Supplementary Information to:

Climate mitigation scenarios with persistent COVID-19 related energy demand changes

Jarmo S. Kikstra[1,2,3,*,**], Adriano Vinca[1,4,**], Francesco Lovat[1], Benigna Boza-Kiss[1,5], Bas van Ruijven[1], Charlie Wilson[1,6], Joeri Rogelj[1,2,3], Behnam Zakeri[1,7], Oliver Fricko[1], Keywan Riahi[1,8]

Affiliations

1 International Institute for Applied Systems Analysis (IIASA), Schlossplatz 1, A-2361 Laxenburg, Austria

2 Grantham Institute for Climate Change and the Environment, Imperial College London, United Kingdom

3 Centre for Environmental Policy, Imperial College London, London, United Kingdom

4 Institute for Integrated Energy Systems, University of Victoria, BC, Canada

5 Central European University (CEU), Hungary/Austria

6 Tyndall Centre for Climate Change Research, University of East Anglia (UEA), United Kingdom

7 Sustainable Energy Planning, Aalborg University, Denmark

8 Graz University of Technology, Graz, Austria

* Corresponding Author. Email: kikstra@iiasa.ac.at

** These authors contributed equally

1 Supplementary Note 1: The bottom-up assessment of impacts in the global energy system

The ultimate role of the energy systems is to provide energy services to end-users to ensure living conditions and well-being, short and long-term economic and non-economic activities, and the institutional environment at minimum[1,2]. Assessing the energy system with a bottom-up perspective helps provide insight in the size and intensity of energy use changes. These changes depend on the constituents and dynamics of lifestyles, consumption, production, and supporting infrastructures. Such bottom-up assessments are relatively rare, and especially the effects of social changes expressed in energy demand is underrepresented in the literature[3]. To understand the kind of social, behavioral, business and infrastructure changes that have been induced by the COVID-19 pandemic and consequential containment measures, and whether and to what extent these can remain persistent, we integrate data and additional qualitative information about the characteristics and response of end-users and businesses to inform our bottom-up assessment.

1.1 Approach

Our approach aims to assess the effects of the COVID-19 pandemic on energy end-use sectors with sufficient detail to provide insights to inform policy decisions using comprehensive scenarios. The analysis assesses COVD-19 induced changes in lifestyle, behavior, institutional and infrastructural environment, business models, etc.. In addition, a detailed energy model is required to model how the energy supply structure could respond to such demand changes. To enable the modelling of price-induced changes on future scenarios with alternative GDP pathways, the energy systems model needs to be coupled with a macro-economic model. The Integrated Assessment Model (IAM) MESSAGE$_{ix}$-GLOBIOM[4] used for this study meets these requirements.

To reflect energy service demand and usage observations of during-lockdown activity in our energy demand recovery narratives and construct subsequent *exogenous* energy demand pathways that drive the IAM results, we followed the next procedure (illustrated in *Supplementary Figure 1*)*:*

1) Data collection (cut-off date: March 2021) at a sub-sectoral level for transportation, industrial processes, and residential and commercial use of the built environment[1]:
    a) Collect maximum observed deviations of demand during lockdowns as well as full-year 2020 data and projections for each end-use sector (often compared to the same period in 2019), constructing informed estimates of the demand shock in 2020 whenever full-year empirical data was missing.
    b) Relate to historically observed changed to further analyze the possible effects of such rapid changes in these end-use sectors, such as identifying subsector share (e.g. separate industrial processes) and modal split changes (in transport).
2) Identify the main drivers (first-order effects) within each of the three considered sectors:
    a) Review literature on societal impacts of the COVID-19 pandemic on private and business activities, and their potential for long-term persistence.

[1] In addition to quantitative data, possible further teleworking effects are also informed by previous non-COVID-19 studies on teleworking.

