Supplementary

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S1 Data Sources in MESSAGEix-Materials for Parametrization

35   Below table summarizes the data sources and their purpose of use for different industry sectors that are represented in MESSAGEix-Materials.

Table S1 Techno-economic data sources for the industries in MESSAGEix-Materials

Industry	Source	Description
Aluminium	IEA Energy Technology Transitions for Industry, 2009 (https://www.iea.org/reports/energy-technology-transitions-for-industry)	Choice of relevant industry technologies
	IEA ETSAP Technology Brief I10, 2012 (https://iea-etsap.org/E-TechDS/PDF/I10_AlProduction_ER_March2012_Final%20GSOK.pdf)	Techno-economic parameters, emission factors
	JRC Report Energy Efficiency and GHG Emissions: Prospective Scenarios for the Aluminium Industry (https://publications.jrc.ec.europa.eu/repository/handle/JRC96680)	Techno-economic parameters
	International Aluminum Institute (https://alucycle.world-aluminium.org/public-access/)	Material flows into product level, available end-of-life materials
	Idoine, N.E., Raycraft, E.R., Price, F., Hobbs, S.F., Deady, E.A., Everett, P., Shaw, R.A., Evans, E.J., and Mills, A.J.: World mineral production 2017-21, British Geological Survey, Nottingham, UK, 98pp., ISBN 9780852727973, 2023.	Historical data
Chemicals	IKARUS Model https://www.energyplan.eu/othertools/national/ikarus/	Refinery techno-economic parameters
	PRELIM Model https://www.ucalgary.ca/energy-technology-assessment/open-source-models/prelim	Refinery techno-economic parameters
	IEA The Future of Petrochemicals, 2018 (https://www.iea.org/reports/the-future-of-petrochemicals)	Determining relevant industry technologies
	IEA Energy Technology Perspectives 2020 (https://www.iea.org/reports/energy-technology-perspectives-2020)	Determining relevant industry technologies, techno-economic parameters
	IEA Energy Technology Transitions for Industry, 2009 (https://www.iea.org/reports/energy-technology-transitions-for-industry)	Determining relevant industry technologies
	IEA ETSAP Bioethylene Production (https://iea-etsap.org/E-TechDS/PDF/I13IR_Bioethy_MB_Jan2013_final_GSOK.pdf)	Techno-economic parameters
	IEA ETSAP Oil Refineries (https://iea-etsap.org/E-TechDS/PDF/P04_Oil%20Ref_KV_Apr2014_GSOK.pdf)	Techno-economic parameters
	Tuna, P., Hulteberg, C., and Ahlgren, S.: Techno-economic assessment of nonfossil ammonia production, Environ. Prog. Sustain., 33, 1290–1297, https://doi.org/10.1002/EP.11886, 2014.	Techno-economic parameters

	IEA Ammonia Technology Roadmap, 2021 (https://www.iea.org/reports/ammonia-technology-roadmap)	Historical data
	Yara Fertilizer Industry Handbook, 2018 https://www.yara.com/siteassets/investors/057-reports-and-presentations/other/2018/fertilizer-industry-handbook-2018.pdf/	Historical data
	FAOSTAT fertilizer trade, 2018 https://www.fao.org/in-focus/remaining-fertilizer-trade-tracker/en	Historical trade data
	IEA Energy Technology Transitions for Industry, 2009 (https://www.iea.org/reports/energy-technology-transitions-for-industry)	Conventional technologies techno-economic parameters
	Carina Oliveira. (2021). ADVANCED METHANOL TO OLEFINS PROCESS - TECHNOLOGY FACTSHEET. TNO. https://energy.nl/media/data/Technology-Factsheet-Advanced-methanol-to-olefins.pdf	Techno-economic parameters
	Dimian, A. C., & Bildea, C. S. (2018). Energy efficient methanol-to-olefins process. Chemical Engineering Research and Design, 131, 41–54. https://doi.org/10.1016/J.CHERD.2017.11.009	Techno-economic parameters
	Guillaume Gaulier & Soledad Zignago, 2010. "BACI: International Trade Database at the Product-Level. The 1994-2007 Version," CEPII Working Paper 2010- 23, October 2010, CEPII.	Historical trade data
	Geyer, R., Jambeck, J. R., & Law, K. L. (2017). Production, use, and fate of all plastics ever made. Science Advances, 3(7). https://doi.org/10.1126/SCIADV.1700782/SUPPL_FILE/1700782_SM.PDF	Techno-economic parameters
	Levi, P. G., & Cullen, J. M. (2018). Mapping Global Flows of Chemicals: From Fossil Fuel Feedstocks to Chemical Products. Environmental Science and Technology, 52(4), 1725–1734. https://doi.org/10.1021/acs.est.7b04573	Material flow data
	METI (2016), Future Supply and Demand Trend of Petrochemical Products Worldwide, Tokyo, www.meti.go.jp/policy/mono_info_service/mono/chemistry/sekkajyukyuudoukou201506.html	Historical data
	Methanol Institute: Global Methanol Supply and Demand Balance: https://www.methanol.org/methanol-price-supply-demand/, last_access: 2023, 2022.	Historical data
	Poluzzi, A., Guandalini, G., Guffanti, S., Martinelli, M., Moioli, S., Huttenhuis, P., Rexwinkel, G., Palonen, J., Martelli, E., Groppi, G., & Romano, M. C. (2022). Flexible Power and Biomass-To-Methanol Plants With Different Gasification Technologies. Frontiers in Energy Research, 9, 978. https://doi.org/10.3389/FENRG.2021.795673/BIBTEX	Techno-economic parameters
	Renewable Energy Agency (IRENA), I., & Methanol Institute. (2021). INNOVATION OUTLOOK RENEWABLE METHANOL. www.irena.org	Techno-economic parameters
	Schemme, S., Breuer, J. L., Köller, M., Meschede, S., Walman, F., Samsun, R. C., Peters, R., & Stolten, D. (n.d.-a). H 2-based synthetic fuels: A techno-economic comparison of alcohol, ether and hydrocarbon production. https://doi.org/10.1016/j.ijhydene.2019.05.028	Techno-economic parameters

