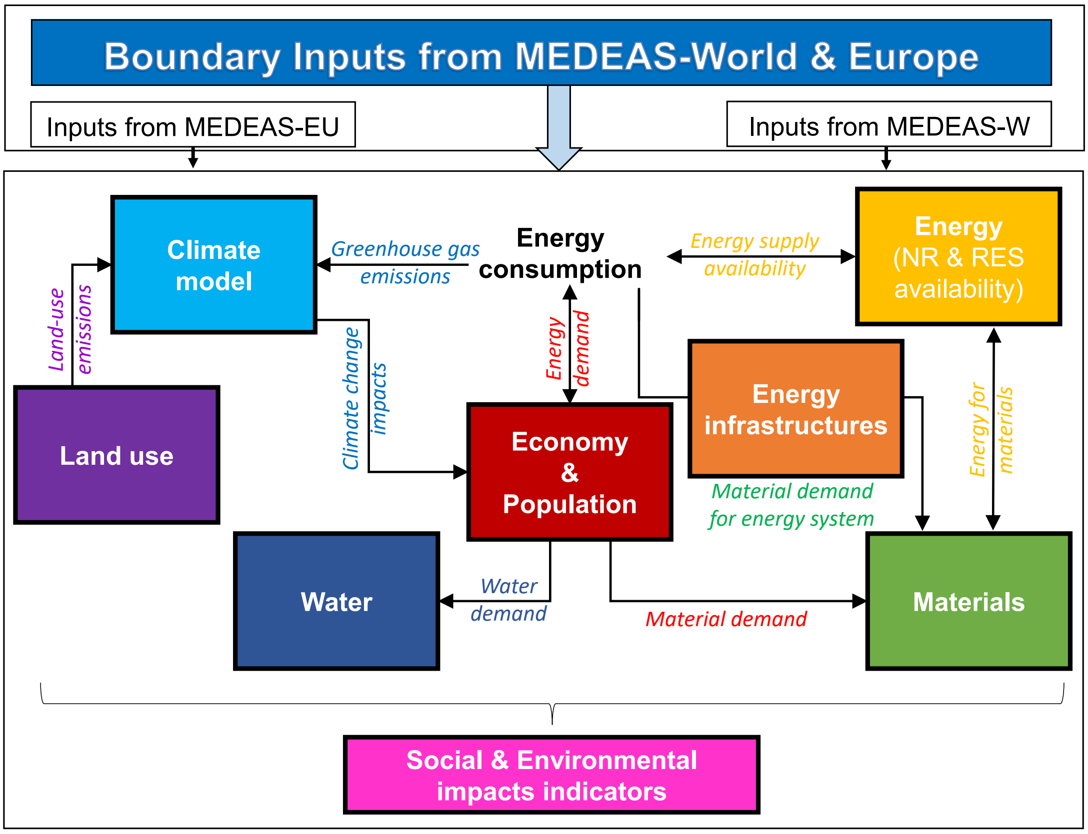

Figure 2. Overview of the MEDEAS-Spain model. Adapted from [65] with permission from the Royal Society of Chemistry. See SI-1, section 2 for a description of the external inputs obtained from MEDEAS-EU and MEDEAS-W.

2. Methodology

Sections 2.1 and 2.2 provide an overview of the MEDEAS-Spain model and of the materials module, respectively. Details of the materials module can be found in supplemental information (SI) 1, and input data are available in SI-2.

2.1. General model

MEDEAS-Spain consists of three different regions: Spain, the Rest of the European Union (RoEU), and the Rest of the World (RoW). Figure 2 shows the general structure of the model, which is formed by a set of 9 modules: the economy, water, energy demand, land use, climate, energy availability, energy infrastructures, materials, and social and environmental impacts modules. An in-depth presentation of the MEDEAS set of models can be found in Capellán-Pérez *et al* 2020 [65]. In brief, MEDEAS is a system dynamics model, coupled with a 35 sector input–output structure based on the World Input Output Database [66, 67]. (See SI-1, section 1 for the sector list.) MEDEAS is a demand-driven model, whereby the demand for each economic sector drives total production. The first step is therefore to determine final demand, broken down by each of the 35 MEDEAS-Spain sectors. Final demand is disaggregated in terms of households consumption, gross fixed capital formation, government expenditures, and exports. Two perspectives can be adopted for the determination of final demand.

(i) Final demand as the demand for goods and services produced in Spain

This perspective includes the final demand of the RoEU and RoW regions for the output of any industry located in Spain (i.e. exports), and only includes the part of the final demand by local residents that is directed towards the output of domestic sectors. This is the perspective adopted by default in MEDEAS-Spain, as it allows the quantification of changes in demand patterns (including by agents located abroad) on the total Spanish production (output), and to derive indicators such as the Spanish final energy consumption, or GHG emissions (production-based approach). We refer to this definition of final demand as the **final demand for Spanish goods and services**.

Table 1. Determination of each of the components of final demand in MEDEAS-Spain.

Component	Determination in model	Inclusion
Households consumption	Households consumption is calculated as a function of disposable income and households' net wealth. The parameters of this equation have been estimated econometrically with historical data.	In the final demand for Spanish goods and services, only the fraction corresponding to the demand for domestic sectors is included. Fully included in the Spanish final demand.
Gross fixed capital formation	Gross fixed capital formation (investment) is estimated at the sector level considering a desired capital stock, deriving using each sector's capital intensity, expected output, and spare capacity. Then, the desired investment is determined considering not only the desired capital stock but also the existing capital stock and capital depreciation. An investment matrix is then used to determine the sectoral breakdown of the investments required by each economic sector, which constitutes the gross fixed capital formation. The gross fixed capital formation required for the deployment of the renewable energy infrastructure is determined separately using the installed capacity and an investment matrix defining the capital investments by sector by unit of capacity deployed, for each technology.	In the final demand for Spanish goods and services, only the fraction corresponding to the demand for domestic sectors is included. Fully included in the Spanish final demand.
Government expenditures	Government spending can be defined using either an exogenous public deficit target, or an exogenous GDP growth target. Both methods simulate government behaviour in a way that allows the modeller to choose the government's main priority. Effectively, the second method (GDP growth target) implies that the simulation, in the absence of constraining feedback loops, achieves the GDP target chosen. For the sake of simplicity and to align with the economic projections reported in the PNIEC and LTDS (in terms of GDP), this is the method employed in this article.	In the final demand for Spanish goods and services, only the fraction corresponding to the demand for domestic sectors is included. Fully included in the Spanish final demand.
Exports	Exports of final goods and services are estimated econometrically using the RoEU and RoW incomes (inputs received as boundary data from the global and European version of MEDEAS). Exports of intermediate goods and services are determined by the input output matrices technical coefficients.	Only included in the final demand for Spanish goods and services.

(ii) Final demand as the demand for goods and services by Spanish residents

This perspective includes the final demand of all Spanish residents, both for domestically produced goods and services and goods and services produced abroad. This is the perspective adopted in the materials module introduced in this paper, and it allows the quantification of consumption-based indicators (e.g. the material footprint). We refer to this final demand as the **Spanish final demand**.

Table 1 explains how each component of final demand is determined in MEDEAS-Spain, and whether each component is included in final demand depending on the two perspectives. More information on the economy module of MEDEAS-Spain, and particularly, on the determination of the Spanish final demand, can be found in SI-1, section 2. Once the final demand for the output of each of the 35 MEDEAS-Spain economic sectors (broken down by each of the three regions) is calculated, the use of the Leontief inverse matrix yields a desired output by sector (for each of the three producing regions) [60]. Then, the upstream requirements (e.g. labour, energy) to satisfy the output by sector are computed, using sectoral intensities (e.g. sectoral labour and energy intensities), respectively [68]. Energy requirements are broken down in five energy carriers; liquids, solids, gas, electricity, and heat. Energy-related emissions are then calculated as function of final energy consumption by energy carrier and of the supply mix for each energy carrier.

Changes and improvements to the model (as compared to the global version of MEDEAS [19, 37]) are predominantly located in the materials module. First, material stocks and flows are now consistently represented (not represented in the initial version of MEDEAS, introduced for the transportation module by Pulido-Sanchez *et al* 2022 [19]), differentiating those induced by LCTs (specified by LCT) and those induced by the rest of economic activities. Second, the linear material demand-GDP relationship has been substituted by sectoral (region-specific) material demand intensities to account for the effects of structural changes on material demand. Third, the model now includes a quantification of the

Table 2. Materials-related nomenclature used throughout the paper and supplemental information. LCT: Low-carbon technology.

Terminology	Definition	Unit
Materials	Refers to the 43 mineral materials covered in the model (thereafter ‘materials’). The list and the extent to which each of these materials is covered is provided in SI-1, section 3.1.	Tonnes
Fossil fuels	The extraction of fossil fuels and its associated impacts (final energy consumption, greenhouse gas emissions, and material footprint) are explicitly covered in the model. Fossil fuels are differentiated in terms of coal, oil, and gas.	Tonnes
Material demand	Refers to the materials demanded by the Spanish economy, either for low-carbon technologies (LCTs) or for the rest of economic sectors. The material demand is added to the in-use stocks of materials.	Tonnes
In-use stocks	Refers to the materials in-use in the Spanish economy. In-use stocks are differentiated by LCT, and represented in an aggregate manner for the rest of economic sectors.	Tonnes
End-of-life materials	Refers to the materials that reach their end-of-life and exit in-use stocks. End-of-life materials are determined using end-of-life LCTs and the average lifetime of materials in the economy (provided in SI-2).	Tonnes
Recycled materials	Refers to the materials reaching their end-of-life which are recycled. They are determined using the flow of end-of-life materials and the end-of-life recycling rates (by default current values, cf SI-2).	Tonnes
Material requirements	Refers to materials required to fulfil the material demand of the Spanish economy. It differs from material demand by accounting for the fact that there are material losses in production processes, through a production losses factor.	Tonnes
Material footprint	Refers to the total mass of materials that have been extracted from the environment to fulfil the material demand of the Spanish economy. It includes all waste materials and burden rock that are extracted alongside the materials of interest. The material footprint associated to the extraction of fossil fuels is included. It differs from the standard definition to the extent that it excludes biomass (biomass is not covered in the model, except when used as bioenergy).	Tonnes
Primary extraction	Refers to the total mass of material of interest (excludes waste materials) that has to be extracted from the environment to fulfil the material demand of the Spanish economy. Determined as the difference between material requirements and recycled materials.	Tonnes
Cumulative primary extraction	Refers to the total mass of material of interest (excludes waste materials) that has to be extracted from the environment to fulfil the material demand of the Spanish economy over the 2025–2050 time period.	Tonnes
Population-weighted reserves	Portion of global reserves for a given material that would correspond to Spain according to the country’s share of global population.	Tonnes
Sectoral material demand intensities	For each of the 43 materials covered and for each final demand sector (specified by region of production), it refers to the mass of materials demanded per monetary unit of final demand.	Tonnes/MUS$
Sectoral material footprint intensities	For each final demand sector (specified by region of production), it refers to the total mass of materials, including waste materials, that has to be extracted per monetary unit of final demand. Materials associated with fossil fuel extraction are excluded from these intensities.	Tonnes/MUS$

environmental impacts related to material requirements (final energy consumption, GHG emissions, and material footprint). Last, the material intensities of LCTs and energy intensities of material extraction and processing have been updated where necessary to reflect the most up-to-date literature. For clarity, table 2 provides the materials-related nomenclature used throughout this paper.

2.2. Materials module

2.2.1. General overview

The materials module of MEDEAS-Spain is structured as a stock-flow model representing dynamically the stocks and flows of 43 mineral materials (see list in SI-1, section 3.1, thereafter ‘materials’) in the Spanish society, from their use phase to their end-of-life. Currently, biomass and fossil fuel-derived materials (such as plastics) are excluded from the materials module. However, fossil fuel requirements are determined in the energy module, and we determine in the materials module the material footprint associated with fossil fuel requirements. The material demand corresponds to the materials associated

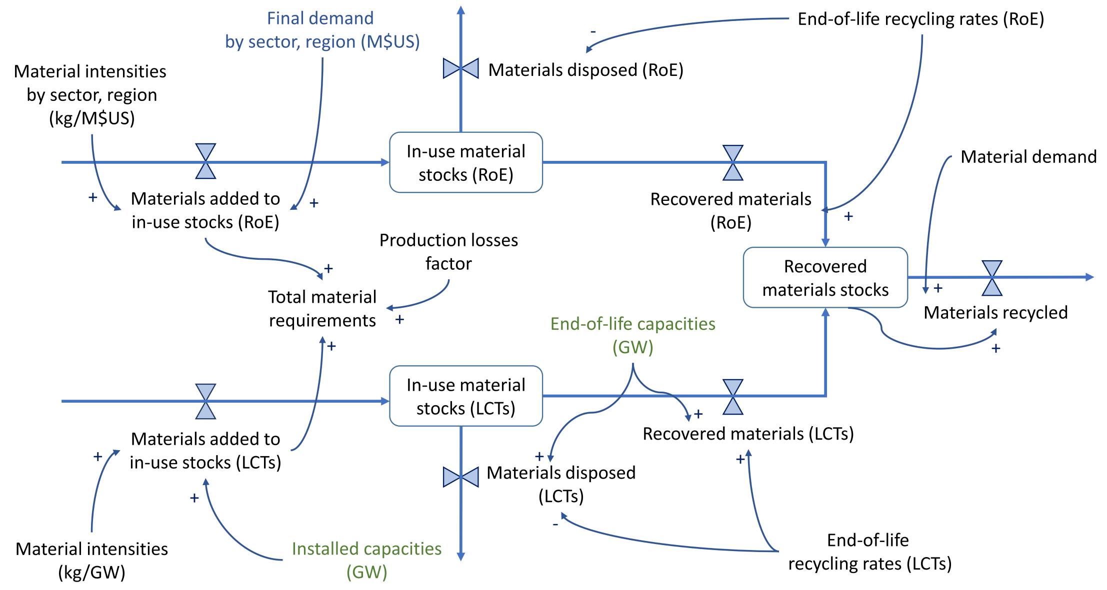

Figure 3. Overview of the materials module of MEDEAS-Spain. Inputs from the economy module are shown in blue, and inputs from the energy module are shown in green. LCT: Low-carbon technology. RoE: Rest of the economy.

with the Spanish final consumption (either satisfied by domestic production or by imports of goods and services) and are added to the in-use stocks of materials. Hence, the module adopts a consumption-based perspective, and includes the material requirements embodied in imports, but excludes the material requirements embodied in exports. Both the material requirements associated with LCTs and with the rest of the economy are considered, avoiding any double accounting (see SI-1, section 4.1). Figure 3 shows the basic and simplified structure of the materials module. The module receives as input from the economy module the Spanish final demand by economic sector and by region of origin, and receives as input from the energy module activity data on the energy system (capacity of LCTs deployed, operated, or decommissioned in a given year).

As the future availability and supply of materials is extremely uncertain and difficult to capture, the model does not represent supply constraints and potential feedback loops on economic activity due to supply bottlenecks or material shortages. With this set-up, material demand is always fulfiled. The model however allows us to account for the required cumulative extraction, and to compare it with currently reported reserves globally, as well as with the global reserves corresponding to Spain according to its share of global population (population-weighted reserves).

2.2.2. Material demand and material requirements

Here, we draw a difference between *material demand* and *material requirements*. By *material demand*, we refer to the materials that are effectively demanded, i.e. contained in final consumption (and which are therefore added to in-use stocks), for instance, the steel and lithium contained in a car or in a battery, respectively. By *material requirements*, we refer to the material demand *plus* any other materials that were required to satisfy final demand. In contrast, material requirements are determined accounting for the inefficiencies and losses occurring in the production process, via a production losses factor (see SI-1, section 4.4).

Considered LCTs are concentrated solar power (CSP), solar photovoltaic (PV), wind onshore, wind offshore, electric vehicle batteries (broken down in five different types: LMO, NMC622, NMC811, NCA and LFP), static storage batteries (LFP), and electric vehicles[12]. Material demand is determined for each LCT using the capacity deployed (in MW, except for electric vehicle batteries, in MWh) and each LCT material intensity (in kg MW^{-1}, or kg MWh^{-1} for electric vehicles). The material intensities of LCTs are modelled as constant over the simulation (discussed in section 5).

Material demand for the rest of the economy is determined using sectoral material demand intensities for each of the 35 MEDEAS-Spain sectors, for each of the three regions (Spain, RoEU, and RoW),

[12] Only the additional material requirements when compared to ICE vehicles are accounted for (e.g. copper requirements for an electric engine).

and for each of the 43 materials. These sectoral material demand intensities are kept constant over the simulation. The process to construct the sectoral material demand intensities is detailed in SI-1, section 4.1. Essentially we combine data from the Exiobase Multi-Regional Input–Output model [69, 70] with primary extraction data from the USGS [71]. Due to data limitations, the sectoral material demand intensities constructed are defined in terms of material demand by unit of final demand, instead of material needed by unit of sector output (which would be the standard approach in an input output analysis).

2.2.3. In-use stocks, end-of-life materials, recycled materials, and primary extraction

Material demand is added to in-use stocks, which are specified by LCT, or undifferentiated for in-use stocks by the rest of the economy. The flow of end-of-life materials is then determined as function of the end-of-life LCTs and of the average lifetime of materials in the rest of the economy. A fraction of end-of-life materials is then recycled based on their end-of-life recycling rate, while the remaining fraction is discarded. We use the current average economy-wide end-of-life recycling rates for both materials in-use in LCTs and in the rest of the economy (no specific data are available for materials contained in LCTs). These recycling rates are obtained through a range of sources (from EU data when available [72–75], or global data alternatively [76, 77]) (data for Spain specifically were not available), and maintained constant throughout the simulation (an uncertainty analysis is run on recycling rates, see SI-1, section 5.3). The required primary extraction is then determined for each material as the difference between material requirements and recycled materials. Last, we note that in-use stocks, end-of-life materials, and recycled materials are represented for most, but not all materials included in the model; the details can be found in SI-1, section 3.1.