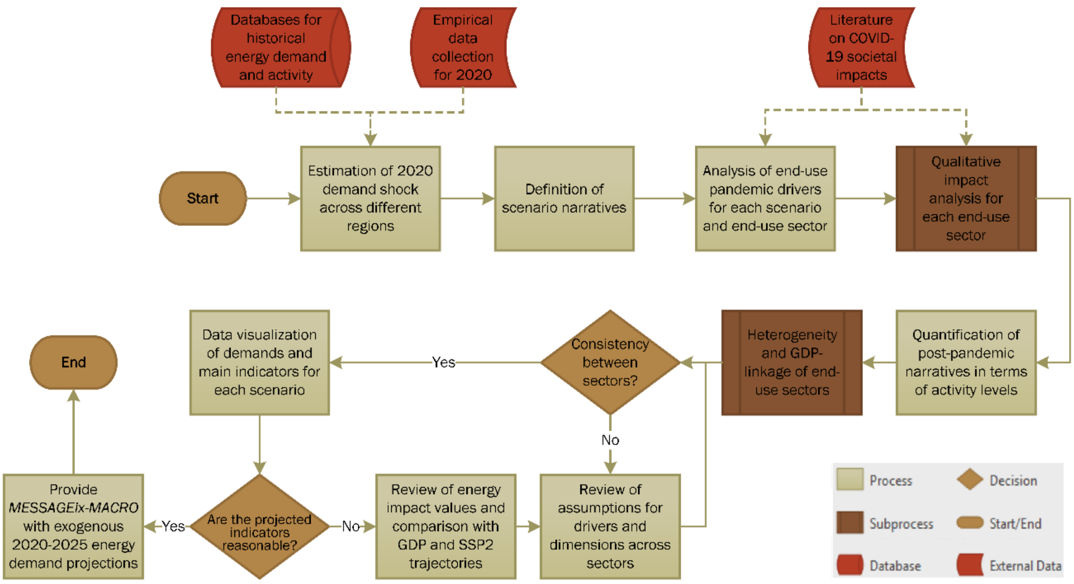
b) Construct a *qualitative* impact analysis, useful for comparing the degree of change across different sectoral dimensions.

3) Quantify alternative post-pandemic scenarios using the main drivers identified, using the qualitative analysis for validating the outcomes with the different narratives.

a) Consider regional heterogeneity of the main assumptions in each recovery pathway.

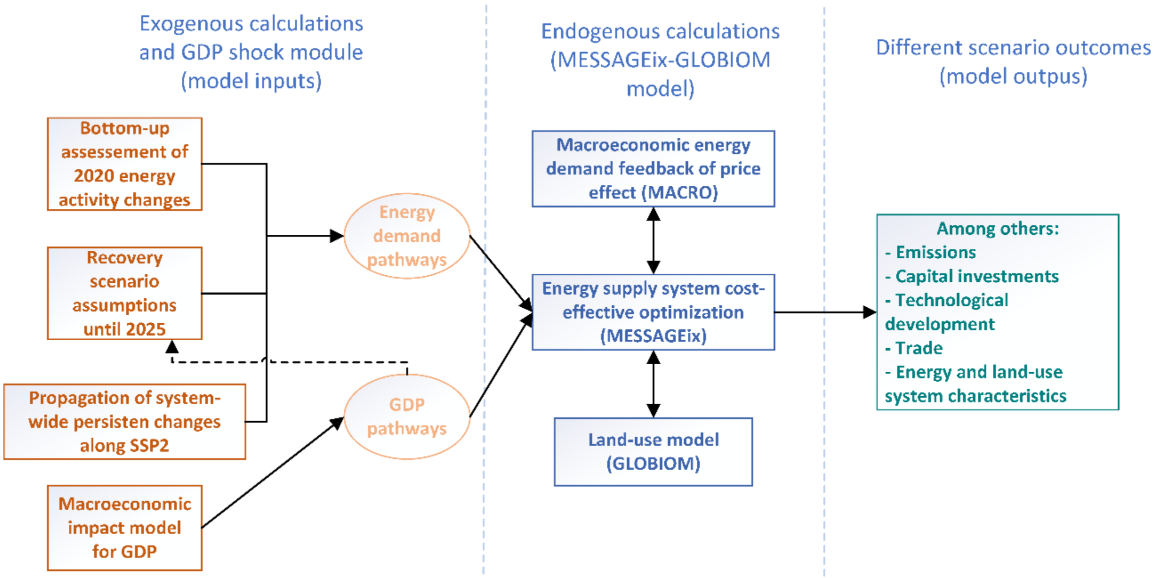
b) Ensure internal consistency (second-order effects) across the three end-use sectors and their sub-sectors in terms of (inter-) sectoral changes on the medium term (until 2025) in activity, energy intensity and energy demand, and ensure complementarity.

4) Prepare the 2020 outcomes and recovery trajectories as exogenous input in MESSAGE$_{ix}$.



Supplementary Figure 1. The bottom-up energy demand scenario development approach of this study.

Supplementary Figure 2 illustrates the methodological steps from inputs to outputs. The bottom-up assessment of the 2020 demand and the construction of exogenous energy demand (Sections 2, 3, 4) and GDP (Section 6) pathways serve as input for the MESSAGE$_{ix}$-GLOBIOM framework. Running MESSAGE$_{ix}$-GLOBIOM coupled with MACRO then eventually produces the resulting scenarios discussed in this study.



Supplementary Figure 2. Overview of the overall research approach used for this study, including bottom-up assessment of the COVID-19 impacts on energy demand on the left linked to the integrated assessment model scenarios on the right.