	S&P Global. (2020). Chemical Economics Handbook – Methanol. https://www.spglobal.com/commodityinsights/en/ci/products/methanol-chemical-economics-handbook.html	Historical data
Power Sector	Arvesen, A., Luderer, G., Pehl, M., Bodirsky, B. L., and Hertwich, E. G.: Deriving life cycle assessment coefficients for application in Integrated Assessment Modelling, Environ. Modell. Softw., 99, 111–125, https://doi.org/10.1016/j.envsoft.2017.09.010, 2018.	Material intensities
Iron and steel	OECD steelmaking capacity database https://stats.oecd.org/Index.aspx?datasetcode=STI_STEEL_MAKINGCAPACITY World Steel Association (https://www.worldsteel.org/en/dam/jcr:0474d208-9108-4927-ace8-4ac5445c5df8/World+Steel+in+Figures+2017.pdf)	Historical data, Past capacity and production
	IEA ETSAP Technology Brief I02, 2010 (https://iea-etsap.org/E-TechDS/PDF/I02-Iron&Steel-GS-AD-gct.pdf)	Techno-economic parameters
	IEA Energy Technology Transitions for Industry, 2009 (https://www.iea.org/reports/energy-technology-transitions-for-industry)	Techno-economic parameters
Cement	Cement Statistics and Information (USGS) (https://pubs.usgs.gov/periodicals/mcs2020/mcs2020-cement.pdf)	Historical data, regional production
	2019 Activity Report (Cembureau) (http://www.cembureau.eu/media/clkdda45/activity-report-2019.pdf)	Historical data
	ADVANCE Modeling Guide for the Cement Industry, 2016 (http://fp7-advance.eu/content/industrial-sector-cement-guideline)	Techno-economic parameters, emission factors
	Voldsund, M., Gardarsdottir, S., De Lena, E., Pérez-Calvo, J.-F., Jamali, A., Berstad, D., Fu, C., Romano, M., Roussanaly, S., Anantharaman, R., Hoppe, H., Sutter, D., Mazzotti, M., Gazzani, M., Cinti, G., and Jordal, K.: Comparison of Technologies for CO2 Capture from Cement Production—Part 1: Technical Evaluation, Energies, 12, 559, https://doi.org/10.3390/en12030559, 2019. Gardarsdottir, S., De Lena, E., Romano, M., Roussanaly, S., Voldsund, M., Pérez-Calvo, J.-F., Berstad, D., Fu, C., Anantharaman, R., Sutter, D., Gazzani, M., Mazzotti, M., and Cinti, G.: Comparison of Technologies for CO2 Capture from Cement Production—Part 2: Cost Analysis, Energies, 12, 542, https://doi.org/10.3390/en12030542, 2019.	Techno-economic parameters of CCS technologies
	Methodology for the free allocation of emission allowances in the EU ETS post 2012, 2009 (https://climate.ec.europa.eu/system/files/2016-11/bm_study-project_approach_and_general_issues_en.pdf) IEA ETSAP - Technology Brief I03, 2010 (https://iea-etsap.org/E-TechDS/PDF/I03_cement_June_2010_GS-gct.pdf)	Historical data, emission factors

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S2 Regions in MESSAGEix-Materials

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Table S2 Regions in MESSAGEix-Materials

NAM	North America	Canada, Guam, Puerto Rico, United States of America, Virgin Islands
WEU	Western Europe	Andorra, Austria, Azores, Belgium, Canary Islands, Channel Islands, Cyprus, Denmark, Faeroe Islands, Finland, France, Germany, Gibraltar, Greece, Greenland, Iceland, Ireland, Isle of Man, Italy, Liechtenstein, Luxembourg, Madeira, Malta, Monaco, Netherlands, Norway, Portugal, Spain, Sweden, Switzerland, Turkey, United Kingdom
PAO	Pacific OECD	Australia, Japan, New Zealand
EEU	Central and Eastern Europe	Albania, Bosnia and Herzegovina, Bulgaria, Croatia, Czech Republic, The former Yugoslav Rep. of Macedonia, Hungary, Poland, Romania, Slovak Republic, Slovenia, Yugoslavia, Estonia, Latvia, Lithuania
FSU	Former Soviet Union	Armenia, Azerbaijan, Belarus, Georgia, Kazakhstan, Kyrgyzstan, Republic of Moldova, Russian Federation, Tajikistan, Turkmenistan, Ukraine, Uzbekistan
RCPA	Centrally Planned Asia	Cambodia, China (incl. Hong Kong), Korea (DPR), Laos (PDR), Mongolia, Viet Nam
CHN	China	China
SAS	South Asia	Afghanistan, Bangladesh, Bhutan, India, Maldives, Nepal, Pakistan, Sri Lanka
PAS	Other Pacific Asia	American Samoa, Brunei Darussalam, Fiji, French Polynesia, Gilbert-Kiribati, Indonesia, Malaysia, Myanmar, New Caledonia, Papua, New Guinea, Philippines, Republic of Korea, Singapore, Solomon Islands, Taiwan (China), Thailand, Tonga, Vanuatu, Western Samoa
MEA	Middle East and North Africa	Algeria, Bahrain, Egypt (Arab Republic), Iraq, Iran (Islamic Republic), Israel, Jordan, Kuwait, Lebanon, Libya/SPLAJ, Morocco, Oman, Qatar, Saudi Arabia, Sudan, Syria (Arab Republic), Tunisia, United Arab Emirates, Yemen
LAM	Latin America and the Caribbean	Antigua and Barbuda, Argentina, Bahamas, Barbados, Belize, Bermuda, Bolivia, Brazil, Chile, Colombia, Costa Rica, Cuba, Dominica, Dominican Republic, Ecuador, El Salvador, French Guyana, Grenada, Guadeloupe, Guatemala, Guyana, Haiti, Honduras, Jamaica, Martinique, Mexico, Netherlands Antilles, Nicaragua, Panama, Paraguay, Peru, Saint Kitts and Nevis, Santa Lucia, Saint Vincent and the Grenadines, Suriname, Trinidad and Tobago, Uruguay, Venezuela
AFR	Sub-Saharan Africa	Angola, Benin, Botswana, British Indian Ocean Territory, Burkina Faso, Burundi, Cameroon, Cape Verde, Central African Republic, Chad, Comoros, Cote d'Ivoire, Congo, Democratic Republic of Congo, Djibouti, Equatorial Guinea, Eritrea, Ethiopia, Gabon, Gambia, Ghana, Guinea, Guinea-Bissau, Kenya, Lesotho, Liberia, Madagascar, Malawi, Mali, Mauritania, Mauritius, Mozambique, Namibia, Niger, Nigeria, Reunion, Rwanda, Sao Tome and Principe, Senegal, Seychelles, Sierra Leone, Somalia, South Africa, Saint Helena, Swaziland, Tanzania, Togo, Uganda, Zambia, Zimbabwe	