2.2.4. Quantification of environmental impacts

Next, the model quantifies the environmental impacts associated with material extraction and processing, using three indicators: (i) the final energy consumption, (ii) the GHG emissions, and (iii) the material footprint.

2.2.4.1. Materials-related final energy consumption

Materials-related final energy consumption refers to the final energy consumption associated with the extraction and processing of materials. We use final energy intensities (in MJ kg^{-1}) to represent the materials-related final energy consumption for each of the 43 material covered in the model, which we derive from the literature (see e.g. [78–80]). We distinguish final energy intensities by primary and secondary (i.e. recycling) material production. (See SI-2 for the detail of values used and all sources.) The dynamic evolution of these final energy intensities is explained in SI-1, section 3.4. For fossil fuels, we use previous work quantifying their Energy Return On Investment (EROI) at the global level [81, 82]. We use the historical primary-stage EROIs to quantify final energy requirements by fossil fuel extracted over the 2000–2020 time period, and extrapolate a moderate decrease in fossil fuel EROIs over the 2020–2050 time period, as presented in SI-1, section 3.4.

2.2.4.2. Materials-related GHG emissions

Materials-related GHG emissions refers to the GHG emissions associated with the extraction and processing of materials. Final energy consumption is differentiated by domestic (in Spain) final energy consumption, and final energy consumption abroad, as well as by final energy carrier (in terms of liquids, solids, gases, electricity, and heat) as explained in SI-1, section 3.4. For the domestic final energy consumption, we apply the GHG intensity of each final energy carrier as endogenously determined by the model, based on the extent of decarbonisation of the energy sector (see [65]). For the final energy consumption occurring abroad, we use (i) the CO_2 intensity of electricity generation as reported in the IEA's Announced Pledges Scenario [83][13], and (ii) the same emission factors for each fossil fuel as for the rest of the energy sector (see SI-2).

2.2.4.3. Material footprint

The material footprint, or raw material consumption [85], represents the total extraction of materials from the environment, and can therefore be used as a proxy of the environmental impacts associated with material use [86]. The material footprint is calculated separately for three factors: LCTs, fossil

[13] We apply a transmission and distribution losses factor of 7.6%, which we determine according to the IEA's Extended World Energy Balances for 2020 [84].

fuel extraction, and the rest of economic activities (excluding fossil fuels extracted)[14]. SI-1, section 3.4 explains how the potential double accounting across these three factors has been avoided.

For materials required by LCTs, we use rock-to-ore factors mostly derived from Nassar *et al* 2022 [87] (kept constant over simulation time period), and then multiply the primary extraction entailed by LCTs by the rock-to-ore ratios. (Values used can be found in SI-2.) For the rest of the economy, we determine sectoral material footprint intensities using the Exiobase Multi-Regional Input–Output model [69, 70], similarly to the determination of sectoral material demand intensities (see SI-1, section 4.2.) Regarding fossil fuels, we use material footprint to extracted fossil fuels factors, expressed in kg MJ^{-1}. As these factors were found to differ highly from study to study, we account for uncertainty by deriving factors from three different sources: (i) from a 2014 study from the Wuppertal Institute [88], (ii) from Exiobase [69, 70], and (iii) from a study by Nakajima *et al* (2022) [89]. (See SI-1, section 4.3.)

3. Scenarios

For the present work, the model historical time period is 2000–2025, and the simulation time period is 2025–2050. Note that throughout the manuscript, the first year of any time period is included, while the last year of any time period is excluded (so, 2025–2050 runs from the beginning of 2025 to the end of 2049, and the last historical data point is $t = 2025$). Scenarios are therefore defined for the 2025–2050 time period.

3.1. Common features across scenarios

Let us first consider common assumptions across all scenarios. First, as the main objective of this work is to assess the material implications of following the Spanish PNIEC and LTDS (and not their feasibility) as well as alternative scenarios, the constraining feedback loops characteristic of the MEDEAS framework (e.g. mechanisms that limit the level of energy availability and hence economic activity) are deactivated throughout the scenarios (see SI-1, section 5.1). Indeed, activating these feedback loops would change the trajectory of the PNIEC-LTDS, which would therefore fail at replicating the Spanish energy and climate plan[15] (and it would be inconsistent to activate these feedback loops only for the other scenarios). Second, the variables characteristic of the materials module, specifically the end-of-life recycling rates (by default set to current values), the average lifetime of different materials, the sectoral material demand and footprint intensities, and the material intensities of LCTs, are set equal across scenarios (see SI-2 for values used), and constant over time (an uncertainty analysis is conducted on the sectoral material intensities, as described in section 3.3. Third, the population evolves according to the projection of the Spanish National Institute for Statistics in all scenarios [90]. Fourth, all economic assumptions other than economic growth and level of final demand (which is set exogenously for the Sufficiency scenario) have been held constant across scenarios, reflecting historical sectoral patterns and behavioural parameters calibrated to Eurostat and national accounts (see SI-1, section 2 for more explanations on the economy module). Thus, differences in results across scenarios will be specifically the consequence of differences in (i) the level and structure of final demand, and (ii) the level of deployment of LCTs.

3.2. Scenario-specific features

Next, we introduce the four scenarios considered here, which are summarised in table 3. There are relatively few features changing between scenarios, the idea being to isolate the effects of a set of very specific parameters. Regarding the deployment of renewable energy, we note that although the target to 2030 is equal in all scenarios (except in the Baseline scenario), the capacity deployed by 2050 is endogenously determined in the model as a result of the level of electricity demand by 2050. Indeed, there is saturation in the deployment of renewable energy as the electricity mix approaches a 100% renewable mix in MEDEAS [65].

3.2.1. Baseline scenario

The Baseline scenario represents a hypothetical scenario without low-carbon transition, and more specifically, in which the deployment of LCTs stops after 2024 (although LCTs reaching their end-of-life

[14] The material footprint quantified here differs from the standard definition, as it accounts for the footprint of mineral materials and fossil fuels, but excludes biomass (which is at this point not covered in the model, with the exception of biomass used for energy purposes). For clarity, water consumption is also excluded from the material footprint, which is consistent with the standard definition of material footprint.

[15] For instance, activating the ‘energy constraining feedback loop’ (documented in SI, section 5.1), may constrain the level of economic activity to a level lower than the one assumed by the PNIEC and LTDS.

Table 3. Summary of key features in each scenario. The level and structure of final demand refer to the level and structure of the Spanish domestic demand for goods and services. PNIEC: National Integrated Energy and Climate Plan. LTDS: Long Term Decarbonisation Strategy. EVs: Electric vehicles.

Feature	Baseline	PNIEC-LTDS	CappedEcon	Sufficiency
Economic growth (GDP growth)	GDP from the baseline scenario in the PNIEC (+1.1% growth rate 2025–2050).	GDP from the PNIEC scenario in the PNIEC and LTDS (+1.7% growth rate 2025–2030, and +1.3% growth rate 2030–2050)	GDP calibrated to yield a constant level of final demand.	Decrease resulting from the reduction of sectoral final demand by 2050 as presented in SI-1, section 5.4.
Level of final demand	Endogenous evolution.	Endogenous evolution.	Constant level of aggregate final demand (2025 value).	Decrease resulting from the reduction of sectoral final demand by 2050 as presented in SI-1, section 5.4.
Structure of final demand	Endogenous evolution.	Endogenous evolution.	Endogenous evolution.	Structural change of final demand resulting from the reduction of sectoral final demand by 2050 as presented in SI-1, section 5.4.
Sectoral final energy intensities	Evolution derived from the Baseline scenario in PNIEC (se SI-1, section 5.2).	Evolution derived from PNIEC and LTDS (see SI-1, section 5.2).	Evolution derived from PNIEC and LTDS (see SI-1, section 5.2).	Evolution derived from PNIEC and LTDS (see SI-1, section 5.2).
Deployment of renewable energy	None post-2024 (only replacement of end-of-life capacities).	Target to 2030 based on the PNIEC (see appendix A). Endogenous evolution to 2050.	Target to 2030 based on the PNIEC (see appendix A). Endogenous evolution to 2050.	Target to 2030 based on the PNIEC (see appendix A). Endogenous evolution to 2050.
Share of EVs	No EV deployment post-2024.	Derived from LTDS: 70% of electrification for all road vehicles by 2050.	Derived from LTDS: 70% of electrification for all road vehicles by 2050.	Derived from LTDS: 70% of electrification for all road vehicles by 2050.
Number of vehicles	Increase according to current trends by 2030 (following the PNIEC). Trend extrapolated to 2050. See appendix B.	Increase according to current trends by 2030 (following the PNIEC). Trend extrapolated to 2050. See appendix B.	Constant in the 2025–2050 time period, except for buses (same as in the PNIEC).	Decrease in the number of all four-wheeled vehicles to 2050, except for buses (same as PNIEC and trends extrapolated to 2050). Increase in two-wheeled vehicles and in the proportion of electric bicycles to 2050. See appendix B.

are replaced). The main function of this scenario is to serve as benchmark for comparison with the rest of scenarios, which all include substantial deployment of LCTs. The scenario follows the projection of economic growth for Spain obtained from the 'Current trend' scenario in the PNIEC [91] (+1.1% yearly growth rate over 2025–2030), and the same growth rate is maintained to 2050[16]. Improvements

[16] Values are taken from the previous draft version of the PNIEC [91], as not available for the 'Current trend' scenario in the current version of the document.

in sectoral energy intensities are derived from the 'Current trend' scenario in the PNIEC [91] (see SI-1, section 5.2).

3.2.2. PNIEC-LTDS scenario

The PNIEC-LTDS scenario represents the current Spanish climate and energy plan, which is defined combining the objectives set out in the PNIEC [6] and in the LTDS [7] to 2030 and 2050, respectively. Economic growth projections are obtained from the PNIEC [6] and the Spanish LTDS [7] (+1.7% yearly growth rate over 2025–2030, and +1.3% yearly growth rate over 2030–2050). LCTs are deployed following the objectives established by the PNIEC to 2030 (see appendix A for renewables). For electric vehicles, the target is set at 5.5 million vehicles by 2030 by the PNIEC, and we derive an electrification of 70% of all road vehicles by 2050 based on the LTDS (ships and airplanes are not represented for now in MEDEAS). The number of vehicles are induced from the PNIEC by 2030, and we extrapolate the trend to derive the number of vehicles to 2050 (see appendix B for details). Sectoral energy intensities are derived according to the PNIEC [6] and the LTDS [7] (see SI-1, section 5.2). This scenario may be interpreted as a 'Green Growth' scenario, whereby ambitious decarbonisation measures are implemented in the supply side, although decarbonisation of energy supply occurs alongside an increase in consumption and production.

3.2.3. CappedEcon scenario

The CappedEcon scenario represents a scenario with the same LCTs deployment target (capacity of renewables by 2030, and share of electric vehicles to 2050) as in the PNIEC-LTDS scenario. Sectoral energy intensities also follow the same improvements as in the PNIEC-LTDS scenario. However, the level of consumption (e.g. the total Spanish final demand) is capped to its value in 2025, which translates into a constant level of final demand (2025 level), and therefore into a lower deployed capacity of renewable energy by 2050, compared to the PNIEC-LTDS scenario. In the CappedEcon scenario, which represents a situation with moderate demand-side measures to keep consumption at its current level, the number of vehicles stays constant over the 2025–2050 time period, except for buses, which follow the same increase as in the PNIEC-LTDS scenario (see appendix B for details). Hence, the number of electric vehicles is somewhat lower than in the PNIEC-LTDS scenario by 2050.

3.2.4. Sufficiency scenario

The Sufficiency scenario represents a scenario consistent with ambitious demand-side measures that reduce the overall level of final demand. Alongside these strong demand-side measures, the Sufficiency scenario adopts the same LCT deployment targets (renewable energy capacity by 2030, share of electric vehicles by 2050) as the PNIEC-LTDS scenario. Sectoral energy intensities also follow the same improvements as in the PNIEC-LTDS scenario. In this scenario, the volume of production and consumption decreases, in different proportions depending on the sector, to a level sufficient to provide good living standards for all. As such, the Sufficiency scenario is aligned with the decent living standards approach and seeks to translate the decent living standards approach in MEDEAS-Spain. To do so, we attempted to determine, for each economic sector, a monetary final demand that would be aligned with the delivery of decent living standards for the whole Spanish population, using underlying physical data whenever possible and a range of references (e.g. [92–100]). Table 4 summarises the key assumptions used to determine the level of final demand by 2050. (See SI-1, section 5.4 for an in-depth presentation of the underlying assumptions). Table 9 (appendix B) shows a summary of the reduction in the level of final demand for each of the 35 economic sectors between 2022 and 2025. It is however worth noting that the determined level of final demand would only allow to meet decent living standards for the whole Spanish population under relatively low levels of inequality in terms of service provision. The Sufficiency scenario therefore supposes a transition to a society with drastically lower levels of inequality compared to currently. The space between the CappedEcon (which contains the level of final demand to the current level) and the Sufficiency scenario may therefore be regarded as a 'sufficiency space,' although nothing prevents from developing even more ambitious scenarios.

The Sufficiency scenario developed here is agnostic as to the form of social organisation, production, and provision of goods and services. In a similar vein, the Sufficiency scenario should not be regarded as a prescriptive policy package, but rather, as a normative benchmark describing the material implications under comprehensive and ambitious demand-side reductions. Translating such reductions into practice would require a combination of policy levers across sectors, such as those found in the literature (see e.g. [41, 98, 101]), which, to our knowledge, does not analyse the material implications of such scenarios. Policy levers could include regulatory measures (e.g. building standards, product lifespan extensions,

Table 4. Summary of key assumptions in the Sufficiency scenario. Detailed explanations for each of the 35 economic sectors can be found in SI-1, section 5.4.

Scenario element	Assumption
Construction	Considering the extent of vacant and second residences in Spain (estimated at 25% in 2020 by the Ministry of Transport, Mobility, and Urban Affairs [92]), and the excessive infrastructure built in the construction boom prior to the 2008 crisis [93, 94], we assume that by 2050, the output of the construction sector is fully directed towards refurbishing and maintaining the existing infrastructure (no new constructions). (We also note that Lage *et al* (2025) [95] estimate that there were about 8.8 million under-occupied dwellings in Spain in 2022.)
Food and agriculture	We assume a gradual evolution of diets towards a more sustainable and healthy diet following the work of Di Donato and Carpintero [96].
Manufacture of new vehicles	The manufacture of new vehicles declines following the reduction in the number of vehicles.
Number of vehicles	The number of vehicles declines following the 'Frugal generation' scenario developed by the French environmental agency [97], except for buses (same as in the PNIEC-LTDS scenario), and two-wheeled vehicles (own assumption). See appendix B for details.
Other industrial sectors	Range of hypothesis and input data. For some sectors, hypothesis based on the CLEVER scenario for Spain (low-demand scenario at the European Union level, disaggregated by country) [45, 99]. For other sectors, hypothesis based on the 'Transform' scenario for the UK [98]. Extension in lifetimes assumed for some products. Final demand for pharmaceutical products remains constant. Demand for coke and petroleum products decline to zero as a result of the phase-out of fossil fuels.
Services	Some services sectors are kept constant to their 2022 value, other services sectors decrease driven by the reduction in final demand of the construction sector which has an indirect contribution to the final demand for other sectors (e.g. on the accommodation and food services sector). Overall the decrease in final demand is very small for services.
Textiles	Decrease in the consumption of textiles to reverse the increasing trend in the 1996–2012 period in the European Union [100]. No data available regarding the evolution over the 2012–2025 time period.
Utilities	Utilities are considered fundamental for providing good living standards to the population and therefore the level of final demand is kept equal to its value in 2022.
Wholesale trade	Reduction driven by the reduction in the final demand for other sectors according to the input shares of each sector to the wholesale trade sector. For the wholesale of motor vehicles we use directly the physical data in terms of number of new vehicles.

urban planning, etc), fiscal instruments (e.g. carbon taxes, incentives for sharing and repair), affordable mass public transport and others. While modelling these policies separately is beyond the scope of the present study, such policies fall within the space of policy action consistent with the Sufficiency scenario explored here.

3.3. Uncertainty analysis

We conduct three uncertainty analysis on critical parameters of the model (see SI-1, section 5.3 for more details). First, we acknowledge the uncertainty on future (as well as current) recycling rates, particularly regarding the recycling rates of materials contained in LCTs. Therefore, in addition to the current economy-wide end-of-life recycling rates, we also apply, to each scenario, a high, 'ideal', recycling rate for materials contained in LCT (see SI-1, section 5.3 for a description of the 'ideal' recycling rate). The recycling rates of materials contained in LCTs then evolve linearly from their current value to this 'ideal' value in the 2025–2030 time period, and are maintained constant thereafter. The objective of this high recycling rate is to account for the end-of-life materials contained in LCTs as a recycling potential. This uncertainty analysis is conducted on the potential for recycling materials from LCTs, on the required cumulative primary extraction, and on the cumulative environmental impacts.

Second, as there is uncertainty associated with sectoral material (both demand and footprint) intensities (see SI-1, section 4.1), we conduct an uncertainty analysis of the effects of the sectoral material intensities, both in terms of (i) the initial sectoral material intensities used, and (ii) the evolution over time of the sectoral material intensities. Regarding (i), we use a lower and an upper value (in addition to the ‘default’ value used in the rest of the paper) for the initial sectoral material intensities, which we derive using the standard deviation of sectoral material intensities time series, as explained in SI-1, section 5.3. Regarding (ii), we conduct the uncertainty analysis by applying a homogeneous reduction in the sectoral material intensities across sectors and materials in the 2025–2050 time period (constant beforehand). The reduction in sectoral material intensities is calibrated so that the PNIEC–LTDS scenario follows a yearly reduction rate of 1.5% in the aggregated material intensity of the economy over the 2025–2050 time period, which corresponds to the yearly reduction rate objective set out by the PNIEC (over the 2010–2030 time period). This uncertainty analysis is conducted on both cumulative (2025–2050) material requirements and on cumulative environmental impacts.