1.2 Model region definitions

Depending on the availability and reliability of data, we discuss each section at the relevant level of spatial aggregation, for either 2, 5, or 11 regions of the global model (adapted from model documentation[5]).

<u>**Aggregation to the 11-region level**</u>

Sub-Saharan Africa (AFR): Angola, Benin, Botswana, British Indian Ocean Territory, Burkina Faso, Burundi, Cameroon, Cape Verde, Central African Republic, Chad, Comoros, Cote d'Ivoire, 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, Zaire, Zambia, Zimbabwe

Centrally planned Asia/China (CPA): Cambodia, China (incl. Hong Kong), Korea (DPR), Laos (PDR), Mongolia, Viet Nam

Eastern Europe (EEU): Albania, Bosnia and Herzegovina, Bulgaria, Croatia, Czech Republic, Estonia, The former Yugoslav Rep. of Macedonia, Latvia, Lithuania, Hungary, Poland, Romania, Slovak Republic, Slovenia, Yugoslavia

Former Soviet Union (FSU): Armenia, Azerbaijan, Belarus, Georgia, Kazakhstan, Kyrgyzstan, Republic of Moldova, Russian Federation, Tajikistan, Turkmenistan, Ukraine, Uzbekistan (the Baltic republics are in the Central and Eastern Europe region)

Latin America (LAM): 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)

North Africa and Middle East (MEA): 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

North America (NAM): Canada, Guam, Puerto Rico, United States of America, Virgin Islands

Japan, Australia, New Zealand (PAO): Australia, Japan, New Zealand

Pacific Asia (PAS): 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

South Asia (SAS): Afghanistan, Bangladesh, Bhutan, India, Maldives, Nepal, Pakistan, Sri Lanka

Western Europe (WEU): 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

Aggregation to the 5-region level

OECD90+EU: Countries that were OECD members in 1990, i.e. countries that make up the **Western Europe**, **North America** and **Pacific OECD** regions.

REF: Countries of **Central and Eastern Europe** and the **Former Soviet Union** undergoing economic reform.

ASIA: This region includes the Asian countries that make up the **South Asia**, **Centrally planned Asia and China** and **Other Pacific Asia** regions.

MAF: This region includes the African and Middle Eastern countries that make up the **Sub-Saharan Africa** and **Middle East and North Africa** regions.

LAM: This region is the same as the **Latin America and the Caribbean** region in aggregation on the 11 region level.

Aggregation on the 2-region level

Global North = Industrialized countries, i.e. countries that make up the **OECD 90** and **Reforming Economies** regions.

Global South = Developing countries, i.e. countries that make up the **Middle East and Africa**, **Asia** and **Latin America and the Caribbean** regions.

2 Supplementary Note 2: Transport

2.1 Data collection for the base year and for 2020 demand shock

We used IEA´s ETP 2017 data[6] on transport modes as starting point to estimate the shock from the COVID-19 crisis in 2020. This historical dataset includes national-level data on activity in both passenger-kilometers and tonne-kilometers and energy consumption for *passenger* and *freight* transport modes. We used this dataset to calibrate the transport shares to the *base year*, 2019 in this case, the last year before the pandemic started.

For the EU-28 area, more detailed data is available for many energy-economy-environment indicators from the Joint Research Centre Integrated Database of the European Energy System[7]. We, for instance, utilize the specific shares of different transport modes in these European countries (such as distinction between international and intra-EU aviation) together with observed activity level reductions (from the 2020 demand shock analysis) to estimate the energy effect of this region and obtain qualitative insights (see Section 2.2.2). We aimed to estimate the combined impacts from the general economic downturn and structural and behavioral changes relating to changes in activity levels, distinguishing differentiated impacts across regions. Resulting from both changes in activity (passenger-kilometer and tonne-kilometer) and structure (modal shares), we calculated energy impacts in 2020 that are subsequently aggregated to the 11-regional aggregation in the model formulation of MESSAGEix-GLOBIOM. Then, these 2020 energy values were used to recalibrate MESSAGEix-GLOBIOM with its coupling to the macroeconomic model MACRO[8].

With that in mind, we undertook a bottom-up approach to estimate the impact of the COVID-19 crisis on mobility in 2020 without accounting for the indirect effects of the GDP reductions. This approach was chosen because the sharp decrease in transport activity in 2020 has been mainly driven by the lockdown restrictions, which imposed a close-to-total halting of mobility for non-essential services[8-9].

We assumed a demand shock intensity which aims to represent a middle-ground in the available literature whenever full-year 2020 data was not available. Where multiple estimates or scenarios depending on different future plausible developments of the COVID-19 pandemic were available, we took the average of estimates. We analyzed shocks across all eleven regions for the each of the following individual transport modes: rail, cars and 2-wheelers, public transport (bus, tram and metro), aviation (domestic and international) and non-motorized transport for passengers; and rail, road, international shipping and aviation for freight.