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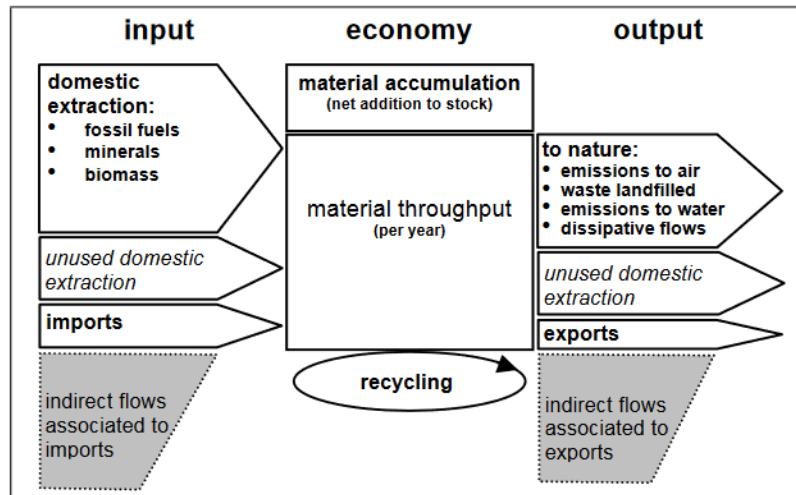
S3 General Material Cycle System Definition in Economy-wide Material Flow Analysis

The system boundary in economy-wide material flow accounting is defined along the System of National Accounts as seen in Fig. S3, starting from: 1. the extraction of primary (i.e., raw, crude or virgin) materials from the national environment and the discharge of materials to the national environment; 2. the political (administrative) borders that determine material flows to and from the rest of the world (imports and exports). Natural flows into and out of a geographical territory are excluded. The key unit of measurement in MFA are metric tons (Krausmann, 2017; Graedel, 2019). Economy-wide material flow accounts (EW-MFA) are rich empirical databases reporting domestic extraction and physical trade for all economies of the world, differentiating 50-60 raw material types (Eurostat, 2018; UNEP and IRP, 2023). From this data, policy-relevant headline indicators are being derived, such as "Domestic Material Consumption" (DMC), in combination with an MRIO, the "material footprint" (MF), as well as relative indicators such as "Resource Productivity" (GDP/DMC or GDP/MF). These indicators are widely used for European and international policy such as in European Green Deal or SDG targets 8 and 12 (Lenzen et al.,2022; European Commission, 2020). Recently, EW-MFA has been further developed by integrating different socio-economic uses of material flows, material stock dynamics, as well as waste and GHG emissions, which enables analysing circular economies (Haas et al., 2020; Kovanda, 2021; Schandl and Miatto, 2018), as well as deriving policy-relevant circular economy indicators for national economies (Mayer, 2019; European Commission, 2023; BMK, 2022).

Recently, research has begun expanding this framework towards explicitly including material stocks and industrial processes and supply chains, opening up the black of "the economy" shown below. This required merging principles of material flow analysis which is relatively flexible, with the standardized economy-wide approach; resulting in a novel approach termed economy-wide material and energy flow analysis (Plank, 2022; Wiedenhofer 2019). For the MESSAGEix-Materials module, we draw on these recent developments to develop the integrative system definition shown in Fig. 1 in the main text.

85   **Figure S3** Economy-wide material balance scheme (excluding air and water flows) (European Commission, 2001)

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S4 Additional Details for Integrative System Definition

This table provides additional information on the Fig. 1 that is presented in the main text. For each process, the mass balance is shown based on the inflows and outflows in the column "Mass Balance". In addition, some generic flows that require more explanation about these processes are also listed in the column "Additional Description of Flows". For example, the term waste is used in general for many processes and the details about the type of waste are provided. The column "Material Levels for Outflows in the Model" shows to which "level" the outflows from the processes go in the model. The definition of model levels and the Reference Material System approach is explained in Sect. 2.2.