Third, as there is uncertainty on the final energy intensities of each material, both in their current values and in their future evolution (related to both decreasing mineral deposit qualities and technological improvements), we conduct an uncertainty analysis on the final energy intensities of materials. We apply a Monte Carlo simulation of results when varying the final energy intensities of materials under a uniform probability distribution function, and determine quantiles and confidence intervals. This uncertainty analysis is conducted on the estimation of the total materials-related final energy consumption.

4. Results

4.1. General pathway results

Figure 4 shows general results to contextualise the rest of the article: a) final energy consumption and GHG emissions by 2050 compared to the 2025 value (dashed dark line) and to Spanish targets to 2050 (dashed green line), b) the capacities of variable renewable energy deployed by 2050, and c) the variation of the Spanish final demand (in monetary terms) by economic sector (as well as total final demand), compared to the 2025 value. The evolution over time of total final demand, final energy consumption, and GHG emissions can be found in appendix C, and that of deployed renewable energy capacities in SI-1 (figure 4). (The share of renewable electricity generation and total generation broken down in terms of renewable and non-renewable electricity can also be found in SI-1, figures 5 and 6.)

All scenarios achieve a very large reduction in final energy consumption by 2050 compared to the 2025 value: by 30% for the PNIEC-LTDS, 48% for the CappedEcon, and 65% for the Sufficiency (note that such reduction is considerably higher in the Sufficiency scenario). Despite the reduction in final energy consumption, the PNIEC-LTDS falls slightly short of the long-term final energy consumption targets in our simulation[17]. Then, all transition scenarios achieve large reductions in GHG emissions, although only the Sufficiency scenario, which reduces emissions by 93% compared to the 2025 level, reaches emission targets by 2050. The Baseline scenario, in contrast, maintains a stable final energy consumption (combined effects of lower improvements in sectoral energy intensities than in the other scenarios and of economic growth), and increases GHG emissions (stable final energy consumption and no decarbonisation), by 16% compared to the 2025 value. The deployment of renewable energy technologies is considerable in all decarbonisation scenarios (and null in the Baseline scenario), although noticeably higher (respectively lower) in the PNIEC-LTDS (respectively Sufficiency) scenario, due to the higher (respectively lower) final energy demand.

The Spanish final demand increases throughout all sectors in the Baseline and PNIEC-LTDS scenarios, albeit less in the Baseline scenario. This is due to the fact that the projected economic growth is higher in the PNIEC-LTDS than in the Baseline scenario. The total Spanish final demand remains equal to its 2025 value in the CappedEcon scenario, consistently with the hypothesis underlying this scenario, and the change in the composition of final demand in the CappedEcon scenario remains limited. Last, in the Sufficiency scenario, the decrease in final demand by 2050 is particularly significant for the construction (and less so, in industrial and agricultural sectors), consistently with the strong assumption adopted of no new constructions by 2050.

4.2. Material requirements results

4.2.1. Material requirements

Figure 5 shows total material requirements (values indexed to 2025) for each material and scenario (values in 2050 are shown in table 5). For materials in the first three columns, material demand is dominated by demand for the rest of the economy, and is therefore very sensitive to the volume and structure of final demand in each scenario.

[17] This is not a predictive finding and is a result of the calibration of the sectoral final energy intensities, which is explained in SI-1, section 5.2. Calibrating the sectoral energy intensities using as criterion the achievement of the long-term final energy targets would have been an alternative approach.

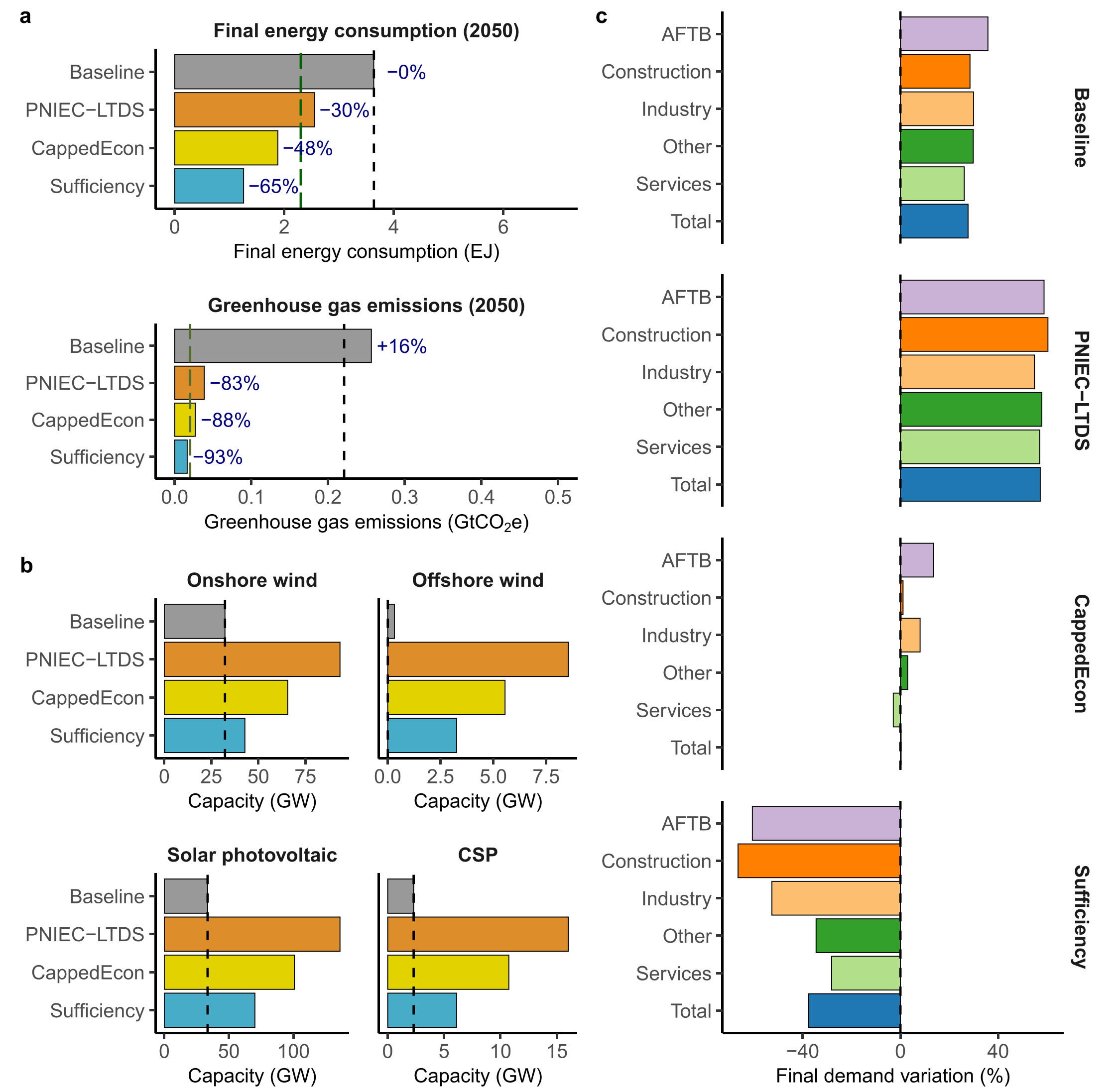

Figure 4. General model results. (a) Final energy consumption and greenhouse gas emissions by 2050 as compared to the 2025 value (dashed dark line) and 2050 target (dashed green line). (b) Variable renewable electricity capacity deployed to 2050 as compared to the 2025 value (dashed dark line). (c) Variation in the Spanish final demand (in monetary terms) by economic sector, as well as variation in the total Spanish final demand (2025–2050). CSP: Concentrated solar power. AFTB: Agriculture, food, tobacco and beverages.

In terms of material intensity of the economy (measured as material requirements by unit of GDP), which is shown in SI-1 (figure 10), we find a moderate increase in the PNIEC-LTDS scenario (by 3%) by 2050, and a moderate decrease in the CappedEcon scenario (by 4%). Only in the Sufficiency scenario does the material intensity of the economy strongly decrease by 2050, by 45%, consistently with the fact that the output of material intensive sectors is significantly reduced (particularly the construction sector). These results contrast with the PNIEC objective of reducing by 30% the overall material intensity of the economy by 2030 (defined as material use divided by GDP) [6] (it is not clear in the PNIEC whether such decrease is expected to be driven by structural changes, or by increasing material efficiency). Such results are explained by the fact that we conservatively use constant sectoral material demand intensities over time in this study. Adopting the (possibly optimistic) yearly reduction in material intensity set out by the PNIEC somewhat reduces the material requirements of the rest of economic activities, as shown in the uncertainty analysis conducted in appendix D, but does not change the conclusions of the analysis.

Figure 6 then shows the breakdown of material requirements by LCT and rest of economic activities, for the cumulative time period 2025–2050 (except for the Baseline scenario, in which no LCTs are deployed post-2024). In the case of aluminium, iron, manganese, molybdenum, and tin, the breakdown is heavily dominated by the rest of economic activities, particularly in the PNIEC-LTDS scenario, in which total economic output is the highest. That prevalence somewhat decreases in the CappedEcon

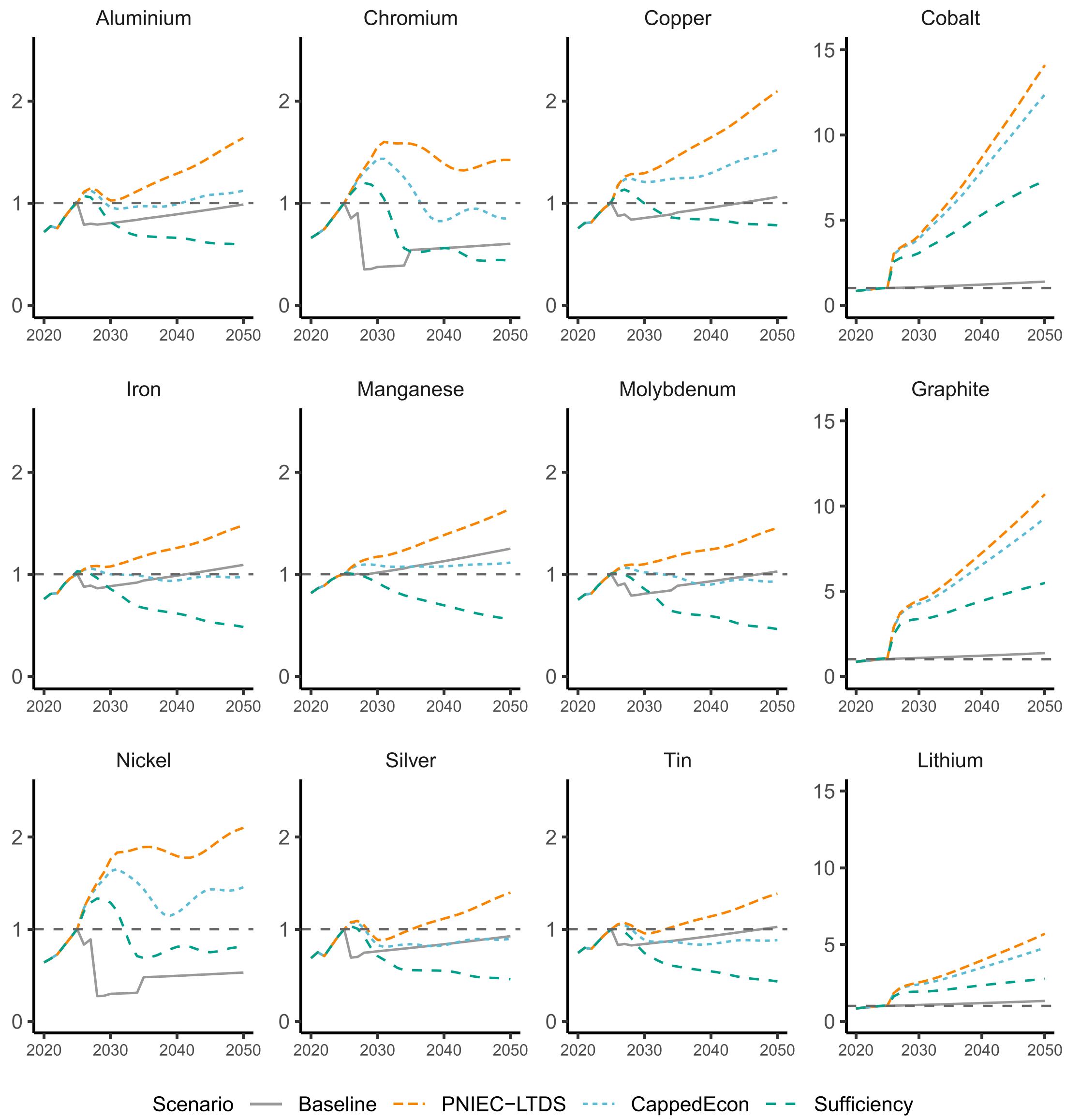

Figure 5. Total material requirements indexed to 2025 for each material and scenario (2025 = 1).

Table 5. Total material requirements in 2050, indexed to 2025 (2025 = 1).

Material	Baseline	PNIEC-LTDS	CappedEcon	Sufficiency
Aluminium	0.99	1.64	1.12	0.59
Chromium	0.60	1.42	0.85	0.43
Cobalt	1.38	14.11	12.39	7.30
Copper	1.06	2.10	1.52	0.78
Graphite	1.36	10.70	9.31	5.48
Iron	1.09	1.48	0.97	0.48
Lithium	1.33	5.71	4.79	2.77
Manganese	1.25	1.64	1.11	0.56
Molybdenum	1.03	1.45	0.93	0.46
Nickel	0.53	2.10	1.46	0.80
Silver	0.92	1.40	0.90	0.46
Tin	1.03	1.39	0.88	0.43

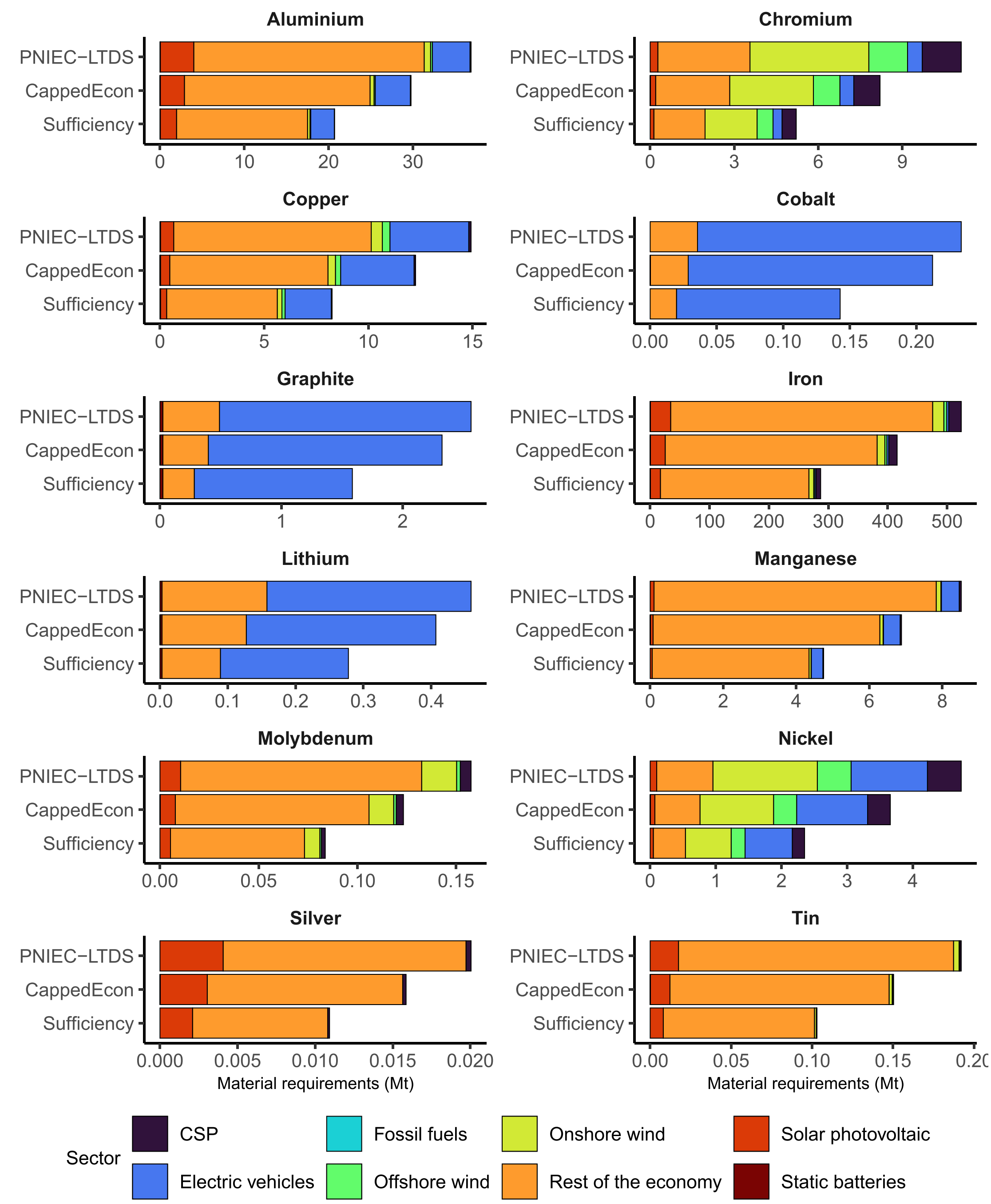

Figure 6. Cumulative material requirements (2025–2050), broken down by demanding sector. The Baseline scenario is irrelevant and not presented, because LCTs are not deployed in the simulation time period (2025–2050).

scenario, and even more so, in the Sufficiency scenario, due to a lower level of final demand. In the case of copper, the rest of economic activities remains the dominant driver of cumulative demand, but the requirements entailed by the deployment of LCTs are substantial (37% for the PNIEC-LTDS scenario, 38% for the CappedEcon scenario, and 36% in the Sufficiency scenario). To some extent, these results are expected, considering that the 'rest of the economy' bundles all economic sectors, excluding activities directly related to the deployment of LCTs. This result however emphasises that for most materials, the general demand volume is the key determinant of material requirements (although the change in economic structure also plays a role in the Sufficiency scenario). By contrast, LCTs are the main driver increasing the material requirements for chromium (average of 68% across scenarios), cobalt (average of 86%), graphite (average of 83%), and nickel (average of 81%).