Our qualitative and quantitative assumptions are based on both peer-reviewed articles and grey literature from both national and international organizations. Especially informative were studies that report empirical data for both *during* (first wave of global high of infections in the countries studied, approximately March-May) and *after* (for countries which saw decreased rates of new infections in June-July) the lockdown periods, as well as those including data for the whole year 2020 –which allowed us to capture possible rebounds in activity for certain transport modes, their magnitude and *recovery* speed.

When just 2020 *recovery* projections for the second half of the year were available, we selected the shocks representing the recovery scenarios from *low-end* W-shaped projections, or in other words projections that captured multiple waves of infections where applicable. For the transport subsectors for which no 2020 projections or empirical data were available, we estimated activity reductions based on other platforms providing with mobility estimates, such as Apple Mobility[9] and Google Analytics[10].

Finally, we gathered sub-sectoral activity reductions and extrapolated our assumptions to match the spatial resolution of MESSAGEix-GLOBIOM, to then calculate the aggregated effect on global transport demand in 2020.

2.1.1 Formulation of the COVID-19 direct shock in 2020

This analysis of the year 2020 culminates in assuming a value $\Delta_{m,n,t}$ representing the year-on-year relative reduction of transport activity compared to 2019 levels for each of the transport modes and regions (both for passenger mobility and freight transport) considered. Following *Equation 2.1*, aggregated 2020 values for each node and type ($\Delta_{2020_{n,t}}$) are obtained, which serve as the inputs for MESSAGEix-GLOBIOM:

$$\Delta_{2020_{n,t}} = \sum_{m} \left[S_{m,n,t} \cdot \left(1 + \Delta_{m,n,t}\right) \right] - 1 \qquad \forall n, \forall t \tag{2.1}$$

Where:

- m, n, t: indexes for the sets *Modes*, *Nodes* and *Types*[2], respectively.
- Δ_{2020} is the aggregated % activity variation compared to 2019 levels.
- S: modal share of transport subsectors in 2019.
- Δ: % variation in sub/sectoral activity in 2020 compared to 2019 (in % of pkm/tkm).

[2] Transport set *Types* accounts for passenger mobility (measured in pkm) and freight transport (tkm).

2.1.2 *Outcome of the 2020 analysis*

The quantitative outcome of the 2020 analysis is shown in *Supplementary Tables 1* and *2*. The values were initially estimated for 7 of the MESSAGEix-GLOBIOM regions (see *Supplementary Table 1*), i.e. the regions with sufficient available data for reliable estimates, from refs[6,7].

We then aggregated the sub-sectoral values, that will be described hereafter, into useful energy and extrapolated the same assumptions to the remaining 4 regions where activity data was missing. This was done under the assumption that economic and structural similarities explain similar effect on modal shares changes:

- WEU was used as reference for EEU and MEA.
- SAS was used as reference for PAS.
- NAM was used as reference for PAO.

Supplementary Table 1. Estimated impacts on transport activity in 2020 compared to 2019, with sub-sectoral activity impacts based on an assessment of the available literature as described in the text.

		Estimated activity reductions in 2020						
Type	**Mode**	**R11_AFR**	**R11_CPA**	**R11_FSU**	**R11_LAM**	**R11_NAM**	**R11_SAS**	**R11_WEU**
Passenger	**Rail**	-20%	-18%	-20%	-20%	-25%	-25%	-25%
	Cars/2 wheelers	-23%	-17%	-13%	-10%	-18%	-21%	-20%
	Buses, Tram and Metro	-32%	-23%	-26%	-13%	-36%	-29%	-30%
	Aviation	-54%	-39%	-54%	-49%	-18%	-39%	-34%
	Aviation (int.)							-62%
Freight	**Rail**	-10%						
	Road	-15%						
	Air Cargo (int.)	7%						
	Shipping (Int.)	-9%						

List of sources and description of the assumptions made to estimate 2020 values in *Supplementary Table 1*:

- **Passenger transport**:

- By the end of March 2020, global road transport activity was almost 50% lower than 2019 levels according to IEA[11], with countries in lockdowns experiencing peak reductions of 75 %. However, during the second half of the year, road transport activity experienced a strong rebound, mainly from increase in private vehicle usage[12]. We used these analyses in combination with data provided by Apple Mobility[9] and Google Analytics[10] to capture the rebound trends of disaggregated road transport activity, comparing public transport with cars & 2-wheelers, mapping national-level data to the 11 MESSAGEix regions, correlating the decreases of private with public modes, using January 2020 as reference index. Estimated values across regions were also checked with global oil demand forecasts[13].
- Regional impacts on passenger aviation activity (aggregated values including both domestic and international) was retrieved from ICAO[14,15]. Furthermore, availability of European data for historical activity[7] and 2020 estimates[15,16,17] for both international and domestic aviation made possible to estimate the 2020 shock for both categories, as reflected in *Supplementary Table 1*.
- Data for rail was obtained from national lockdown estimates[18,19] and used as reference for the 2020 estimations.