Table S4 Additional Details for Processes in Integrative System Definition

Process	Mass Balance (inflow = outflow)	Additional Description of Flows	Material Levels for Outflows in the Model
P1: Extraction	$F_{0.1} = F_{1.2} + F_{1.6}$	$F_{1.6}$: Extraction losses.	primary_material
P2: Production	$F_{1.2} = F_{2.3} + F_{2.6}$	$F_{2.6}$: Waste or by-products that occur during production e.g. blast furnace slag.	secondary_material tertiary_material final_material
P3: Finishing	$F_{2.3} + F_{8.3} = F_{3.4} + F_{3.6} + F_{i.3} - F_{e.3}$	$F_{3.4}$: Product in semi-finished state. $F_{3.6}$: Waste or by-product that occur during the finishing process	useful_material
P4: Manufacturing	$F_{3.4} = F_{4.5} + F_{4.8}$	$F_{4.8}$: New scrap generated during manufacturing of metals. It directly goes to recycling.	product new_scrap
P5: Use phase of material stocks	$F_{4.5} = S1 + S2 - F_{5.6}$	$F_{5.6}$: This waste flow includes the end-of-life materials from power sector stocks (S1) and from other stocks (S2) defined as a share of the quantity of generic products.	end_of_life
P6: Waste Collection	$F_{1.6} + F_{2.6} + F_{3.6} + F_{5.6} + F_{8.6} = F_{6.7} + F_{6.9}$	$F_{6.7}$: Total amount of collected recyclable waste. $F_{6.9}$: Waste that is not recycled but treated in other ways. $F_{8.6}$: Recycling losses	total_end_of_life_1/2/3 old_scrap_1/2/3
P7: Waste Preparation	$F_{6.7} = F_{7.8}$	$F_{7.8}$: There are no losses in the waste material but just energy is consumed for preparing recyclable waste for recycling.	new_scrap
P8: Recycling	$F_{4.8} + F_{7.8} = F_{8.3}$	-	final_material
P9: Final Waste Treatment	$F_{6.9} = F_{9.0}$	$F_{9.0}$: Amount of non-recyclable waste	-

S5 Generic Representation of Material Cycles in MESSAGEix-Materials

120   Figure S5 shows the generic representation of material cycles in MESSAGEix-Materials by using the reference material system approach. All the thermal energy needs during these steps are satisfied by a set of generic furnace technologies seen at the left of the figure. These technologies allow fuel switching and enable different decarbonization pathways for the high-temperature heat demand in the industry. Below the figure, it is shown how the different processes from Fig. 1 relate to the reference material system.

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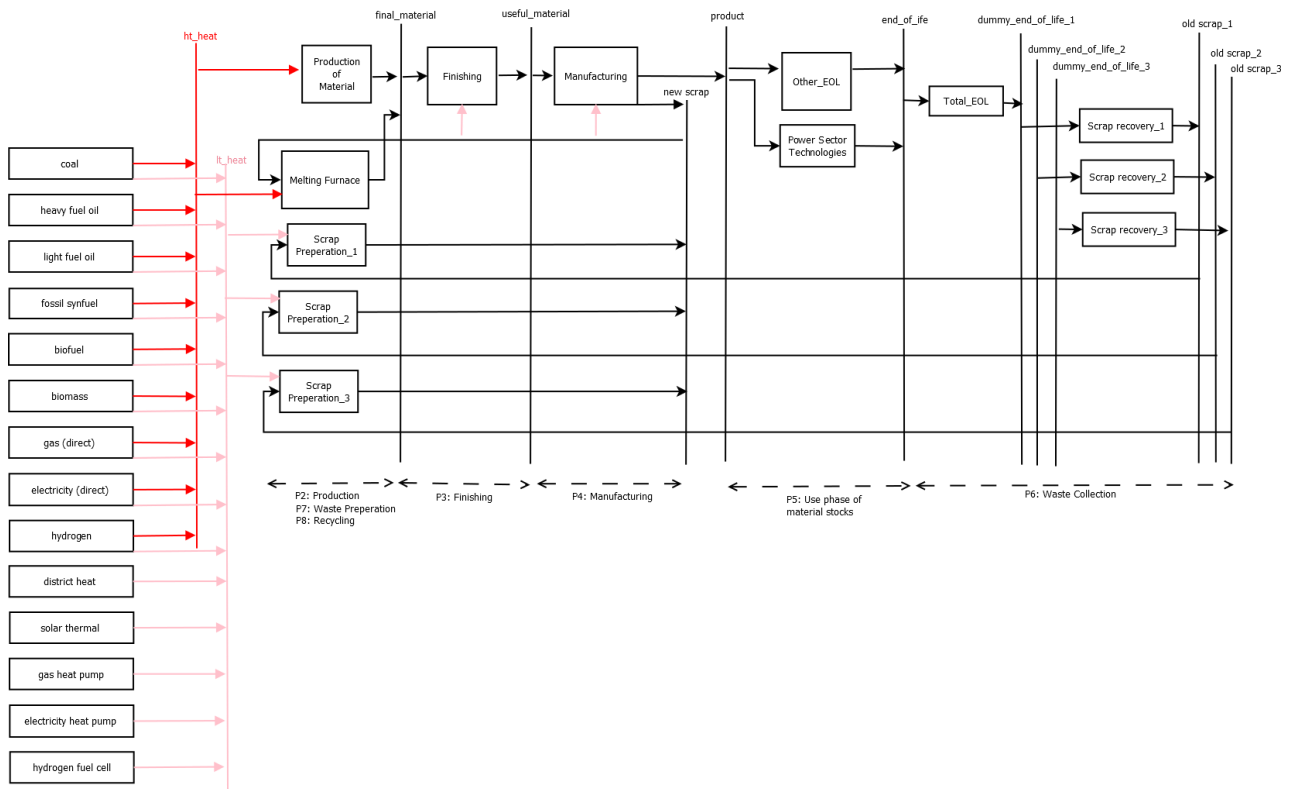
Figure S5 Generic representation of material cycles in MESSAGEix-Materials.