Figure 6 shows that electric mobility is a key sector in terms of material requirements. In the case of aluminium, copper, cobalt, graphite, lithium, and nickel, electric mobility is the highest contributor within LCTs, and the highest contributor altogether for cobalt, graphite, and lithium. In the case of iron, silver and tin, solar PV is found to be the LCT contributing the most to cumulative demand, although that demand is moderate when compared to the rest of economic activities. Last, wind power (particularly wind onshore, given the relatively low deployment of wind offshore expected according to the PNIEC) significantly contributes to the cumulative requirements for chromium, molybdenum, and nickel, mostly due to the use of stainless steel. Last, appendix D presents an uncertainty analysis of the effects of the sectoral material demand intensities on these results, both in terms of (i) the initial sectoral material demand intensities, and (ii) the evolution over time of the sectoral material demand intensities. Specifically, figure 13 shows that for some materials (particularly silver and tin), the results can be significantly affected by the uncertainty on the sectoral material demand intensities. However, overall, figure 13 shows that the results and findings are robust to the approach and values for sectoral material demand intensities. For comprehensiveness, SI-1 (figure 13) shows the effects of changing the evolution of sectoral material demand intensities on material requirements in 2050, instead of in cumulative terms.

In general, the CappedEcon (compared to the Baseline and PNIEC-LTDS) and the Sufficiency scenarios (compared to the Baseline, PNIEC-LTDS and CappedEcon) considerably decrease cumulative material requirements for all materials. This is due to both lower material requirements for the rest of economic activities and for LCTs (which are quantified as a result of the dynamic integration between the energy and the materials module). This result underlines that the critical factor in driving material requirements is the general final demand volume. In both the CappedEcon and Sufficiency scenarios, the material requirements for LCTs are reduced (compared to the PNIEC-LTDS scenario) as a result of the reduction in final energy demand, which results from structural changes (for the Sufficiency scenario) and a contained level of total economic output (and reduction in the number of vehicles for the Sufficiency scenario).

4.2.2. Recycling potential

The dynamic nature of the materials module allows us to quantify end-of-life materials and recycled materials in each year. Figure 7 shows the share of total material demand that could be covered, in 2050, by recycling end-of-life LCTs (except for the Baseline scenario, in which no LCTs are deployed post-2024). Results are shown both applying the current economy-wide and ideal recycling rate (uncertainty analysis) to materials contained in LCTs. The first finding is that the Sufficiency scenario improves the degree of circularity, as a greater share of material demand can be covered by recycling LCTs in 2050, due to a lower material demand in 2050 compared to the other scenarios.

The figure shows that the potential for recycling LCTs (quantified as the share of material demand that could be covered by recyling, obtained with the ideal recycling rates) is very high for some materials, such as cobalt (average of 54% across the scenarios), chromium (average of 54%), graphite (average of 54%), lithium (average of 37%), and nickel (average of 67%). The share is also significant in the case of aluminium (average of 20%), and copper (average of 32%). These are all materials for which a substantial part of the demand is due to the deployment of LCTs (figure 6). In reality, however, not all LCTs will be collected for recycling. And even for LCTs entering the recycling process, there are still challenges associated to the functional recovery of metals used in diluted applications (e.g. involving many metals in small quantities). For instance, the use of complex alloys may compromise the functional recycling of all metals (e.g. when the sorting of end-of-life steel is not sufficient) [102, 103].

Figure 7 shows that the share of material demand that could be covered by recycling materials would be considerably lower for some materials under the current economy-wide recycling rates: 17% for cobalt, 30% for chromium, 4% for graphite, 0.2% for lithium, 34% for nickel, 14% for aluminium, and 21% for copper (values all average across scenarios). These results highlight that while recycling the materials contained in LCTs can provide a substantial contribution towards fulfiling future material demand, there is little room for complacency. There is therefore an urgent need for an industrial policy supporting the development of the required infrastructure, technology, and industrial ecosystem needed to achieve high recycling rates of LCTs, but also for the standardisation of LCTs design and adoption of practices that will facilitate their recycling. This includes limiting the dilution of scarce metals with other metals [104], and preferably mixing metals which recovery is compatible, using analytical tools such as the Metal Wheel [105]. Last, SI-1 (figure 11) shows how these results are affected by the speed of the decrease in final demand in the case of the Sufficiency scenario, by comparing results obtained with the exponential decay used in the Sufficiency scenario with results obtained with a linear decay. The sensitivity of results on this assumption is found to be minimal.

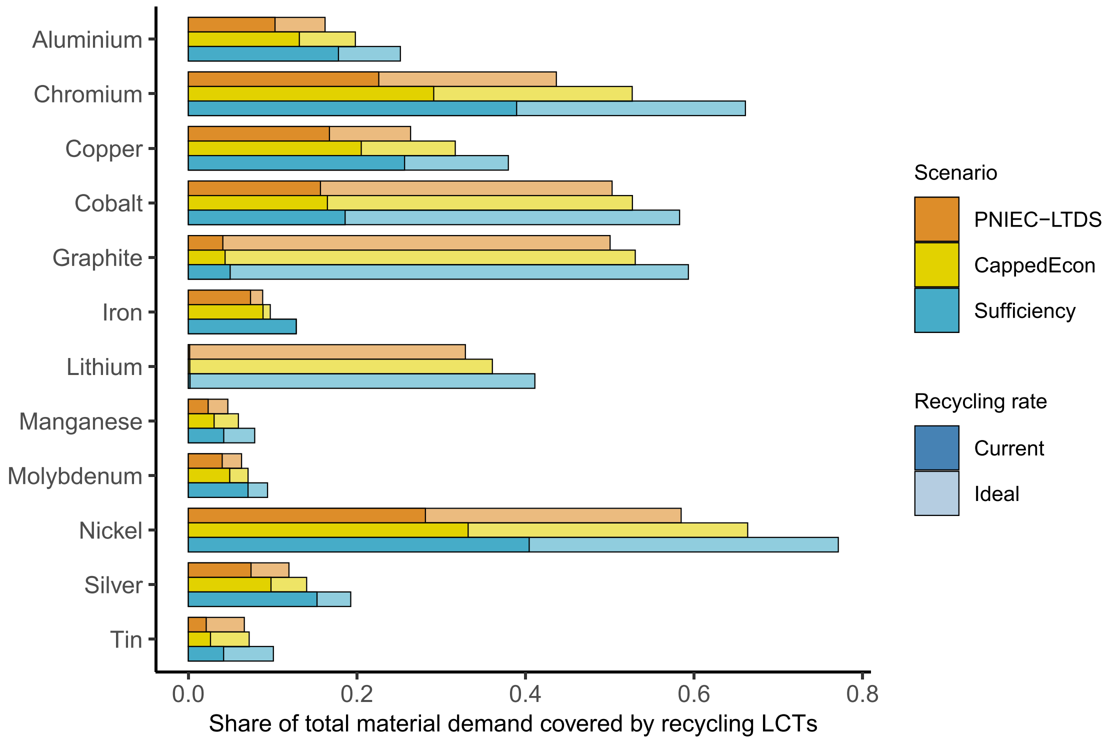

Figure 7. Share of total material demand covered by recycling low-carbon technologies (LCTs) in 2050, for both the current economy-wide and the ideal (uncertainty analysis) recycling rate for materials contained in LCTs. The Baseline scenario is irrelevant and not presented, because LCTs are not deployed in the simulation time period (2025–2050).

4.2.3. Primary extraction

Figure 8 shows the required cumulative primary extraction for each material and scenario, broken down by demand induced by LCTs and by the rest of economic activities. For each material, reported values are indexed to the population-weighted reserves corresponding to Spain, which is an indicator of how much materials would be available to Spain should reserves be distributed according to Spain's share in global population in 2025 (this indicator, however, does not adjust for the fact that historically, extracted materials have been very unequally distributed [122]). The vertical dashed black line represents the level where the required cumulative extraction is equal to the population-weighted reserves corresponding to Spain. The barplots are shown using the low bound of recycling rates for each material (average economy-wide recycling rates).

The figure shows that required cumulative primary extraction is higher than population-weighted reported reserves in many cases. Indeed, only for aluminium and manganese does the cumulative primary extraction remain below population-weighted reserves in all scenarios. In the case of copper, molybdenum, and graphite, the Sufficiency scenario reduces required cumulative primary extraction below population-weighted reserves. For graphite, however, most of the high-grade graphite used in batteries' cathodes is synthetic graphite, obtained from needle coke, a by-product of oil refining [106] (while in our accounting, extracted graphite is ascribed to natural graphite reserves)[18]. For many materials, even in the case of the Sufficiency scenario, the required cumulative primary extraction is higher than population-weighted reserves. These results highlight again the material challenges of a low-carbon transition, even in highly ambitious scenarios with substantial demand-side efforts.

Last, the figure shows how results change under the ideal recycling rates assumption for materials contained in LCTs (part of the uncertainty analysis) as a solid vertical line within each barplot. The effect on cumulative primary extraction is relatively important for chromium, copper, cobalt, graphite, lithium, nickel (very important), silver, and tin. However, that reduction in the required cumulative primary extraction can be regarded as moderate considering that the ideal recycling rate used is an

[18] Therefore, actual bottlenecks in graphite supply are likely to be related to the combination of the phase-out of oil, relatively long timeframes to open new graphite mines, and geopolitical tensions and concentration of graphite deposits [106].

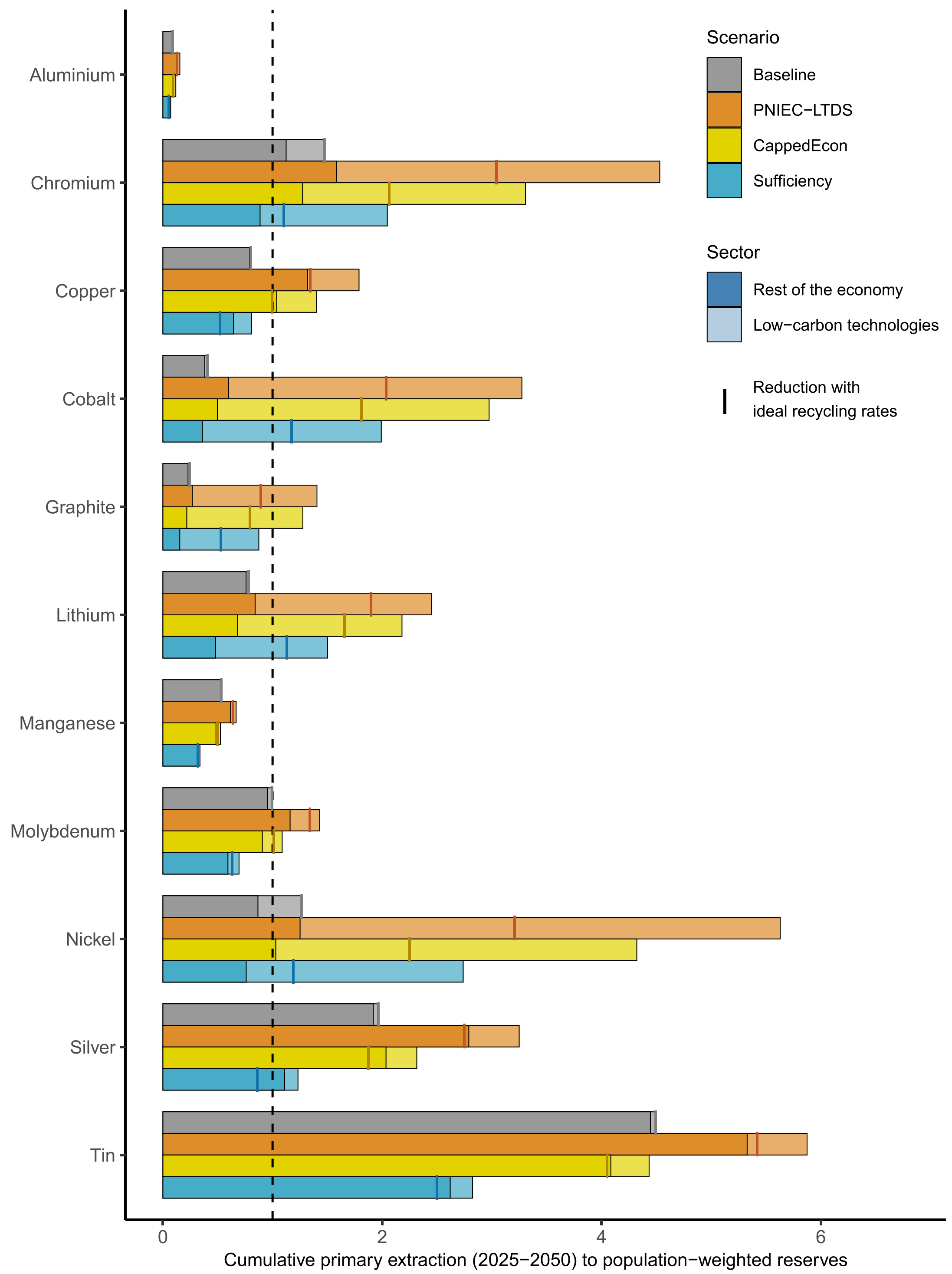

Figure 8. Required cumulative primary extraction broken down by low-carbon technology (LCT) and rest of economic activities against the population-weighted reserves corresponding to Spain. The figure assumes the current average economy-wide recycling rates for materials contained in LCTs. The potential reduction in cumulative primary extraction obtained with the ideal recycling rates for LCTs are shown as vertical solid lines under each bar. Values indexed to the population-weighted reserves corresponding to Spain.

upper bound unlikely to be reached. The fact that the potential reduction in cumulative primary extraction through recycling will likely be moderate is a consequence of (i) material demand being predominantly driven by the general final demand volume for most materials, and (ii) the temporal delay between the year in which a LCT is deployed and the year in which its material content is available for recycling, which is quantified in the dynamic stock-flow materials module introduced in this paper. The potential for reducing primary extraction by recycling LCTs is higher when looking at the last years of the simulation, as shown in figure 7.

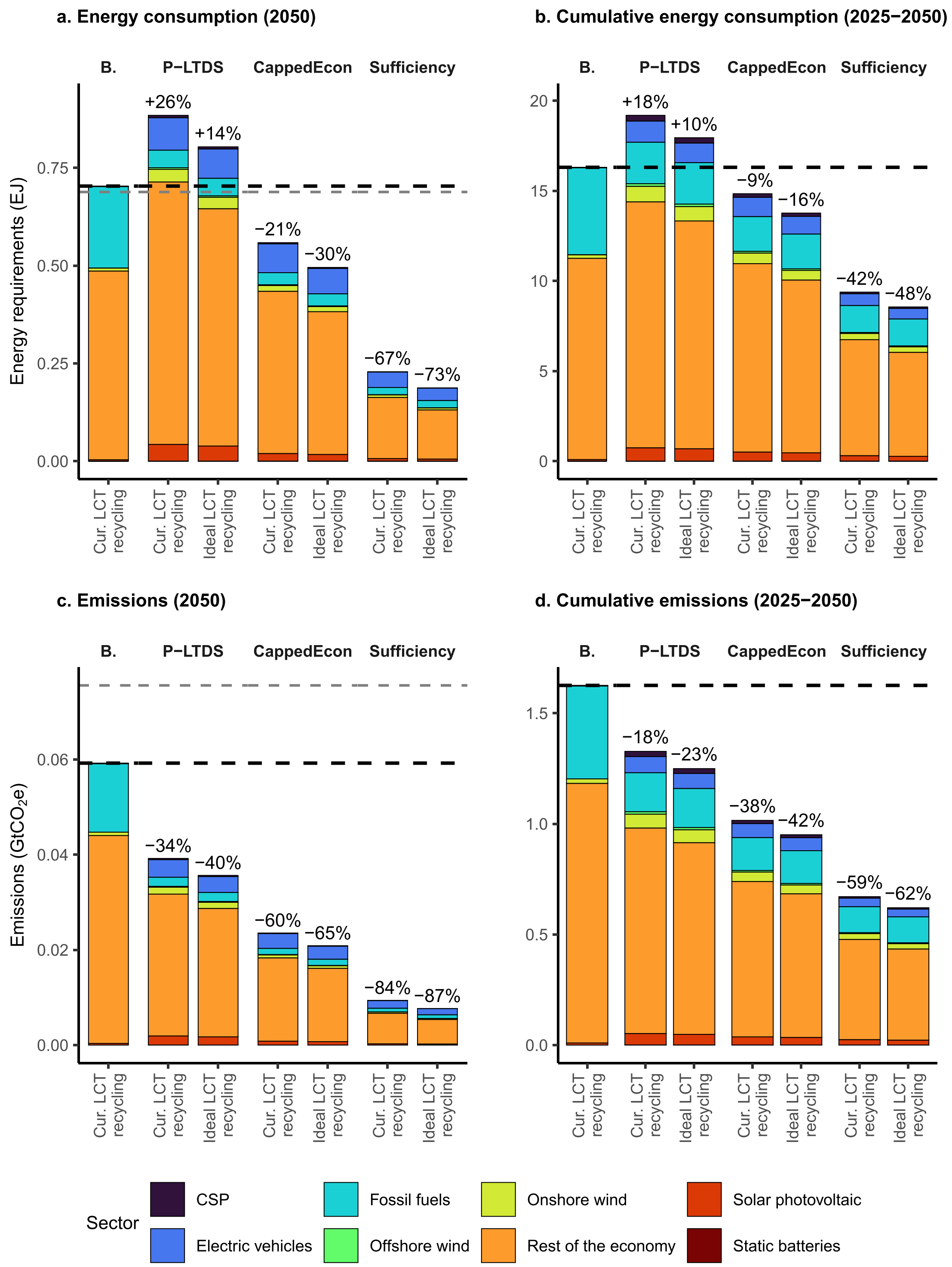

Figure 9. Environmental impacts associated to the material requirements of each mitigation scenario, broken down by low-carbon technology (LCT), fossil fuel extraction, and rest of the economy. (a) Final energy consumption in 2050, (b) cumulative (2025–2050) final energy consumption, (c) greenhouse gas emissions in 2050, (d) cumulative greenhouse gas emissions. Estimations are shown with the current (Cur.) and ideal recycling rates for LCTs. Values are compared in percentage terms against the Baseline (B.) scenario (dashed horizontal black line). The dashed grey line in the left-hand side figure shows the value in 2025.