- **Freight transport**: freight transport values were assumed to be global due to the interdependence of the impacts across regions from international shipping (consequently also negatively impacting road and rail) and, to a lesser degree, international aviation and due to the lack of detailed reliable data for road and rail data in many parts of the world.
  - International freight shipping is accounted globally in MESSAGEix-GLOBIOM. For this study we used the estimate from WTO, according to which

the world’s merchandise trade volume is forecast to fall 9.2 % in 2020[20,21,22], having analyzed in parallel the impact in Chinese[23] and American ports[24]. Intra-EU shipping from Joint Research Center[7] was also included under this category.

- Indian Railways’ claimed that 36 % of the Indian rail cargo activity was wiped off by the national lockdown[25]. This has been used a as peak reference for estimating a 2020 value; also accounting a loss due to the expected decrease in global trade[20,21,22,26].
- Road freight estimate was used as an average value between the peak decrease in activity captured by Germany’s truck-toll-mileage index, which was down by 15 % on April compared to pre-pandemic levels[27], and 2019 levels. Overall, with revisited data for the whole 2020, the average reduction compared to 2019’s index was less than 5 %.

The value for international air cargo activity even though reaching a low peak of 16 % reduction in international activity (tkm) in March 2020[28] (stringent lockdowns worldwide), a quick recovery and the operations of reconverted passenger aircrafts for freight transport led to an actual overall increase in air cargo activity of 6.55 % year-on-year with 2019[15]. The aggregated values for all regions in useful energy are shown in *Supplementary Table 2*.

Supplementary Table 2. Regionally aggregated total useful energy change in 2020, compared to 2019. Regions follow the spatial resolution of MESSAGEix-GLOBIOM.

Region	2019-2020 (YoY) change in useful energy for transport
AFR	-19%
CPA	-17%
EEU	-22%
FSU	-14%
LAM	-14%
MEA	-22%
NAM	-16%
PAO	-16%
PAS	-21%
SAS	-21%
WEU	-22%

2.2 Recovery elements (drivers) considered in the analysis for the transport sector

Following the approach specified in *Supplementary Figure 1* in Section 1, we perform an extended literature and data review to determine alternate plausible transport recovery pathways for transport. We use five combinations of distinct drivers that translate the scenario narratives into different transport pathways.

Mass international tourism. Health concerns and international travel restrictions have led to unprecedented reductions in international tourism, and thus a reduction of especially aviation, which makes up 58 % of international travel for tourism, with road transport accounting for a 37 % mode share[29]. Appetite for domestic tourism has increased in several cases. During the post-pandemic recovery, policies could be implemented to promote domestic tourism stimulated over international tourism, to avoid energy intensive tourism (aviation). Additionally, this would allow for easier stimulation of the use of low-carbon modes of transport for tourism, including rail and long-haul coaches.

Commuting level. Partial or full teleworking rates in certain sectors of the workforce have sharply increased during the pandemic. These experiences have led to the increasing recognition that in many parts of the world, such teleworking could reasonably be retained after the pandemic. Possibly, shares of employers and employees might prefer increased or retained levels of working from home, having the potential to increase a work-life balance. The relationship between teleworking and average levels of passenger transportation is highly uncertain[30], and can have a wide range of effects explored through our scenarios. If retained or stimulated, home office could lead to strongly reduced transport needs for commuting, and consequently lower energy demand.

International corporate travel. Similarly, increased digitalization and subsequent learning during the pandemic (especially the use of international teleconferencing tools) has the potential to drastically reduce International corporate travel.

Online retailing. During the pandemic (where people spend more time at home) online retailing has spiked across almost all varieties of goods[31,32]. This has inevitably come with increased road freight activity for their distribution[33,34], and thus increased emissions and pollution. If retained by keeping digitalization levels as during the pandemic, policies that lead to less fast, concentrating package deliveries and to penalize returns would be needed to counterbalance that increase.

Use of public transport (mass transit). The use of public transport was severely affected during the lockdown, with measures to reduce infection risk still being enforced widely[19]. A complicating factor hindering the recovery of public transport utilization may thus be the higher actual and perceived health risks in such means of transport where social distancing and other health measures cannot be successfully implemented. Reduced occupancy rate could be enforced by public transport providers, or they could result from higher aversion due to perceived health risks by travelers. This leads to the possibility of private transport (e.g. car use) substituting some of the travel needs previously met by public transport, as was for instance observed in China[35].