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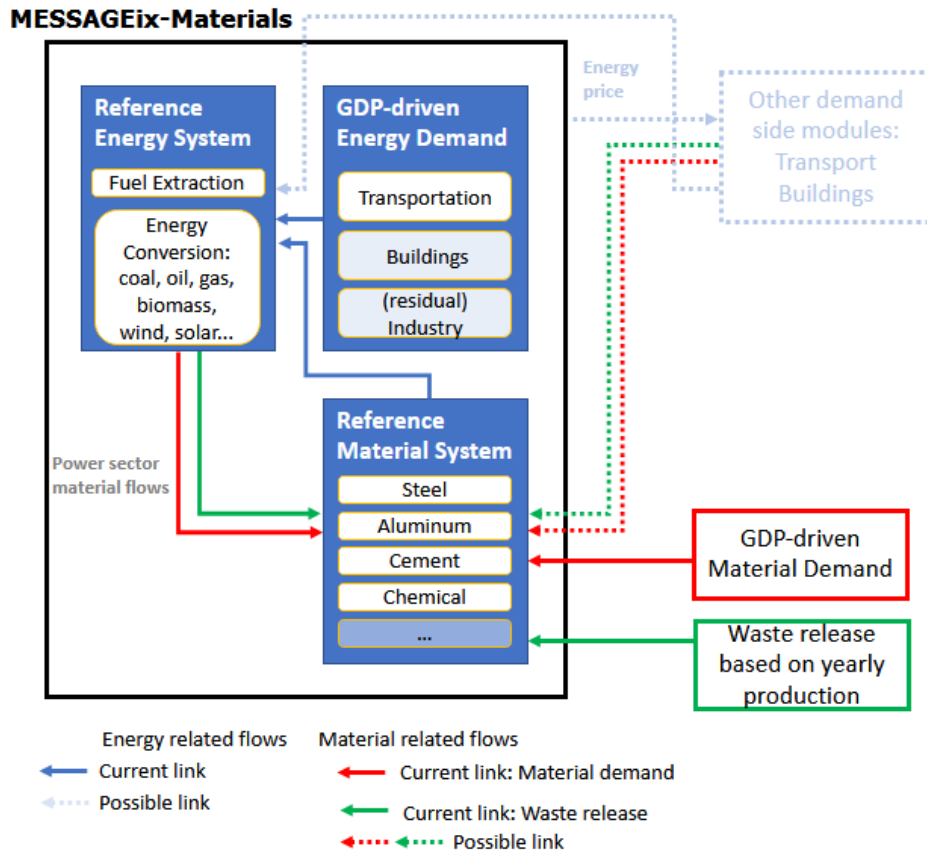
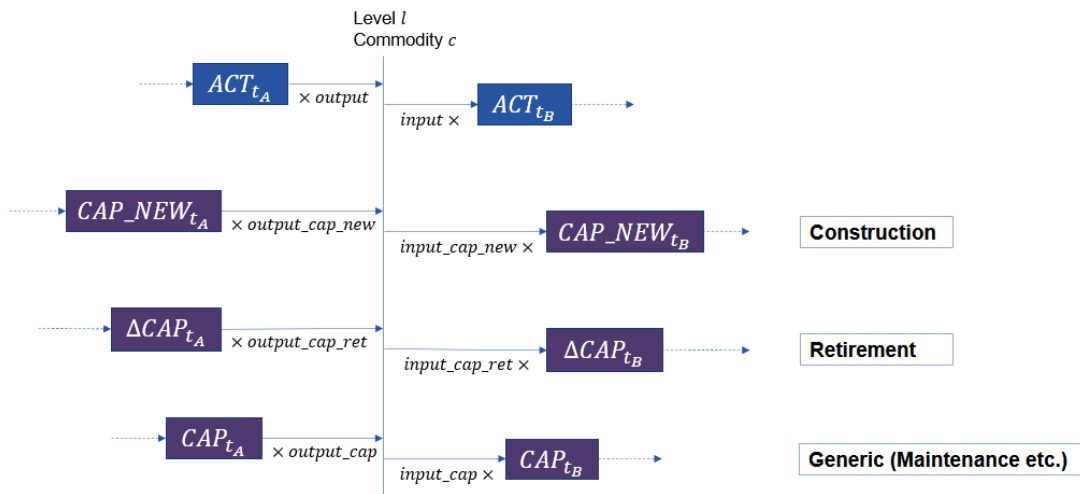
135 S6 Integration of MESSGAEix-Materials

Figure S6 shows the integration of MESSAGEix-Materials which is depicted as Reference Material System with a MESSAGEix-GLOBIOM base scenario which is referred as Reference Energy System. GDP-driven energy demand consists of transportation, buildings and the residual industry for the sectors that are not explicitly represented in the model. Material

140 demand is either GDP driven and exogenously provided or can be endogenously represented such as the power sector that is connected to the Reference Material System (see section 2.3). Similarly, other demand side modules such as transport and buildings can be also added to the framework and provide information on material demand and end-of-life material release which is not available in this version.