4.2.4. Materials-related final energy requirements and GHG emissions

Figure 9 shows the materials-related final energy requirements and GHG emissions in each scenario. The values are shown both for the year 2050, and in cumulative terms over the time period 2025–2050. The dotted dark horizontal line compares the obtained values in each scenario with the value in the Baseline scenario. On the left-hand side, the 2025 value is also shown in grey dotted lines for comprehensiveness. Figure 9 shows results obtained both with the current and ideal recycling rates for materials contained in LCTs. The figure shows that both final energy requirements and emissions are largely dominated by the rest of economic activities, with a substantial contribution of fossil fuel extraction. The contribution of fossil fuel extraction is endogenously determined by the dynamic integration of the energy and materials module, whereby the energy module determines the fossil fuel energy required (mismatch between energy demand and renewable energy supply, for each of the five energy carriers) and the materials module quantifies the environmental implications applying a decreasing EROI that follows historical data. The sum of LCTs only amount for 17% (PNIEC-LTDS), 17% (CappedEcon) and 15% (Sufficiency) of cumulative final energy requirements over the 2025–2050 time period, and for 17% (PNIEC-LTDS), 16% (CappedEcon), and 15% (Sufficiency) of cumulative GHG emissions[19].

The PNIEC-LTDS has substantially higher final energy consumption in 2050 than the Baseline (by 26%), due to higher economic growth and to the deployment of LCTs. Conversely, the CappedEcon scenario and the Sufficiency scenarios both reduce final energy consumption substantially compared to the Baseline, by 21% and 67%, respectively. The Sufficiency scenario is however the only scenario that significantly reduces final energy consumption compared to its 2025 value (by 67%), shown as a dotted grey line. These results are consistent with the fact that material requirements are mostly driven by the general demand volume. For comprehensiveness, appendix E decomposes the effect of sectoral changes in final demand in the reduction in environmental impacts in 2050, by applying stepwise the reductions in sectoral final demand. The reductions in the final demand for the industry, transport, and construction sectors are found to have the largest impact (in the given order). All scenarios reduce GHG emissions by 2050 compared to the Baseline, although much more significantly in the Sufficiency (–88%) and CappedEcon (–69%) scenarios than in the PNIEC-LTDS scenario (–48%). These results are expected considering the substantial decarbonisation occurring in all the considered scenarios (see figure 4(a)). When using the ideal LCTs recycling rates (uncertainty analysis), final energy consumption and GHG emissions are moderately reduced by 2050 (compared to values obtained with the current recycling rates), for instance final energy consumption is reduced by 9% in the PNIEC-LTDS scenario, 11% in the CappedEcon scenario, and 18% in the Sufficiency scenario.

As explained in section 3.3, we conduct two uncertainty analysis. Appendix D presents an uncertainty analysis of the effects of the sectoral material demand intensities on these results, and shows that the general findings are robust to the material intensities used. Appendix F presents an uncertainty analysis of the effects of the energy intensities of mining and downstream material processing on (i) the evolution of the materials-related final energy consumption, and (ii) the share of materials-related final energy consumption due to LCTs by 2050. The results are also found to be robust to the energy intensities used for materials mining and processing. Last, SI-1 (figure 12) shows how the cumulative materials-related environmental impacts are affected by the speed of the decrease in final demand in the case of the Sufficiency scenario, by comparing results obtained with the exponential decay used in the Sufficiency scenario with results obtained with a linear decay. The sensitivity of results on this assumption is found to be minimal.

4.2.5. Material footprint

Next, figure 10 shows the equivalent graph looking at the material footprint. Similar conclusions can be drawn: LCTs are responsible for a relatively minor (although substantial) portion of the material footprint over the time period 2025–2050; 21% in the PNIEC-LTDS scenario, 20% in the CappedEcon scenario, and 19% in the Sufficiency scenario[20]. In 2050, the PNIEC-LTDS scenario presents a material footprint 39% higher than the Baseline scenario. The CappedEcon moderately reduces the material footprint in 2050 compared to the Baseline, by 8%, and the Sufficiency scenario considerably reduces the material footprint, by 58% compared to the Baseline. However, only the Sufficiency scenario reduces the material footprint when compared to the 2025 value (by 55%). Similarly, when looking at the cumulative material footprint (right-hand side), only the Sufficiency scenario achieves a lower material footprint than the Baseline (by 35%). Appendix E decomposes the effect of sectoral changes in final demand in the reduction in the total material footprint in 2050, by applying stepwise the reductions in sectoral final demand. The reductions in final demand for the construction, industry, and transport sectors are found to have the largest effect (in this order). As for energy consumption and GHG emissions, appendix D presents an uncertainty analysis of the effects of the sectoral material footprint intensities on these results, and shows that the general findings are robust to the material intensities used. In 2050, the material footprint due to fossil fuel consumption is relatively small in all scenarios, but remains higher in the PNIEC-LTDS scenario (0.03 Gt) than in the CappedEcon (0.02 Gt) and Sufficiency (0.01 Gt) scenarios, in which the phase-out of fossil fuels by 2050 is deeper.

[19] In the absence of precision, values are given for the current recycling rates for materials contained in LCTs.

[20] If no precision, values provided are determined using the current recycling rates for materials contained in LCTs.

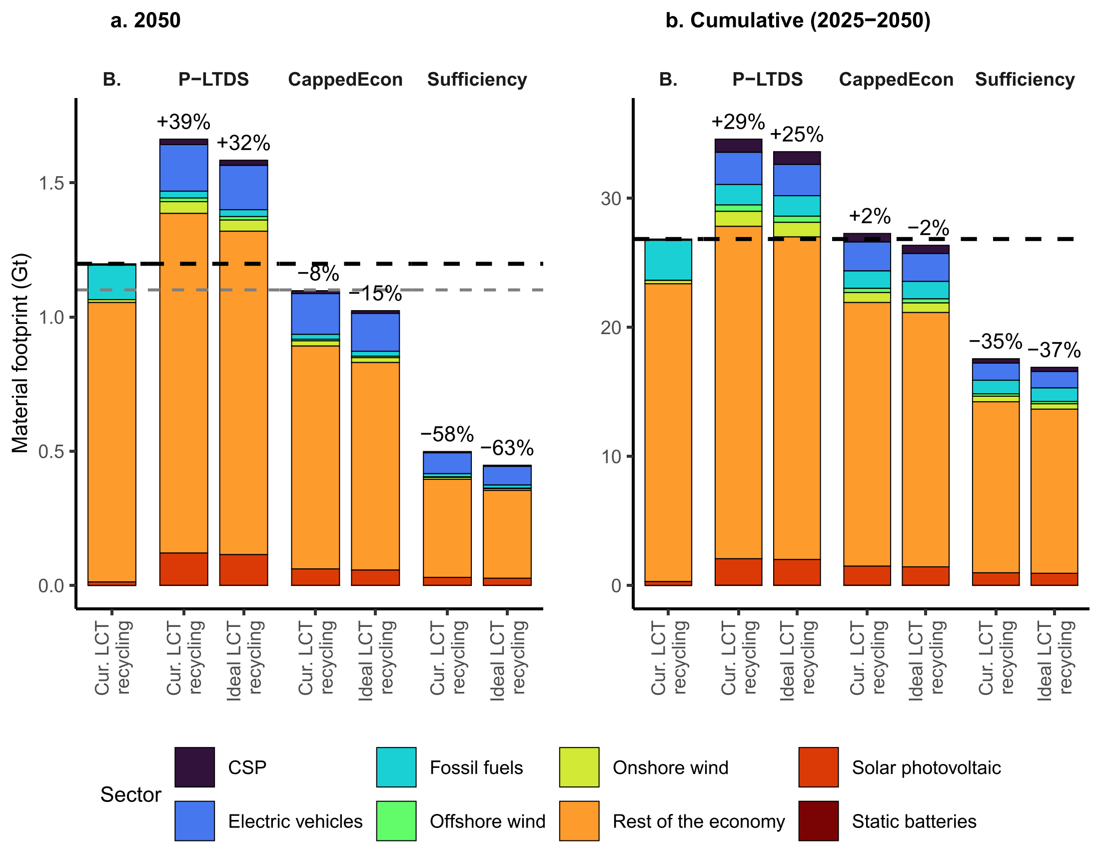

Figure 10. Material footprint (a) in 2050. (b) Cumulative (2025–2050) for each mitigation scenario, broken down by low-carbon technology (LCT), fossil fuel extraction, and rest of the economy. Estimations are shown with the current (Cur.) and ideal recycling rates for LCTs. Values are compared in percentage terms against the Baseline (B.) scenario (dashed horizontal black line). The dashed grey line in the left-hand side figure shows the material footprint in 2025. Here, the material footprint associated with fossil fuel extraction is quantified using the material footprint to extracted fossil fuels factors derived from the Wuppertal Institute, which are in the middle range of estimated factors (see SI-1, section 4.3).

Figure 11 focuses on the evolution of the material footprint of the energy sector, to analyse the effects of the deployment of LCTs. On the one hand, figure 11(a) shows the material footprint associated with fossil fuel extraction in 2025. On the other hand, figure 11(b) shows the material footprint entailed by LCTs in both 2030 and 2050. To account for to the uncertainty in the material footprint to extracted fossil fuels factors, we use values derived from three different studies to derive a range of values, all shown in figure 11(a). The results show that both for the PNIEC-LTDS and CappedEcon scenarios, the material footprint associated to deployed LCTs in 2050 is found to be higher than all three estimations of the material footprint associated to fossil fuels in 2025. Thus, it seems likely the deploying LCTs will entail an increase in the material footprint of the energy sector. However, the Sufficiency scenario presents a material footprint of LCTs by 2050 on the lower end of the estimations of fossil fuels material footprint in 2025. The Sufficiency scenario therefore shows that within a postgrowth paradigm, it seems realistic to at least contain (if not to reduce) the material footprint of the energy sector while achieving a high deployment of LCTs.

Last but not least, in 2025, the fossil fuel consumption in Spain is lower than its 2007 peak, particularly for coal[21]. Therefore, comparing the material footprint of LCTs in 2050 against the one of fossil fuels in 2007 (peak of material footprint due to fossil fuels in Spain) shows a slightly different picture, with a reduction in the material footprint of the energy sector over the 2007–2050 time period for the CappedEcon and Sufficiency scenarios, and possible reduction (depending on the material footprint to extracted fossil fuels factors used) for the PNIEC-LTDS scenario (see SI-1, figure 9).

[21] Total fossil fuel consumption, measured at the final energy stage in ktoe, has decreased by 22% between 2007 and 2019 (specifically, by 25% for oil, 8% for gas, and 55% for coal.) All data according to the International Energy Agency World Energy Extended Balances.

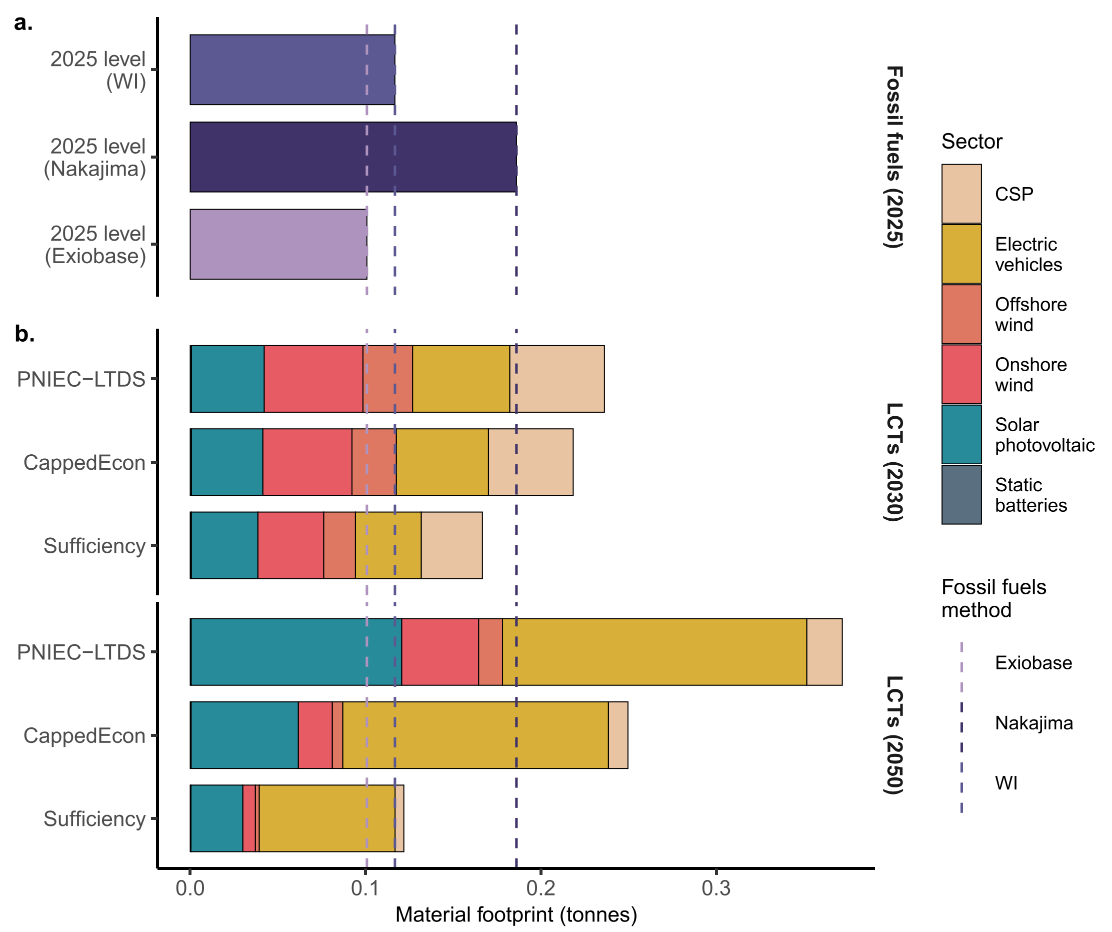

Figure 11. Material footprint of the energy sector, (a) for fossil fuels in 2025, and (b) for low-carbon technologies (LCTs) in 2030 and 2050 in each of the mitigation scenarios, broken down by LCT. The material footprint of fossil fuels is estimated based on three references due to the uncertainty on the material footprint factors: the Exiobase input output model [69, 70], Nakajima *et al* 2006 [89], and the Wuppertal Institute (WI) 2014 [88].

5. Discussion

The discussion is organised around four main topics. First, we address the material and environmental impacts associated with the material requirements of a low-carbon transition in Spain (sections 5.1 and 5.2, respectively). Second, section 5.3 offers reflections on the potential of the novel method applied in this study for postgrowth modelling and includes a comparison with related literature on sufficiency and decent living standards. Finally, section 5.4 discusses the limitations of the study and outlines directions for future research.

5.1. About the material impacts of a low-carbon transition

We have shown that the material requirements of an energy transition in Spain will be large, particularly for some materials such as cobalt, lithium, graphite, copper, and nickel. While transitioning to a postgrowth economic paradigm can considerably reduce material requirements, as shown with the Sufficiency scenario, results show that the cumulative material extraction required is higher than the population-weighted reserves for a range of materials. Even in the Sufficiency scenario, the cumulative extraction required is higher than population-weighted reserves for chromium, cobalt, lithium, nickel, silver, and tin. Such a result would be expected for most, if not all, Global North countries. While such a result highlights the scale of the material requirements for a low-carbon transition, reserves are a dynamic concept at the intersection of technical, geological, and economic factors, and may vary over time as a result of for instance technological change, or change in economic conditions (e.g. prices increasing or decreasing) [26–28]. On the other hand, reserves are determined mostly using corporate data, which are shared according to corporate strategies, for instance to raise funds or reassure investors. For instance, table 6 shows how global reported reserves have increased considerably since 2010 for almost all covered materials, with the exception of iron (+13%) and tin (−23%) [107, 108] — data were

Table 6. Evolution of global reserves over the 2010–2024 time period for the materials covered in this paper. Data from the United States Geological Survey [107, 108]. Data for aluminium were not available.

Material	Reserves change
Chromium	+60%
Cobalt	+67%
Copper	+85%
Graphite	+294%
Iron	+13%
Lithium	+183%
Manganese	+252%
Molybdenum	+72%
Nickel	+83%
Silver	+52%
Tin	−23%

not available for aluminium. The temporal variability of reserves, which are dependent on numerous factors, therefore emphasises that reserve values are of limited use to assess future availability of mineral materials[22]. The fact that reserves are not to be regarded as a hard limit, however, does not imply that continued extraction will be harmless.