Active modes and micro mobility. The environmental impact of tough lockdowns at the early stages of the pandemic was pronounced[36,37]. Especially wide-spread reduced road transport has led to lower NO_2 and PM2.5 levels in many cities across continents[38–43]. The experiences of reduced traffic congestion, reduced air and noise pollution, more public space on the streets, and concurrent simultaneous revived surges of individual *active* modes (walking, cycling, small-wheeled transport) has the potential to lead to a persistent move towards more non-motorized transport for instance for commuting and sports. If such behavioral changes during the lockdown would thus be supported, by for instance price incentives or improved infrastructure, they could play a role in reducing the per capita transport energy demand.

2.2.1 *Narratives along key drivers*

After identifying a set of key drivers for the transport sector, we create 3 different transport recovery narratives that are consistent with the overarching narratives (*smart use*, *self-reliance* and *green push* scenarios) and interact with the rest of the system within each scenario. Together, these key drivers, as presented in *Supplementary Table 3* allow for systematically assessing possible combinations that help explore the post-pandemic uncertainty in recovery along the dimensions of old-to-new normality as well as the dimension of endogenous-exogenous drivers.

Supplementary Table 3. Overview of key qualitative drivers for the transport sector in the three different narratives.

Element	Smart Use	Self-Reliance	Green Push
Mass international tourism	*Reduced*: re-discover of domestic tourism	Back to original levels	Tourism *reduced* internationally and substituted by low-carbon modes when domestic
Commuting level	*Reduced*: partial teleworking increased due to experiences of a better work-life balance benefits and still high productiveness levels	Back to original levels: partial teleworking is marginally adopted, and offices adopt a central role as before the pandemic	*Reduced*: partial teleworking increased due to discovery of better working-life balance benefits and still high productiveness levels
International corporate travel	*Reduced*: part of the trips substituted by video conferencing during the pandemic persists	Back to original levels	*Sharply reduced*: substituted by video conferencing, discouraged through corporate policies
Online retailing	*Increased* adoption leads to net increase in road freight activity	*Lower increase* than in rest of scenarios, most of the shopping practices back to original levels	*Increased* adoption leads to net increase in road freight activity. Also, international shipping increases due to higher international cooperation adopted during the pandemic
Use of public transport (mass transit)	*Reduced*: some short-distance trips replaced by non-motorized transport. Also, negatively affected by teleworking.	*Sharply reduced*: health concerns remain leading to avoid mass transit when possible/ affordable, leading to increase of private car usage to commute	*Increased*: people are incentivized to use public transport through policies (such as car-free zones in city centers).
Active modes and micromobility	*Increased*: Levels of usage during pandemic retained, driven by increased health benefits and perceived reduction of pollution levels	Back to original levels	*Sharp increase*: from high investment in infrastructure together with disincentivizing use of private cars.

2.2.2 *Qualitative analysis*

With these drivers at hand, we recognize that the response will not be homogeneous across regions. Hence, we disaggregate the narrative when quantifying the response in two rough global regions (Global North and Global South) for which it is possible to identify distinct responses. We translate these drivers into quantitative estimates required as model input by first doing a qualitative analysis to understand the role they play in potential permanent structural changes after the pandemic (using as a starting point the societal behavior changes and concerns during the lockdowns in early 2020).

We chose a color scale going from red to green to illustratively represent decreases or increases in energy service levels, respectively, compared to projected levels at a point after the pandemic (assuming that yellow implies no variation). Tables in Sections 2.2.2.1 and 2.2.2.2 provide an overview and insights to understand which transport factors (based on the mobility restrictions and behavioral changes of society listed previously) have a higher or lower potential to see persistent changes compared to pre-pandemic levels. Simultaneously, it illustrates the subsectors with large uncertainty and maneuvering space, and thus identifies the key point of the system where different societal and policy action can have the most effect. Since changes in maritime passenger transport are a very small share of total activity levels, the effects of these narratives were not quantified in this analysis.

2.2.2.1 *Qualitative outcome: Passenger Transport*

Supplementary Table 4. Detailed qualitative sub-sectoral passenger transport analysis for the Global North. The red-yellow-green scale illustratively represents decreases (red) or increases (green) in energy service levels as compared to previously projected levels (yellow implies no change from the expected structure without a pandemic).