145   **Figure S6** Integration of MESSAGEix-Materials in MESSAGEix framework

S7 Extension of MESSAGEix Model Formulation

It is mentioned in the main text that the MESSAGEix formulation currently can represent flows related to the activity (operation) of the technologies such as the energy flows. Figure S7 shows the newly added parameters to the model formulation and how they work to represent material flows related to the technology capacity. Boxes represent the decision variables in the model. Blue boxes that represent activity (ACT) and the purple ones that represent capacity (CAP) are already part of the current model formulation together with the parameters *input* and *output* associated with technology activity (e.g., coal input to produce 1 GWh of electricity). The parameters associated with the capacity are newly added. These flows can be either related to newly built capacity (CAP_NEW) or existing cumulative capacity (CAP). Material flows related to construction use CAP_NEW variable while material flows related to retirement and maintenance use CAP variable in the formulation.

Figure S7 Change of model formulation to represent the material flows related to technology capacity

ACT: Activity of a technology (yearly average over period duration)

CAP_NEW: Newly installed capacity (yearly average over period duration)

CAP: Total maintained capacity in an operational and vintage year combination

input: Relative share of input per unit of activity

output: Relative share of output per unit of activity

output_cap_new: Relative share of output per unit of new capacity built. (Material released during the construction of a technology).

input_cap_new: Relative share of input per unit of new capacity built. (Material needed to build a certain capacity of a technology).

output_cap_ret: Relative share of output per unit of capacity retired. (Scrap material that becomes available as a result of the retirement of a technology.)

input_cap_ret: Relative share of input per unit of capacity retired. (Material needed for the retirement of certain capacity of a technology.)

output_cap: Relative share of output per unit of capacity. (Material released during the operation of a technology.)

input_cap: Relative share of input per unit of capacity. (Material needed during the lifetime of a technology for example for maintenance.)

S8 Validation of the Base Year Model Results

The comparison of the 2020 model values and statistical values is provided in the main text. Table S8.1 is the collection of data sources that are used as the expected values for 2020 based on different sources (IEA, British Geological Survey, Statista). Table S8.2, S8.3 and S8.4 provide extra details on the comparison of the material stocks from power sector in 2015 in
180 MESSAGEix-Materials with the other literature studies.

Table S8.1 Sources for data comparison between 2020 model values and statistics per industry sector

Industry Sector	Final Energy	Production	Emissions
Iron and steel	IEA: Final energy demand of selected heavy industry sectors by fuel, IEA, Paris, https://www.iea.org/data-and-statistics/charts/final-energy-demand-of-selected-heavy-industry-sectors-by-fuel-2019 *Final energy demand includes blast furnace and coke oven energy consumption.	Statista. (2023). World crude steel production (September 1, 2023). https://www.statista.com/statistics/267264/world-crude-steel-production/	1880 Mt production * 1.42 (emission intensity of iron and steel production in 2020) IEA: Direct CO_2 intensity of the iron and steel sector in the Net Zero Scenario, 2010-2030, IEA, Paris https://www.iea.org/data-and-statistics/charts/direct-co2-intensity-of-the-iron-and-steel-sector-in-the-net-zero-scenario-2010-2030
Cement	IEA: Final energy demand of selected heavy industry sectors by fuel, IEA, Paris, https://www.iea.org/data-and-statistics/charts/final-energy-demand-of-selected-heavy-industry-sectors-by-fuel-2019	IEA: Global cement production in the Net Zero Scenario, 2010-2030, IEA, Paris https://www.iea.org/data-and-statistics/charts/global-cement-production-in-the-net-zero-scenario-2010-2030-5260	IEA: CO_2 emitted and captured in the cement sector and clinker-to-cement ratio in the Net Zero Scenario: 2015-2030, IEA, Paris, https://www.iea.org/data-and-statistics/charts/co2-emitted-and-captured-in-the-cement-sector-and-clinker-to-cement-ratio-in-the-net-zero-scenario-2015-2030
Aluminium	IEA: World Energy Statistics and Balances, IEA [dataset], https://doi.org/10.1787/data-00512-en, 2019 value	Primary Production: British Geological Survey, World mineral production 2017-21 Secondary Production: International Aluminum Institute, Global Aluminum Cycle, 2018. https://alucycle.world-aluminium.org/public-access/	IEA, Industry direct CO_2 emissions in the Sustainable Development Scenario, 2000-2030, IEA, Paris https://www.iea.org/data-and-statistics/charts/industry-direct-co2-emissions-in-the-sustainable-development-scenario-2000-2030 2018 value
Chemicals	Non-Energy Use: IEA Sankey Diagram:	For Ammonia: IEA Ammonia Technology	IEA: Direct CO_2 emissions from primary chemical production in the Net Zero

https://www.iea.org/sankey/#?c=World &s=Final%20consumption, 2020 value. Calculation of Energy Use Excluding Feedstock: Share of primary chemicals (47%) * IEA value (IEA Sankey Diagram, 2020 value (covering all chemicals)) Share of primary chemicals in final energy: IEA, ICCA, DECHEMA: Technology Roadmap Energy and GHG Reductions in the Chemical Industry via Catalytic Processes, 2013.	Roadmap, 2020 For High Value Chemicals: IEA The Future of Petrochemicals, 2017 value Methanol: Methanol Institute, 2019 value	Scenario: 2015-2030, IEA, Paris, https://www.iea.org/data-and-statistics/charts/direct-co2-emissions-from-primary-chemical-production-in-the-net-zero-scenario-2015-2030 Methanol emissions multiplied with the share of the methanol used as feedstock in the industry: 222 * 0.67 = 149 Methanol Institute, 2019

185 **Table S8.2** Exogenous data on globally installed capacity of electricity generation technologies in 2015 used by MESSAGEix-Materials (this work), Kalt et al. (2021) and Deetman et al. (2021). The three sources use different sets of technology classifications, which were mapped to the common technology set shown in the table below. Data from Deetman et al. (2021) are for the scenario 'BL default'. UNIT: GW