Further, the size of mineral material reserves is only an element in a complex equation. For some metals, which are mostly produced as by-product of a major metal (e.g. gallium as by-product of aluminium production), the primary production may be primarily constrained by the dynamics of their carrier metal production [104, 111]. Supply bottlenecks and supply chain disruptions, which have been extremely pronounced in the context of the post-pandemic recovery [112], may also limit the availability of materials, and hence compromise the possibility to reach climate targets [38, 113]. A key challenge is to ramp up the production capacity for materials required for LCTs. As an example, according to the IEA, currently the key bottleneck in the manufacturing of solar PV seems to lie in the manufacturing capacity of pollysilicon (50% gap) [114], for which additional investments are needed. McNeil *et al* 2023 [115] argues that the capacity to open new lithium extraction facilities at the required pace for a rapid deployment of electric vehicles seems questionable. Further, the extreme geographical concentration, for some materials, of deposits and reserves [116], of mines currently in activity, but also of metallurgical plants for post-extraction processing [11], may exacerbate supply bottlenecks risks, particularly in the context of extremely high geopolitical tensions around materials (both raw and processed) [117].

5.2. About the environmental impacts associated to material requirements

Our results show that the general demand volume is the main driver of the three measures of materials-related environmental impact quantified (final energy consumption, GHG emissions, and material footprint). Although the deployment of LCTs requires a large amount of specific materials, it only contributes to a moderate portion to these environmental impacts. The Sufficiency scenario shows the possibility to strongly reduce all environmental impacts while achieving a large deployment of LCTs. Again, this finding is expected to be generalisable to most, if not all, Global North countries. Results show that the material footprint entailed by the deployment of LCTs in 2050 is likely to be higher than the material footprint associated with fossil fuel extraction in 2025[23]. Only the Sufficiency scenario contains the material footprint entailed by the deployment of LCTs in 2050 to a similar level as the one entailed by fossil fuel extraction in 2025 (figure 11), which is due to a lower final energy demand in the Sufficiency scenario compared to the other scenarios, which feed back to material requirements. However, it is also noteworthy that (i) Spain is a country where the use of coal in the electricity mix has already been almost phased-out, and the use of coal across the economy, relatively low, and (ii) coal is the fossil fuel for which the material footprint (expressed in kg MJ^{-1}) is highest (see SI-1, section 4.3). Therefore, a similar analysis conducted at the global level, or for a country with a higher use of coal, would be of interest, and may yield insights more favourable for LCTs than the present study.

The material footprint indicator aggregates very heterogeneous types of extraction. For instance, the impacts associated with the extraction of copper are very different from those of oil extraction, and will depend on the location of extraction, presence of vulnerable communities and ecosystems, as well as

[22] An example would be Henckens *et al* 2016 [109] finding that antimony is one of the scarcest metals using a reserves-based methodology (see [110] for a criticism).

[23] These findings show the importance of accounting for waste rock when conducting this type of renewable energy versus fossil fuel comparison, as excluding waste rock will considerably underestimate the material footprint of deploying LCTs.

on the local legislation. Furthermore, many environmental (as well as social) impacts are not quantified here. Indeed, mining activities are known for their considerable impacts on the local environment (biodiversity, pollution, land use) and on local communities (health, land-grabbing, working conditions, etc), which may worsen as mineral deposits of decreasing qualities are extracted (e.g. increasing energy use by unit mass of valuable mineral extracted). Mining activities therefore pose critical questions of environmental, social, and international justice [118, 119]. A potential way forward is the use of environmentally-weighted material consumption, using data derived from the Life Cycle Analysis literature [85], or the use of a social Life Cycle Analysis [120, 121]. Examples include impacts on biodiversity, water use, local pollution and toxicity, as well as impacts on local communities. Of these complementary impact indicators, only the land requirements of LCTs are explicitly represented in MEDEAS-Spain, with a dynamic integration between the energy module (providing deployment of LCTs) and the land-use module. We show (and discuss) in appendix G that the deployment of LCTs in Spain[24] implies moderate (though non-negligible) land requirements, of 2% of agricultural land by 2050 for the PNIEC-LTDS scenario, and 1.5% and 1.1% for the CappedEcon and Sufficiency scenarios, respectively.

5.3. The Sufficiency scenario: postgrowth modelling, and decent living standards

In this work, we have represented a Sufficiency scenario in an IAM using a novel approach: imposing exogenously the level and structure of monetary final demand to a level (i) considered consistent with the provision of good living standards for the whole Spanish population, and (ii) decreasing significantly energy and material consumption in Spain. Consistently with a postgrowth economic paradigm, this approach allows us to selectively downscale the final demand for specific sectors. To define the 'sufficient' level of final demand at the sector level, we have used underlying physical data and assumptions where possible. This approach, combined with the model's dynamic nature and its demand-driven input–output structure, enables us to trace how changes in the level and composition of final demand ripple through the economy, leading to variations in sectoral output and associated environmental impacts over time. This work is also an important step towards a better integration of biophysical limits (here quantified via the cumulative primary material extraction and population-weighted reserves) in postgrowth modelling [57]. However, while the Sufficiency scenario is a valuable contribution to the emerging postgrowth modelling literature, it lacks the representation of some key aspects to be a full-fledged postgrowth scenario (for instance, changes in the structure and location of production, or explicit consideration of redistributive policies). It also lacks representation of concrete policy levers (or policy instruments), and instead represents mostly what one may refer to as policy outcomes (e.g. an exogenous change in the level and structure of final demand)[25].

Defining the underlying physical basis for a 'sufficient' level of activity required difficult choices, and was not possible for all sectors (particularly difficult for services sectors). Further, beyond the present modelling exercise, these are critical societal choices and fall within the broader range of socio-economic choices that need to be democratically decided [122]. Then, the translation of physical activity levels into a corresponding monetary final demand comes with substantial associated uncertainty. Data and assumptions were obtained from a range of literature with diverse assumptions and approaches, raising the issue of consistency. We believe that future work aiming at representing human activities and service provisioning with a physical bottom-up perspective (for instance in terms of transportation, infrastructure, and production of goods and services), and at translating endogenously these physical activities in terms of monetary final demand, would be a valuable way to develop this approach further in the MEDEAS framework (see review by Widenhofer *et al* [31]). Such representation would also be essential to represent policy levers for a postgrowth transition. For instance, further work representing the levers mobilised to allow for the provision of good living standards at decreasing levels of energy and resource use [123] and to curtail potential rebound effects[26] would be very valuable.

There is a possible blindspot in our Sufficiency scenario regarding the effects of future regional or national economic pathways abroad. Indeed, the Sufficiency scenario is defined independently of economic pathways abroad, via an exogenously defined change in the level and structure of final demand for Spanish goods and services. In the absence of countervailing measures, the productive capacity of the Spanish economy could potentially be used to export more goods and services, assuming that the

[24] Solar PV and hydropower—wind power is not considered here as competing for land.

[25] We note that the lack of explicit representation of policy levers tends to be a shared limitation of IAMs, which often rely heavily on a price of carbon to represent environmental and climate policies.

[26] Rebound effects are currently not explicitly modelled in MEDEAS-Spain, although they are arguably captured in the behavioural parameters calibrated to Eurostat data and to national accounts, see SI-1, section 2.

Spanish economy is competitive on global markets (a full-fledged postgrowth scenario would therefore be needed for such a modelling). This would in turn raise domestic final energy consumption, and therefore GHG emissions, but potentially displace even more emissions abroad in the context of a rapid Spanish decarbonisation. Assessing and balancing such a trade-offs would be essential and raises interesting questions: should a postgrowth strategy focus on reducing domestic emissions (and more generally, impacts) while achieving good living standards for all, or instead encourage higher domestic emissions when it contributes to displacing even more emissions (and more generally, impacts) elsewhere?

In relation to the decent living standards literature, the results obtained for per capita final energy use in 2050 are 7 GJpc yr^{-1} for household direct final consumption (vs 22 GJpc yr^{-1} in 2025) and 19 GJpc yr^{-1} for the upstream energy requirements associated with the supply chain of the Spanish final demand[27] (vs 61 GJpc yr^{-1} in 2025), i.e. a total of 26 GJpc yr^{-1} (vs 83 GJpc yr^{-1} in 2025). These are reductions of 69% in the per capita final energy footprint. Such results are consistent with the decent living standards literature, being closer to the global averages of the Low Energy Demand scenario from Grubler *et al* [41] by 2050 (25 GJpc yr^{-1}) and the High Demand scenario of Millward-Hopkins *et al* [44] (15.3 GJpc yr^{-1} as mean value for the global level, cf their figure 4). Last, in the EU context, Wiese *et al* (2024) [45] find a reduction of 52% in final energy consumption between 2020 and 2050 (from 103 GJpc yr^{-1} to 50 GJpc yr^{-1}) in their low energy demand scenario featuring ambitious sufficiency measures. (We note, however, that our approach, which relies to a large extent on top-down sectoral final energy intensities derived from the Spanish national energy and climate plan, is not aligned with the bottom-up approach usually adopted in the decent living standards literature.)

5.4. Limitations

First, we recall that the present work focuses on assessing the material implications of the Spanish national energy and climate plan (as well as of two alternative scenarios), as layed out in the PNIEC [6] and LTDS [7]. To this end, the constraining feedback loops from the MEDEAS framework were disabled. While this scope is appropriate for conducting an impact analysis, it does not allow for an assessment of the feasibility of the scenarios under study. Future research could therefore explore how different constraints may affect the questions analysed in this work. The following sections delve into specific limitations related to energy, GHG emissions, and materials.

5.4.1. Energy system and GHG emissions

There are a few noteworthy limitations on the modelling of the energy system. Technological breakthroughs and the uptake of new technologies are difficult to forecast, and incompletely captured in our model, which mostly considers mature technologies. A clear example is the uncertainty regarding the composition, lifetimes, and capacities of batteries in the field of electric mobility (but also solar PV [124]). For instance, it is uncertain whether sodium-based batteries may displace lithium ion-battery [125], and under which timespan, although such an evolution would strongly modify the future material requirements of electric mobility. Hydrogen is another example; while green hydrogen projects are already in the pipeline in Spain (national targets aim at 11 GW of electrolysers by 2030 [6]), green hydrogen and its material requirements are not modelled in MEDEAS-Spain (see Lallana *et al* [30] for an assessment of material requirements).

We note that the deployment of renewable energy technologies capacities are set exogenously to 2030, and extrapolated to 2050 (with endogenous saturation when renewable energy approaches 100% of the energy mix for a given energy carrier). The renewable electricity mix obtained in 2050 is therefore one possible outcome. As a comparison, when representing the PNIEC and LTDS with an optimisation model of the power sector, García-Gusano *et al* [29] finds an installed capacity by 2050 of approximatively 90 and 130 GW for solar PV and wind onshore, respectively (in our PNIEC-LTDS scenario, we find 136 and 93 for solar PV and wind onshore, respectively). Regarding materials-related final energy consumption and GHG emissions, it is important to note that these should be regarded as a first-order, coarse estimation. Neither the roll-out of new technologies to decarbonise the metallurgical sector nor the efficiency gains that may be obtained by electrifying end-uses are explicitly accounted for (e.g. heat pumps for low and medium temperature heating). In a similar vein and with a counteracting effect, the effects of the decreasing quality of mineral deposits due to resource depletion, which will tend to increase the energy intensities of mining [33, 126], were not modelled in this study. Further, we do not make use in our scenarios of additional levers to reduce material requirements and materials-related final

[27] Includes both the supply chain of the household final demand and of the rest of final demand (gross fixed capital formation and government expenditures).

energy consumption and GHG emissions (e.g. lifetime extension, lightweight design, material substitution) — see [127] for an example in the buildings sector. Quantifying the potential of these levers and implementing them in the model at the sectoral level is a promising avenue for future work.

An additional important limitation is related to the use of exogenous sectoral final energy intensities derived from the PNIEC [6] and LTDS [7]. A rapid deployment of LCTs may increase final energy demand (due to the energy required for manufacturing and deploying LCTs), and put downward pressure on the net energy available to society, at least during the transition phase [37]. Including such a dynamic on a nationally-focused study would require a detailed assessment of the trade origins across the full LCT supply chain—an effort beyond the scope of this work. The deployment of decarbonisation technologies in hard-to-abate sectors, such as carbon capture and storage, or alternative fuels such as electrolytic hydrogen, may also considerably increase final energy requirements [128–130]. Further, it is difficult to forecast the emergence of entirely new, or rapidly evolving, demand sectors. The case of digitalisation (particularly in the context of rapid advances in AI), which is frequently mentioned in the PNIEC and LTDS as a way to unlock productivity gains without explicitly acknowledging its potential contributions towards increasing electricity demand, is a clear example [131]. Addressing the future impacts of climate change will also require additional energy requirements, the extent of which are still unknown.

5.4.2. Material demand, requirements, and footprint

The material requirements of upgrading the electricity grid are marginally covered. Indeed, only the overgrids required to connect new renewable plants and EV chargers to the existing grid are captured, but the material requirements (aluminium, copper) needed to upgrade the electricity grid (for instance to deal with the variability of renewable energy systems and with the electrification of end-uses, or to connect new renewable plants in remote locations) are not covered in this study [16]. Furthermore, it is difficult to forecast the evolution of the material intensities of LCTs to 2050. First, there is uncertainty on the remaining room for incremental material intensity improvements for each technology. But also, as mentioned in the previous section, there is substantial uncertainty of the actual future LCTs, as radical changes in the deployed technologies may happen (e.g. sodium-based batteries [132], or perovskite solar cells [124]). Future material intensities may also dependent on the future scarcity of materials, supply bottlenecks, and geopolitical conflicts affecting supply chains (due to substitution strategies). Considering these uncertainties, we adopted a neutral assumption of constant material intensities of LCTs.

Last, regarding the material footprint, it is noteworthy that this article does not consider the effects of the decrease in the quality of mineral deposits, for instance in terms of ore grade. The consequence of such decrease in quality and ore grades would be an increase in the rock-to-metal ratios, i.e. in the burden mass of materials that need to be extracted per unit mass of valuable metal recovered. This effect would tend to increase the material footprint in 2050.

6. Conclusion

In this paper, we have conducted an impact analysis of the material requirements of a low-carbon transition in Spain using a system dynamics IAM, MEDEAS-Spain. Then, we have quantified the environmental impacts associated with material requirements in terms of final energy requirements, GHG emissions, and material footprint. The use of an input–output structure to represent the economy allowed us to quantify at the sectoral level the material requirements of the rest of economic activities. We have quantified material requirements for a baseline and three decarbonisation scenarios (alongside a baseline); first, a scenario representing the Spanish national climate and energy plan (PNIEC-LTDS). Second, a CappedEcon scenario, which achieves the energy targets of the national climate and energy plan while curtailing the final demand level to its 2025 level. Third, the input–output structure also allowed us to represent a Sufficiency scenario, which is consistent with a postgrowth paradigm, and in which the final demand for each sector is downscaled to a level sufficient to meet good living standards for the Spanish population. As the objective was not to assess the viability of these scenarios, the constraining feedback loops of the MEDEAS framework were deactivated. Exploring the implications of activating these feedback loops would be an interesting avenue for future work.

In line with previous work, we find that the material requirements of the low-carbon transition are large, although heterogeneous across materials. Particularly, the material requirements for cobalt, graphite, and lithium (mostly driven by the automotive sector), and for nickel (mostly driven by the automotive sector and wind power), are considerable and represent a very large increase compared to current material requirements. However, we also find that for most materials, the rest of economic activities are responsible for the largest share of material demand. While such a result may be expected, the comprehensive representation of all material requirements emphasises that (i) the general demand volume is the key determinant of material requirements, and (ii) there is considerable scope to reduce material requirements while still achieving a large scale deployment of LCTs, although this requires deep socioeconomic changes. Indeed, we attempt to quantify this scope in the Sufficiency scenario, which shows a decrease in material footprint by 58% (proxy for total material requirements) compared to the 2025 value. This decrease is due to both a reduction in the deployment of LCTs, and in the material requirements of the rest of economic activities. Further, our results show that only in the case of the Sufficiency scenario is the material footprint associated with the deployment of LCTs in 2050 contained to a level comparable to the one associated with fossil fuel extraction in 2025. Our results therefore suggest that sector-specific reductions in the level of final demand of goods and services in the Global North, in line with the transition to a postgrowth paradigm, could be crucial to reconcile a rapid and large deployment of LCTs with a reduction in material footprint.

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Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

Conflicts of interest

There are no conflicts to declare.

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Appendix A. PNIEC objectives

Table 7 shows the renewable energy and static batteries capacities deployment objectives to 2030. In the model, the growth rate of each renewable energy technology is calibrated to meet these objectives by 2030. In line with the PNIEC, hydropower and pumped hydro storage capacities are kept constant. In terms of number of electric vehicles, the PNIEC sets as target 5.5 millions of electric vehicles by 2030.

Table 7. Renewable energy and static batteries deployment objectives to 2030 according to the National Integrated Energy and Climate Plan [6].

Technology	Capacity (GW)
Solar photovoltaic	76.39
Concentrated solar power	4.80
Onshore wind	59.04
Offshore wind	3.00
Static batteries	12.50

Appendix B. Further details on scenario assumptions

Table 8 shows the evolution of the number of vehicles to 2050 for each scenario. Table 9 shows a summary of the reduction in the level of final demand for each of the 35 economic sectors between 2022 and 2050.

Table 8. Evolution of the stock of vehicles to 2050 for each scenario. Increases (in percentage) are provided as cumulative increase over each time period (e.g. 2025–2030), and not as yearly increases. Except for the Baseline scenario, the share of electric vehicles reaches 70% in each vehicle category. PNIEC: National Integrated Energy and Climate Plan. LTDS: Long Term Decarbonisation Strategy. EVs: Electric vehicles.