	Passenger transport (Global North)					
	Smart Use		Self-Reliance		Green Push	
Mode	**Impact on activity levels**	**Narrative behind structural and behavioral changes**	**Impact on activity levels**	**Narrative behind structural and behavioral changes**	**Impact on activity levels**	**Narrative behind structural and behavioral changes**
Rail		Reduced commuting levels during pandemic are retained (part of work from home remains, corporate travel reduced), slightly replacing rail transport. Decrease in commuting is offset by increase in usage for domestic tourism (people stay closer to countries of origin after the pandemic).	-10%	Individualism becomes dominant, both at national level and between single individuals. Also, concerns about future pandemics and pathogen propagations remains. This results in a decrease of overall public transport, and in an increase in private ownership of cars.	15%	Reduced commuting by rail (part of work from home remains) is offset by the takeover of private-car commuting in suburban areas, due to policy instruments. Also, high-speed rail is supported by public spending, competing with short-distance flights.
Cars, 2-wheelers		Reduced commuting has a larger impact in private car use, since people in urban areas want to retain observed benefits in air pollution, substituting some trips with non-motorized transport.	15%	For the health risks mentioned above, the shift away from public transport implies a direct increase in private cars.	-20%	Overall commuting decrease (part of work from home remains)together with disincentives (car-free zones in city centers are implemented and shared mobility is supported in most of the biggest cities) have a considerable effect in private car use, resulting in dwellers shifting towards public transport and active mobility, to retain and even improve the air quality levels reached during the pandemic.
Buses, Tram and Metro		Due to same reasons of rail, yet the impact of this behavioural change is felt more since buses and metro/tram trips can be more easily replaced by non-motorized transport (shorter trips on average compared to rail).	-10%	Due to same reasons of rail, yet the decrease is especially noticeable in small and congested means such as buses and metro/tram.	10%	As in rail, the reduction of usual public transport commuters (part of telework remains) is offset due to incentives and policy instruments (urban mass transit absorbs a share of the private-car activity).
Aviation		Mass international tourism will not fully recovery to pre-pandemic levels, in part because of increase in domestic tourism by other transport means.	0%	Aviation bounces back to pre-pandemic levels and growth, both domestic and international, being attractive in spite of the percieved health risks.	-41%	Mass international toursism will not recover to pre-pandemic levels. With climate activism being strongly present, carbon-intensive domestic aviation is even more affected than international due to disincentives and conditions on bailouts, facing increased competition with a largely improved high-speed rail network.
Aviation (int.)			0%		-28%	
Non-motorized transport		Walking and cycling surge as means for short-distance trips. However, development is region-dependent, reliant on infrastructure availability and commuting distance.	0%	Spike in non-motorized transport during the pandemic is not retained since air pollution is secondary compared to percieved health risks. Non-motorized transport retakes the role it has before the pandemic.	30%	Walking and cycling surge as means for short-distance trips, supported by investments in infrastructure and car-free zones in cities. However, development is region-dependent, reliant on terrain and commuting distance.

Supplementary Table 5. Detailed qualitative sub-sectoral passenger transport analysis for the Global South. The red-yellow-green scale illustratively represents decreases (red) or increases (green) in energy service levels as compared to previously projected levels (yellow implies no change from the expected structure without a pandemic).

	Passenger transport (Global South)					
	Smart Use		Self-Reliance		Green Push	
Mode	Impact on activity levels	Narrative behind structural and behavioral changes	Impact on activity levels	Narrative behind structural and behavioral changes	Impact on activity levels	Narrative behind structural and behavioral changes
Rail		Public trasport more affected than private care usage due to health-related concerns.	-5%	Same reasons as in developed economies. The impact is lower due to lower income level that allow flexibility to shift towards less affordable private alternatives to public transport.	25%	Reduced commuting (part of work from home remains), but to less extent than in developed countries due to the lower degree of digitalisation. On the other hand, rail intakes trips that were previously made by private cars and planes, since high-speed rail also replaces most of the short-haul flights supported by the policy packages.
Cars/2 wheelers		Less degree of digitalization in households than in Global North. More workforce is reliant on commuting to work consequently leading to a lower negative impact on private car use compared to developed economies.	10%	The mode shift from public to private means of transport results in a lower % increase compared to developed economies due to lower income levels.	-15%	Overall commuting decrease (part of work from home remains)together with disincentives (car-free zones in city centers are implemented and shared mobility is supported in most of the biggest cities) have a considerable effect in private car use, resulting in dwellers shifting towards public transport and active mobility, to retain and even improve the air quality levels reached during the pandemic.
Buses, Tram and Metro		Public trasport more affected than private care usage due to health-related concerns. There is no significant mode shift from buses tram/metro to non-motorized transport since it was already being substantially used before the pandemic in most of the developing economies.	-5%	Lower % decrease compared to Global North, same assumption as in rail.	15%	Metro and road public transport activity levels increase, in spite of rise of non-motorized transport, compensating the reduction (in absolute terms) from the private car use, supported by incentives in urban areas.
Aviation		Aviation decreases similarily as in developed economies.	0%	Aviation bounces back to pre-pandemic levels and growth, both domestic and international, being attractive in spite of the percieved health risks.	-41%	Following similar trajectory compared to developed economies.
Aviation (int.)			0%		-28%	
Non-motorized transport		It incresaes, yet not as much as in % terms as in developed economies. Non-motorized transport was already more present in these economies before the pandemic.	0%	Spike in non-motorized transport during the pandemic is not retained since air pollution is secondary compared to percieved health risks. Non-motorized transport retakes the role it has before the pandemic.	15%	Walking and cycling surge as means for short-distance trips, supported by investments in infrastructure and car-free zones in cities. However, development is region-dependent, reliant on terrain and commuting distance.