Global capacity 2015 [GW]	MESSAGEix-Materials (this work)	Kalt et al. (2021)	Deetman et al (2021)
Bioenergy & MSW	50.0	106.7	127.3
Coal	1,858.5	1,991.6	1,349.9
Gas	1,621.8	1,561.0	1,200.6
Geothermal	-	11.8	-
Hydro	1,045.1	1,200.0	1,204.2
Nuclear	352.3	343.2	394.8
Oil	464.1	384.1	341.5
Solar CSP	4.7	4.7	4.3
Solar PV	222.6	220.1	175.3
Tidal	-	0.5	-
Wind Offshore	12.0	11.7	8.8
Wind Onshore	425.7	404.9	360.3
Other	-	-	12.6
Sum	6,057.0	6,240.4	5,179.5

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Table S8.3 Material intensities assumed in MESSAGEix-Materials (this work), Kalt et al. (2021) and Deetman et al. (2021). Where sources report different technology types for one technology category in table above, we calculated the mean for the table categories. For some sources in which regions showed different material intensities. Here we report the minimum and maximum over all regions for MESSAGE-Materials. For Kalt et al. (2021) regional material intensities only differ for the technology Solar PV, which is reported in comment **. To reproduce results, material intensities for each source and technology capacity need to be multiplied at the highest level of granularity. UNIT: ton/GW

Technology	Material	MESSAGEix-Materials max	MESSAGEix-Materials min	Kalt_low	Kalt_med	Kalt_high	Deetman
Bioenergy & MSW	aluminum	1,186	1,166	1,000	2,250	3,500	288
	cement*	54,892	54,369	57,000	81,000	105,000	26,380
	steel	167,599	166,414	70,000	197,500	325,000	39,756
Coal	aluminum	2,246	2,175	200	1,600	3,000	520
	cement*	17,812	17,625	15,000	41,250	67,500	44,739
	steel	41,486	41,120	30,000	65,000	100,000	82,567
Gas	aluminum	1,239	1,211	100	850	1,600	432
	cement*	8,360	8,284	6,750	9,000	11,250	7,102
	steel	19,168	19,034	10,000	30,000	50,000	9,492
Hydro	aluminum	9,264	8,317	269	572	876	-
	cement*	285,209	254,763	375,000	787,500	1,200,000	424,893
	steel	457,091	407,553	20,000	45,000	70,000	70,694
Nuclear	aluminum	1,015	965	200	600	1,000	79
	cement*	62,410	61,975	60,000	97,500	135,000	35,285
	steel	75,698	75,254	70,000	90,000	110,000	43,457
Oil	aluminum	1,239	1,211	650	1,000	1,350	600
	cement*	8,360	8,284	7,500	9,375	11,250	32,004
	steel	19,168	19,034	15,000	32,500	50,000	83,499
Solar CSP	aluminum	18,855	13,184	2,600	13,300	24,000	5,500

	cement*	365,484	162,458	15,000	69,750	124,500	202,772
	steel	690,726	483,985	170,000	510,000	850,000	576,236
Solar PV**	aluminum	21,989	16,416	29,150	44,575	60,000	10,176
	cement*	29,301	20,684	11,515	54,542	97,570	-
	steel	69,544	51,530	43,150	106,827	170,503	150,000
Wind Offshore	aluminum	3,654	2,189	784	2,683	4,582	1,438
	cement*	69,651	42,010	-	118,650	237,300	76,370
	steel	494,633	295,361	250,000	400,000	550,000	157,942
Wind Onshore	aluminum	5,263	1,671	784	2,683	4,582	868
	cement*	111,602	35,645	38,100	75,300	112,500	65,093
	steel	355,424	113,489	100,000	142,290	184,580	121,376

* material intensities for concrete from Deetman et al. (2021) and Kalt et al. (2021) were re-calculated to cement intensities at an assumed cement content of 15% in concrete**material intensities of Kalt et al. (2021) are different between regions for Solar PV power plants; the respective minimum and maximum intensities are respectively (t/GW): 18,440/29,150 (aluminum_low), 39,220/44,575 (aluminum_med), 60,000/60,000 (aluminum_high), 25,858/76,767 (concrete_low), 122,481/363,615 (concrete_med), 219,104/650,464 (concrete_high), 19,840/43,150 (steel_low), 55,215/106,827 (steel_med), 90,590/170,503 (steel_high)