Variable	Baseline	PNIEC-LTDS	CappedEcon	Sufficiency
Household four-wheeled vehicles	Same as PNIEC-LTDS scenario.	Increase by 2.8% over 2025–2030 (PNIEC), and by 3.8% over 2030–2050 (following population growth).	Constant over 2025–2050.	Decrease by 39% over 2025–2050 ('Frugal generation' scenario from the 'Transition(s) 2050' report by the French environmental agency) [97].
Household two-wheeled vehicles	Same as PNIEC-LTDS scenario.	Increase by 35% over 2025–2030 (PNIEC), and by 3.8% over 2030–2050 (following population growth).	Increase by 35% over 2025–2030 (PNIEC), and by 3.8% over 2030–2050 (following population growth).	Double in the 2025–2050 (own assumption).
Buses	Same as PNIEC-LTDS scenario.	Constant over 2025–2050.	Increase by 236% over 2025–2030 (PNIEC), and by 3.8% over 2030–2050 (following population growth).	Increase by 236% over 2025–2030 (PNIEC), and by 3.8% over 2030–2050 (following population growth).
Commercial light duty vehicles	Same as PNIEC-LTDS scenario.	Increase by 18% over 2025–2030 (PNIEC), and by 3.8% over 2030–2050 (following population growth).	Constant over 2025–2050.	Decrease by 39% over 2025–2050 (following household four-wheeled vehicles).
Commercial heavy duty vehicles	Same as PNIEC-LTDS scenario.	Increase by 18% over 2025–2030 (PNIEC), and by 3.8% over 2030–2050 (following population growth).	Constant over 2025–2050.	Decrease by 39% over 2025–2050 (following household four-wheeled vehicles).
Electric bicycles	No deployment.	Negligible, not accounted for (assumption that two-wheeled vehicles are not displaced by electric bicycles).	Negligible, not accounted for (assumption that two-wheeled vehicles are not displaced by electric bicycles).	50% of the electric household two-wheeled vehicles in 2050 (own assumption).

Table 9. Relative level of final demand in the Sufficiency scenario by 2050, indexed to 2022.

No	Sector	Relative level
S1	Crop and animal production, hunting and related service activities, forestry and logging, fishing and aquaculture	0.43
S2	Mining and quarrying	0.42
S3	Manufacture of food products, beverages and tobacco products	0.43
S4	Manufacture of textiles, wearing apparel and leather products	0.66
S5	Manufacture of wood and of products of wood and cork, except furniture; manufacture of articles of straw and plaiting materials, Manufacture of paper and paper products, Printing and reproduction of recorded media	0.63
S6	Manufacture of coke and refined petroleum products	0.00
S7	Manufacture of chemicals and chemical products	0.76
S8	Manufacture of basic pharmaceutical products and pharmaceutical preparations	1.00
S9	Manufacture of rubber and plastic products, Manufacture of other non-metallic mineral products	0.60
S10	Manufacture of basic metals, Manufacture of fabricated metal products, except machinery and equipment	0.55
S11	Manufacture of computer, electronic and optical products	0.70
S12	Manufacture of electrical equipment	0.70
S13	Manufacture of machinery and equipment n.e.c.	0.70
S14	Manufacture of motor vehicles, trailers and semi-trailers, Manufacture of other transport equipment	0.45
S15	Manufacture of furniture; other manufacturing, Repair and installation of machinery and equipment	0.70
S16	Electricity, gas, steam and air conditioning supply	1.00
S17	Water collection, treatment and supply, Sewerage; waste collection, treatment and disposal activities; materials recovery; remediation activities and other waste management services	1.00
S18	Construction	0.42
S19	Wholesale and retail trade and repair of motor vehicles and motorcycles	0.45
S20	Wholesale trade, except of motor vehicles and motorcycles; Retail trade, except of motor vehicles and motorcycles	0.66
S21	Land transport and transport via pipelines, Water transport, Air transport, Warehousing and support activities for transportation, Postal and courier activities	0.62
S22	Accommodation and food service activities	0.98
S23	Publishing activities, Motion picture, video and television programme production, sound recording and music publishing activities; programming and broadcasting activities	0.97
S24	Telecommunications	0.99
S25	Computer programming, consultancy and related activities; information service activities	0.97
S26	Financial service activities, except insurance and pension funding, Insurance, reinsurance and pension funding, except compulsory social security, Activities auxiliary to financial services and insurance activities	0.99
S27	Real estate activities	0.42
S28	Legal and accounting activities; activities of head offices; management consultancy activities; Architectural and engineering activities; technical testing and analysis	0.99
S29	Scientific research and development	0.97
S30	Advertising and market research, Other professional, scientific and technical activities; veterinary activities	0.99
S31	Administrative and support service activities	0.99
S32	Public administration and defence; compulsory social security	1.00
S33	Education	1.00
S34	Human health and social work activities	1.00
S35	Other service activities; Activities of households as employers; undifferentiated goods- and services-producing activities of households for own use; Activities of extraterritorial organisations and bodies	0.97

Appendix C. Additional results over time

Figure 12 shows general results indexed to 2025 over the time period 2020–2050 in terms of (a) gross domestic product, (b) total final demand, (c) final energy consumption, and (d) GHG emissions.

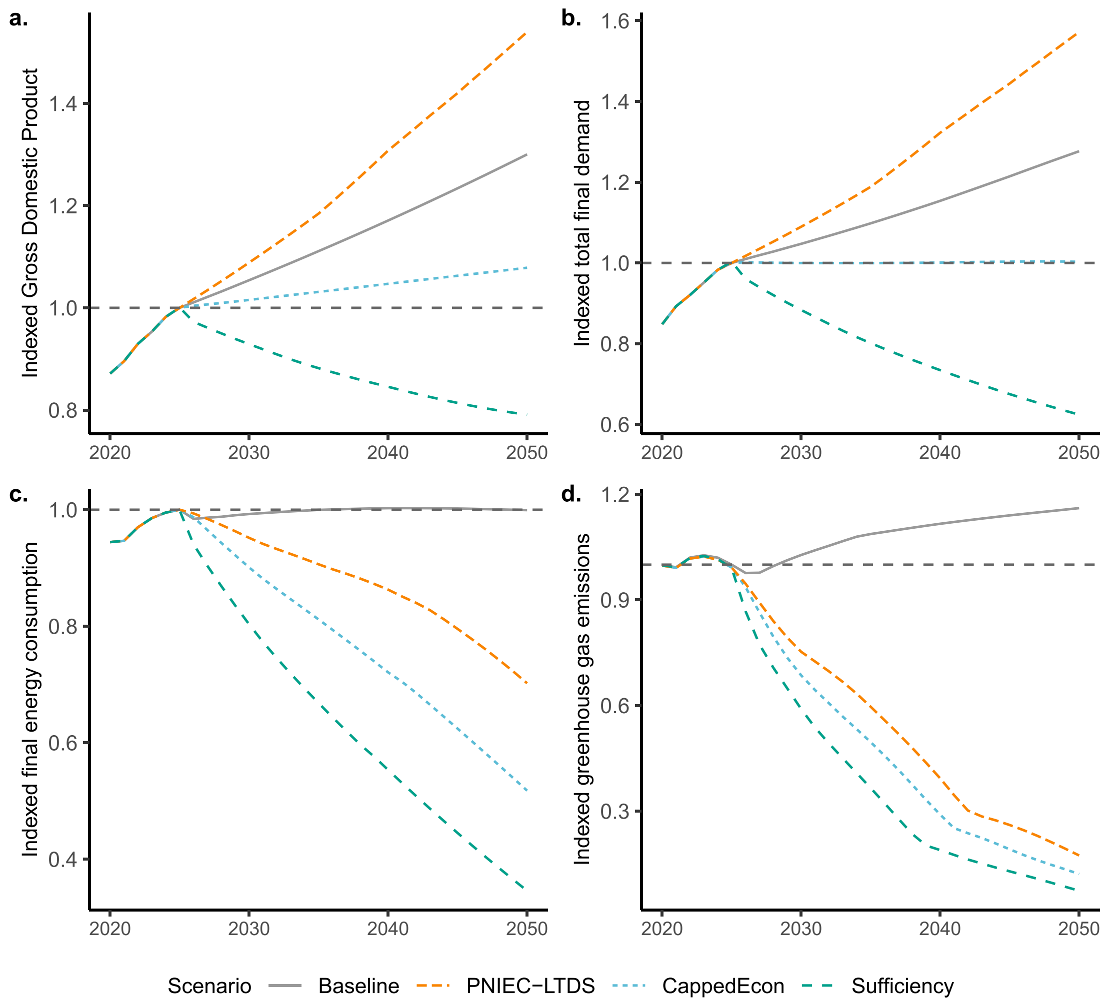

Figure 12. General results over the 2020–2050 indexed to 2025. (a) Gross domestic product, (b) total final demand, (c) final energy consumption, and (d) greenhouse gas emissions.

Appendix D. Uncertainty analysis on the sectoral material intensities

This section presents the results obtained when conducting the uncertainty analysis on the sectoral material demand and footprint intensities, both in terms of (i) the initial sectoral material demand intensities used, and (ii) the evolution over time of the sectoral material demand intensities. First, figure 13 shows the breakdown of cumulative material requirements for the PNIEC-LTDS scenario (i) for each of the three initial sectoral material demand intensities (min, default, max) (ii) under the hypothesis of decreasing sectoral material intensities (following the yearly reduction rate in the aggregate material intensity of the economy set out by the PNIEC) as opposed to constant sectoral material intensities (which is shown in dotted red line). The additional material requirements with the constant sectoral material intensities all fall under 'Rest of the economy'. Figure 13 shows that for some materials (particularly silver and tin), the results can be significantly affected by the uncertainty on the sectoral material demand intensities. However, overall, the figure shows that the results and findings are robust to the approach and values for sectoral material demand intensities. Indeed, for those materials for which the rest of economic activities is the dominant driver of cumulative material requirements, it remains so

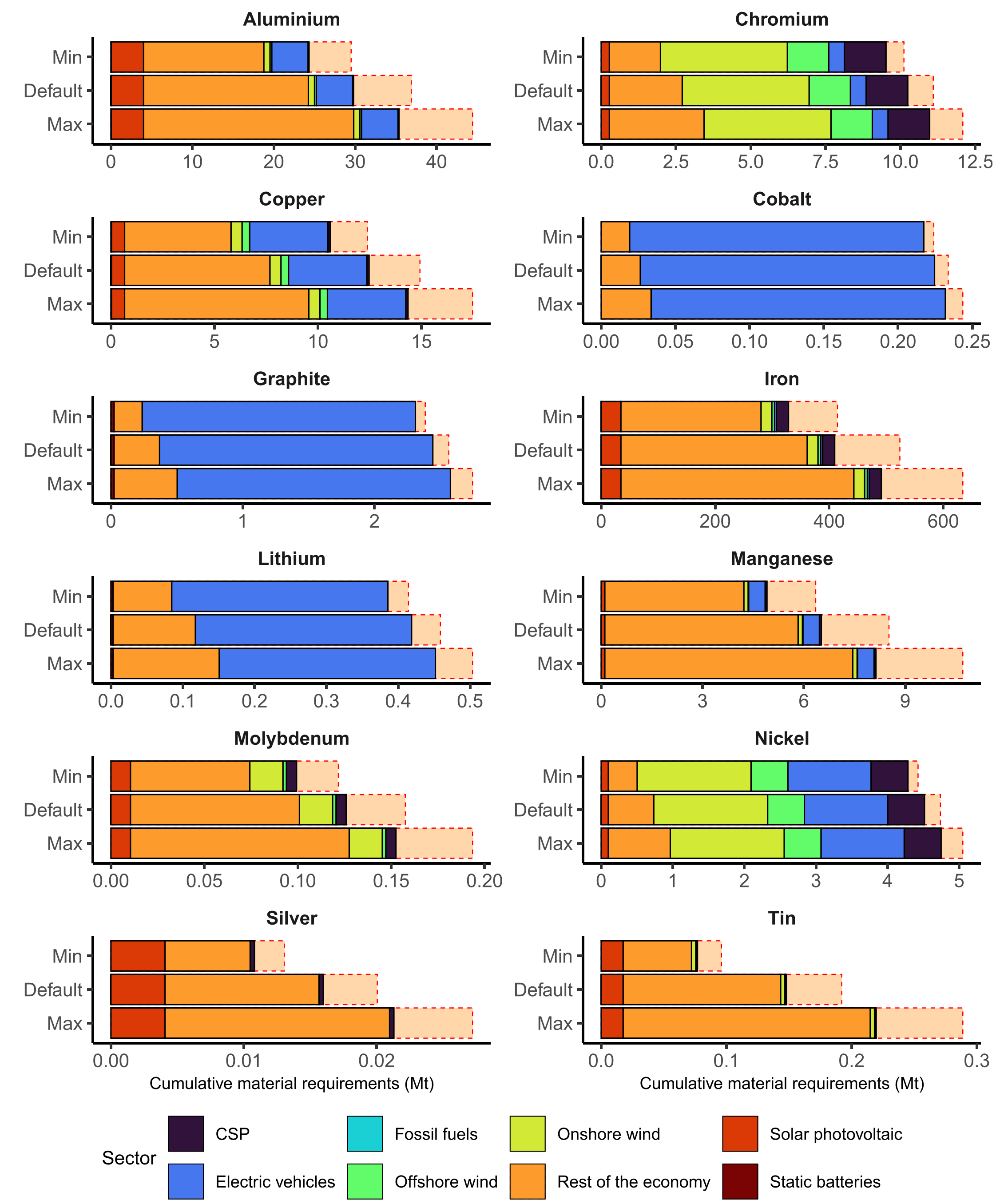

Figure 13. Uncertainty analysis: effect of changes in sectoral material demand intensities on cumulative (2025–2050) material requirements for the PNIEC-LTDS scenario. The bar delineated by the dotted red line shows the additional material requirements (all fall under the 'Rest of the economy' sector) obtained with the assumption of constant sectoral material demand intensities as opposed to material requirements obtained with the assumption of decreasing sectoral material demand intensities.

under each of the three initial sectoral material demand intensities, and disregarding the assumption on the evolution of sectoral material demand intensities (constant vs decreasing).

Next, figure 14 shows the effects of changes in sectoral material intensities (both material demand and material footprint intensities) on the three cumulative (2025–2050) environmental impact categories, again, in terms of (i) the initial sectoral material demand intensities (min, default, max) used, and (ii) evolution over time regarding the sectoral material intensities. Def (default) stands for the sectoral material intensities used in the paper. The abbreviation -C stands for constant sectoral material intensities (as in the rest of results), while -D stands for decreasing sectoral material intensities. The number at the top of each bar gives the percentage of impacts due to the rest of economic activities. The results show that the effect of the initial sectoral material intensities is substantial, with a large gap between results obtained with the minimum and maximum sectoral material intensities. The hypothesis regarding

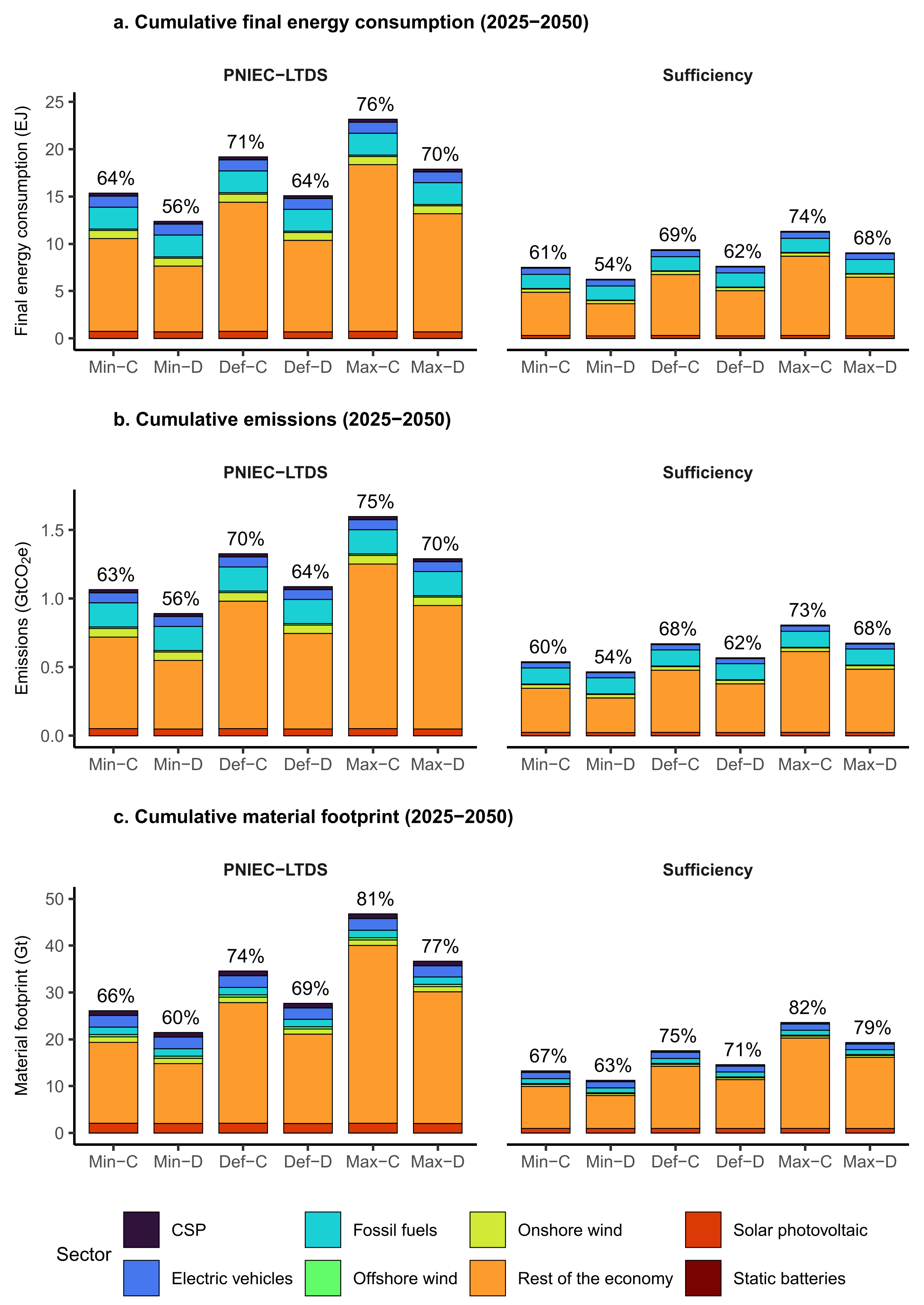

Figure 14. Uncertainty analysis: effect of changes on sectoral material demand and footprint intensities on environmental impacts. The number on the top of each bar gives the percentage of impacts due to the rest of economic activities. Min and Max stand for the lower and higher bound of initial sectoral material intensities, respectively. Def (default) stands for the sectoral material intensities used in the paper. The abbreviation -C stands for constant sectoral material intensities (as in the rest of results), while -D stands for decreasing sectoral material intensities.

the evolution of sectoral material intensities (constant '-C' vs decreasing '-D') also has substantial effects on the results. However, here too, the results of this uncertainty analysis do not alter the findings and conclusions of this study, with the environmental impacts associated with the rest of economic activities remaining the largest impact sector under all hypothesis. It is noteworthy, however, that the effects of different hypothesis regarding the evolution of the sectoral material intensities are larger at the end than at the beginning of the simulation time period (and therefore, also larger when measured at the end of the simulation time period as opposed to when measured in cumulative terms. Therefore, for comprehensiveness, SI-1 (figures 13 and 14) shows and discusses similar results focusing on material requirements and environmental impacts in 2050, instead of in cumulative terms.