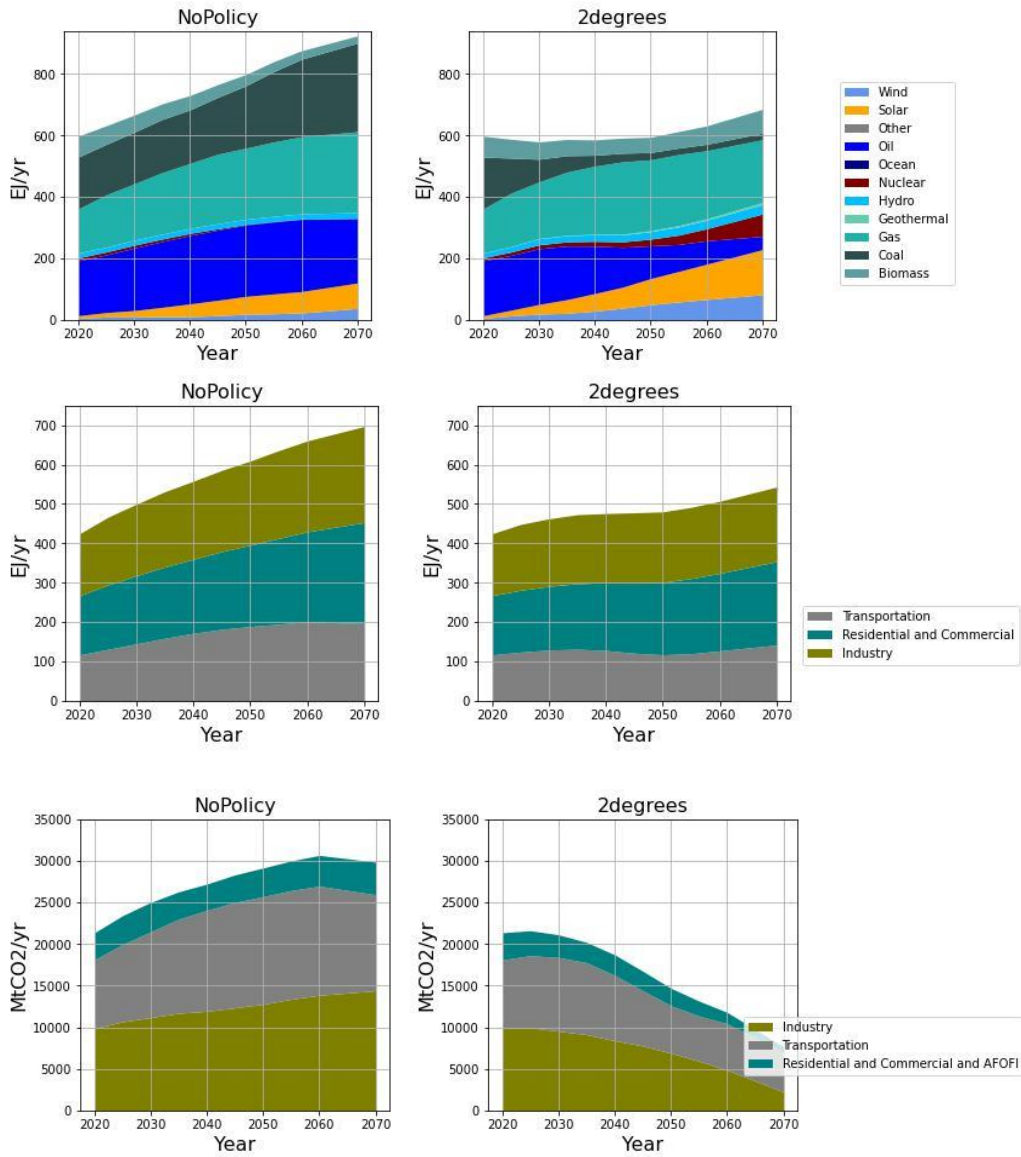
Note on data from Deetman et al. (2021):

- From USA/Canada comparison: For Deetman et al., material stock results varied slightly for the year 2015 (0-2.2% per material) in different scenarios, indicating slight deviations of base data. Due to the small differences, we did not follow up on these but instead used the baseline scenario ('BL' + 'default'; see resp. study for details)

Table S8.4: Data for Fig. 11. Data from Deetman et al. (2021) slightly differ for the base year 2015, the results here represent the scenario 'BL default'.

unit: Mt	Aluminum					Steel					Cement				
technology	MESSAGEix	Deetman	Kalt_low	Kalt_med	Kalt_high	MESSAGEix	Deetman	Kalt_low	Kalt_med	Kalt_high	MESSAGEix	Deetman	Kalt_low	Kalt_med	Kalt_high
Bioenergy & MSW	0.06	0.06	0.11	0.24	0.37	8.36	7.53	7.47	21.08	34.69	2.73	4.19	6.08	8.65	11.21
Coal	4.11	0.68	0.40	3.19	5.97	76.75	114.20	59.75	129.45	199.16	32.94	71.43	29.87	82.15	134.43
Gas	1.97	0.59	0.16	1.33	2.50	30.95	17.66	15.61	46.83	78.05	13.48	9.41	10.54	14.05	17.56
Hydro	9.31	-	0.32	0.69	1.05	457.43	85.13	24.00	54.00	84.00	284.95	511.66	449.98	944.97	1,439.95
Nuclear	0.34	0.03	0.07	0.21	0.34	26.60	17.16	24.03	30.89	37.75	21.89	13.93	20.59	33.46	46.33
Oil	0.57	0.20	0.25	0.38	0.52	8.87	24.89	5.76	12.48	19.21	3.86	10.93	2.88	3.60	4.32
Solar CSP	0.07	0.02	0.01	0.06	0.11	2.36	2.49	0.81	2.42	4.04	0.92	0.88	0.07	0.33	0.59
Solar PV	4.12	1.78	5.16	9.18	13.21	12.76	26.29	6.77	17.48	28.18	5.12	-	1.64	7.77	13.91
Wind Offshore	0.03	0.01	0.01	0.03	0.05	4.06	1.38	2.93	4.69	6.44	0.57	0.67	-	1.39	2.78
Wind Onshore	0.91	0.31	0.32	1.09	1.86	62.43	43.73	40.49	57.61	74.73	19.60	23.45	15.43	30.49	45.55
Geothermal	-	-	0.04	0.06	0.08	-	-	0.18	1.27	2.36	-	-	0.21	0.21	0.21
Tidal	-	-	0.00	0.00	0.00	-	-	0.01	0.02	0.04	-	-	0.19	0.40	0.62
Other	-	0.05	-	-	-	-	2.72	-	-	-	-	1.94	-	-	-

220 S9 Additional Graphs on Energy System Transition, End-Use Sectors and Technologies

Figure S9.1 Primary Energy, Final Energy by end-use sector, Direct CO2 Emissions by end-use sector respectively

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245   **Figure S9.2** Regional MTO Use