Appendix E. Sufficiency scenario: breakdown by sector

Figure 15 decomposes the effect of the sectoral changes in final demand in the reduction in environmental impacts (in 2050). Starting from the CappedEcon scenario, the figure shows the gradual evolution towards the Sufficiency scenario as changes in sectoral final demand are applied stepwise and in

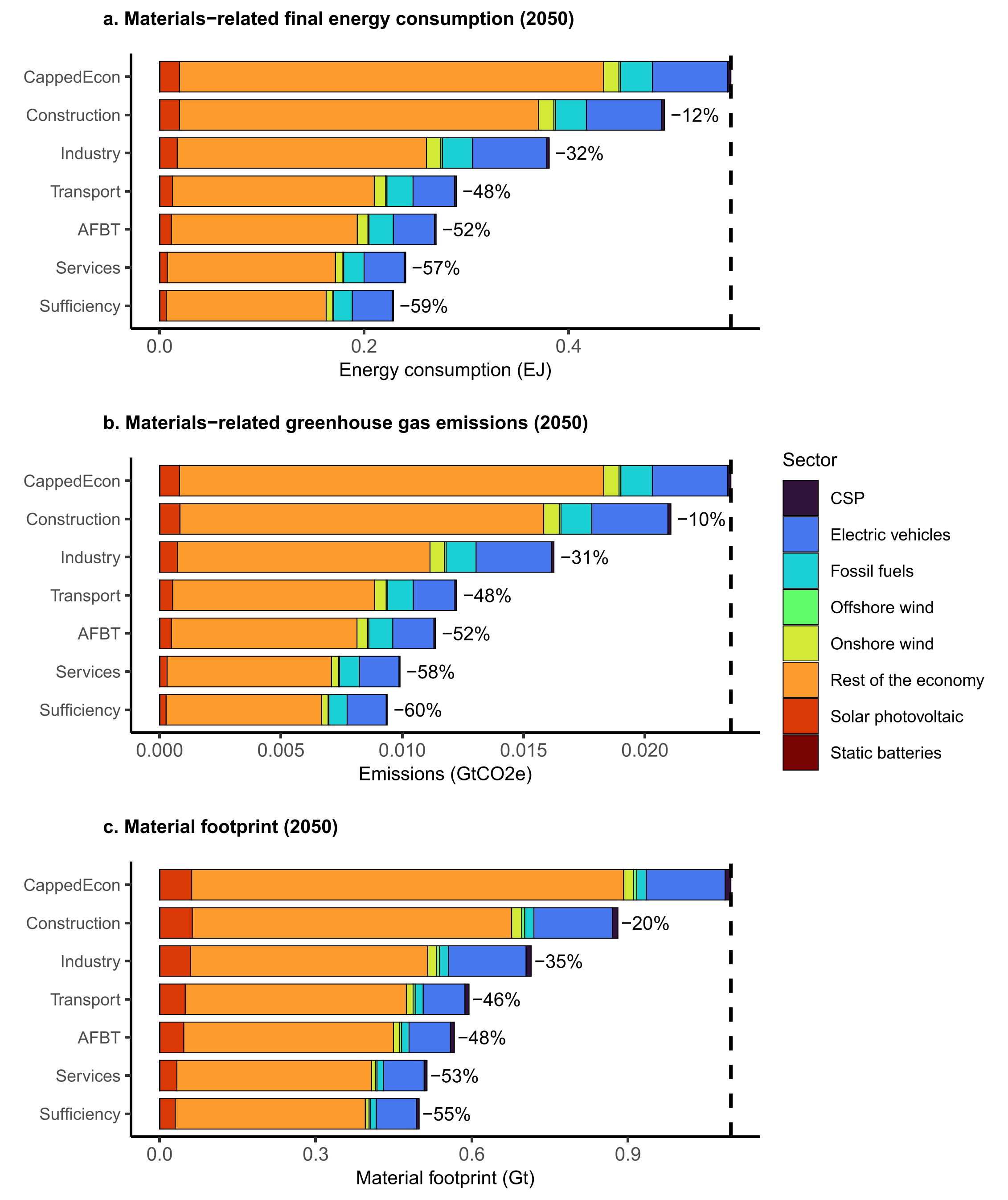

Figure 15. Stepwise application of the reduction of sectoral final demand from the CappedEcon to the Sufficiency scenario and effects on quantified environmental impacts: (a) materials-related final energy consumption, (b) materials-related greenhouse gas emissions, and (c) material footprint. AFBT: Agriculture, food, tobacco, and beverages.

the following order: (i) construction sector, (ii) industrial sector (excluding manufacture of vehicles), (iii) transport sector (including manufacture of vehicles), (iv) AFBT, (v) services; and (vi) rest of measures (mostly, utilities, and any synergy between measures). One can see that the effects of the reduction of the construction, industry, and transport sectors have each substantial effects, somewhat different depending on the type of environmental impacts. The materials-related energy consumption and GHG emissions are closely correlated, while the difference with the material footprint can be substantial. For instance, the reduction in the final demand for the construction sector is responsible for a decrease of 10% in materials-related greenhouse consumption, and for a decrease of 20% in the material footprint.

Appendix F. Uncertainty analysis on the energy intensities of materials

This section presents the results of the uncertainty analysis on the final energy intensities of materials. Figure 16 shows the 90% and 95% confidence intervals obtained for the evolution of the materials-related final energy consumption, both when the final energy consumption is shown in absolute terms (left column) and when the final energy consumption is shown in relative terms, indexed to 2025 (right column). Figure 16 shows that there are non-negligible, although moderate, effects on the absolute level of materials-related final energy consumption (left column). However, when looking specifically at the evolution of the materials-related final energy consumption, i.e. when results are indexed to 2025 for each run of the Monte Carlo simulation (right column), the effects of changes in energy intensities are negligible.

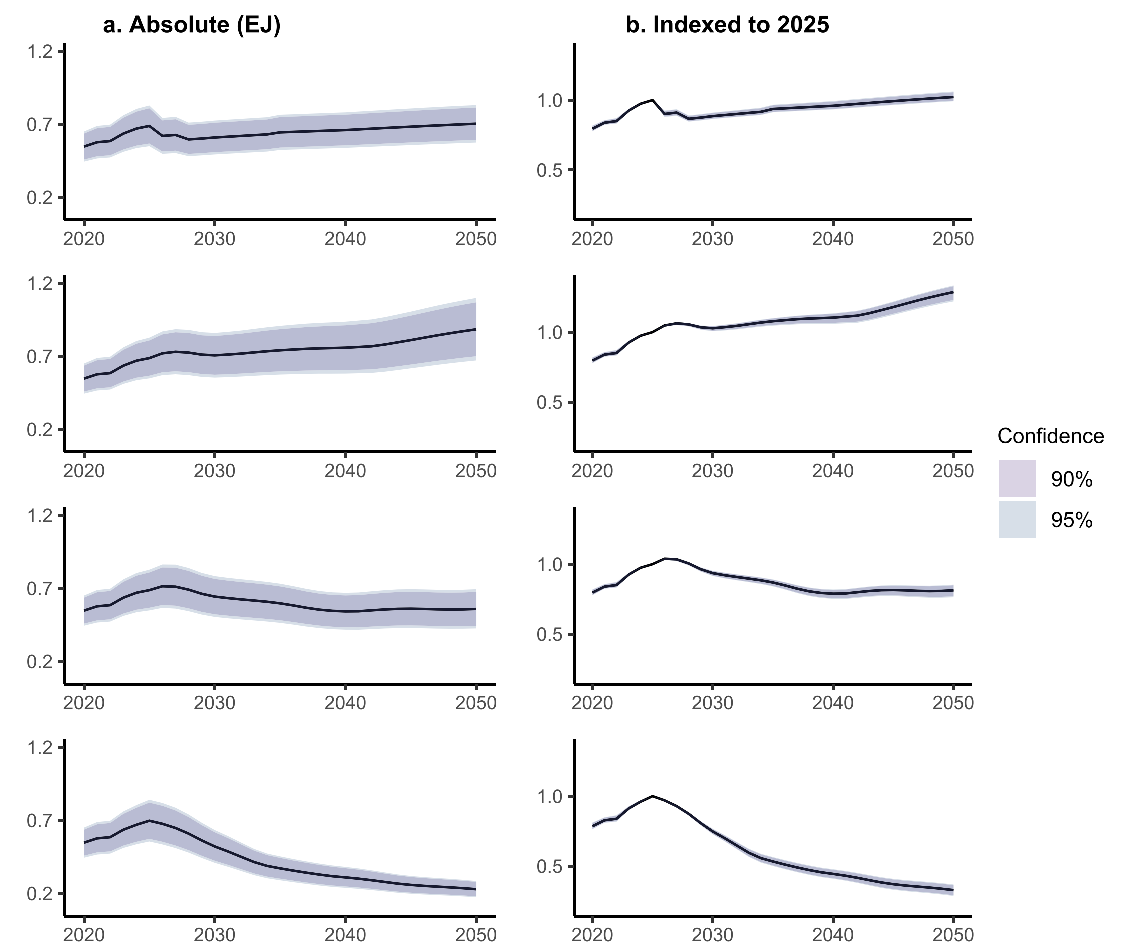

Figure 16. Uncertainty analysis of the effects of the energy intensities of mining and downstream material processing on the evolution of the materials-related final energy consumption, both in absolute terms (left column) and relative terms, indexed to 2025 (right column). The evolution obtained using the default energy intensities is shown as a solid black line. Confidence intervals of 80% and 90% are shown as shaded areas.

Next, figure 16 shows the effects of changes in energy intensities on the share of materials-related final energy consumption due to the deployment of LCTs in 2050, by showing a boxplot of the results obtained with the 1000 simulations alongside the results obtained with the default energy intensities (solid bars). The figure shows that the effects of a reasonable change in the energy intensities of mining and downstream material processing only entail a minor change in the share of materials-related final energy consumption induced by the deployment of LCTs.

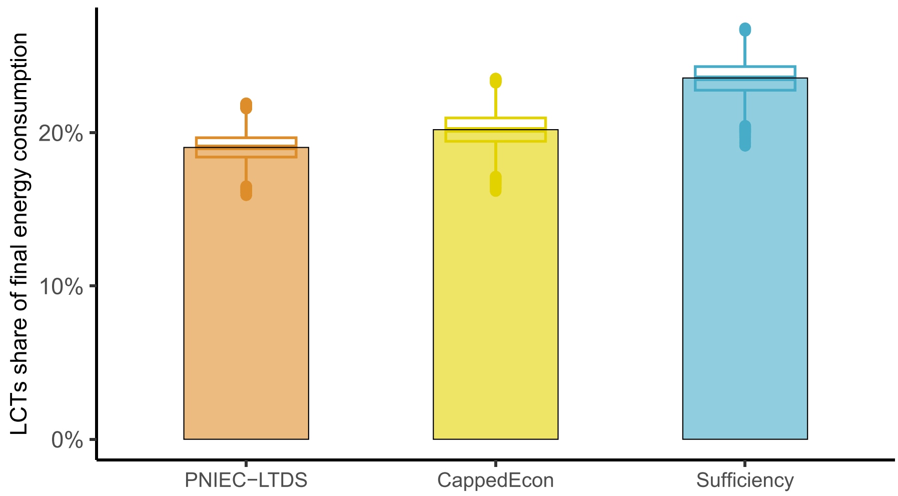

Figure 17. Uncertainty analysis of the effects of the energy intensities of mining and downstream material processing on the share of materials-related final energy consumption entailed by the deployment of low-carbon technologies (LCTs) in 2050.

Appendix G. Land requirements

Figure 18 shows the land requirements of hydropower and solar power as share of total agricultural land in Spain for each transition scenario. Although substantial, even in the case of the PNIEC-LTDS, the land requirements remain below 2% of the Spanish agricultural land by 2050. As a comparison, Correa *et al* [133] estimate the land requirements to cover the whole final energy consumption of the transportation sector in Spain with first generation biofuels (competing with agricultural land for food) locally produced to be in the range 26%–151% of the total Spanish land area (i.e. 49%–287% of total agricultural area in Spain), depending on the crop. Further, we have attempted a comparison with the current (value estimated for 2022 as no data for 2024 at time of writing) land requirements of biofuel consumption in Spain using data from ECODES [134], which reports biodiesel and bioethanol consumption in 2022 in Spain[28]. The land requirements we obtained are shown as a dashed horizontal line in figure 18, and amount to a large 3.3% of the total Spanish agricultural land, which is higher than the land requirements of solar PV and hydropower in 2050 in any of the three scenarios conducted in this study.

This result highlights the fact that the land requirements of electricity-yielding renewables are moderate compared to those of biomass. Indeed, most of the land-use implications of a low-carbon transition will likely come from the demand for biomass, be it in the form of biofuels for aviation and navigation, in the form of solid biomass for heating and electricity generation, or in the form of feedstock (e.g. methanol, bioethanol, bioethylene) for the chemical industry. The future land requirements of biomass is of particular relevance as biomass-based fuels and chemicals are regarded as a key lever to decarbonise hard-to-abate sectors (specifically iron and steel, aviation and navigation, and the chemical industry) [137].

It is worth noting that the impacts of land requirements from biomass are of different nature from those of electricity-yielding renewables. First, these may be offshored (and indeed are often offshored)

[28] According to ECODES, almost all biodiesel is produced from maize in Spain (thus competing with food production), and 97.2% of bioethanol is produced from crops (thus competing with food production too). Therefore, we assume that the share of first generation biofuels in Spain in 2024 is 100% and 97.2% for biodiesel and bioethanol, respectively. Then, we use an average energy yield of 0.06 GJ ha^{-1} for first generation biofuels, which is in the range reported in the review and study by de Castro *et al* [135], and is also consistent with the range of maximum theoretical yields for biofuel production in Europe reported by Fischer *et al* [136].

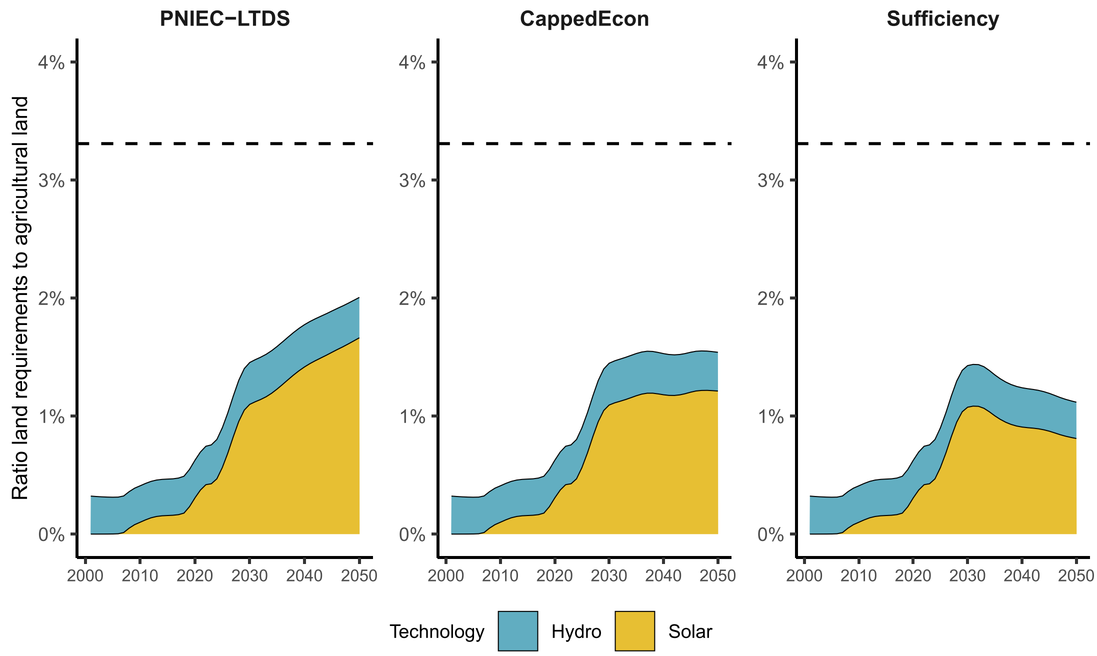

Figure 18. Land requirements of hydropower and solar power as a share of total agricultural land for each transition scenario. The dashed horizontal line shows our estimation of the 2022 land requirements of biofuel consumption in Spain.

to countries different from those where energy consumption occurs. Indeed, crops used for biofuel production tend to be located in areas of high biodiversity and tend to worsen biodiversity loss [133]. In the case of Spain, the vast majority of feedstock for biodiesel (by far most used biofuel in Spain) production come from Southeast Asia (China, Malaysia, and Indonesia) [134]. Second, the land requirements of crops used for biomass are of a different nature than the land requirements of solar PV and hydropower, to the extent that they can be compatible with conventional farming practices (e.g. soybean, maize, rapeseed), therefore potentially defusing conflicts related to land use in western countries, but also potentially masking the critical underlying question of land use.

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