2.2.2.2 *Qualitative outcome: Freight Transport*

Supplementary Table 6. Detailed qualitative sub-sectoral freight transport analysis for the Global North. The red-yellow-green scale illustratively represents decreases (red) or increases (green) in energy service levels as compared to previously projected levels (yellow implies no change from the expected structure without a pandemic).

Freight transport (Global North)						
	Smart Use		Self-Reliance		Green Push	
Mode	Impact on activity levels	Narrative behind structural and behavioral changes	Impact on activity levels	Narrative behind structural and behavioral changes	Impact on activity levels	Narrative behind structural and behavioral changes
Shipping (int.)		Overall, a cooperative recovery sharing resources due to international and national solidarity as a result of the pandemic would impact positively global trade. Also, dominance of online retail will also consequently increase the road freight activity.	0%	Overall, an individualist, less cooperative future would reduce the number of shared resources, inevitably increasing carbon-intensive domestic freight activity of most of the subsectors. Less carbon intensive global trade would be affected negatively.	5%	Global trade positively affected as in Smart Use. Carbon-intesive heavy-duty road transport is regulated more effectively, leading to slight reduction of activity. Air cargo impacts are lager than in Smart Use since air cargo capacity is affected by reductions on passenger flights.
Rail			5%		5%	
Road			5%		-5%	
Air Cargo			-5%		-10%	

Supplementary Table 7. Detailed qualitative sub-sectoral freight transport analysis for the Global South. The red-yellow-green scale illustratively represents decreases (red) or increases (green) in energy service levels as compared to previously projected levels (yellow implies no change from the expected structure without a pandemic).

Freight transport (Global South)						
	Smart Use		Self-Reliance		Green Push	
Mode	Impact on activity levels	Narrative behind structural and behavioral changes	Impact on activity levels	Narrative behind structural and behavioral changes	Impact on activity levels	Narrative behind structural and behavioral changes
Shipping (int.)	5%	Overall, a cooperative recovery sharing resources due to international and national solidarity as a result of the pandemic would impact positively global trade. A lower adoption of online retailing (due to lower digitalization) leaves unchanged rail and road freight levels compared to projections.	0%	Overall, an individualist, less cooperative future would reduce the number of shared resources, inevitably increasing carbon-intensive domestic freight activity of most of the subsectors. Less carbon intensive global trade would be affected negatively.	5%	Global trade positively affected as in Smart Use. Carbon-intesive heavy-duty road transport is regulated more effectively, leading to slight reduction of activity. Air cargo impacts are lager than in Smart Use since air cargo capacity is affected by reductions on passenger flights.
Rail	0%		5%		5%	
Road	0%		5%		-5%	
Air Cargo	-5%		-5%		-10%	

2.3 Cumulative impact in *post-pandemic* recoveries on useful energy demand

The combined impact on energy use resulting from the global GDP changes and structural changes in the energy system under alternative post-pandemic recovery is given by:

$$UE_{TRP_{n,s}} = EI_{SSP2_n} \cdot GDP_{SSP2_n} \cdot \left[\left(1 + \Delta_{GDP_n}\right) \cdot \epsilon_{d_n}\right] \cdot \sum_{m,t} \left[S_{m,n,t} \cdot \left(1 + \Delta_{COVID-19_{m,n,s,t}}\right)\right] \quad \forall n, \forall s \tag{2.2}$$

Where:

- m, n, s, t: indexes for the sets *Modes*, *Nodes*, *Scenarios* and *Types*, respectively
- UE_{TRP}: transport useful energy $[GWa/yr]$
- EI_{SSP2}: original energy intensity in SSP2 $\left[\frac{GWa}{billion\ USD_{2005}}\right]$
- GDP_{SSP2}: original GDP at Market Exchange Rates in SSP2 $[bnUSD_{2005}/yr]$
- Δ_{GDP}: GDP impact from COVID-19 pandemic [%]
- ϵ_d: income elasticity of transport useful demand $\left[\frac{\%\ change\ in\ useful\ demand}{\%\ change\ in\ income}\right]$
- S: modal share of transport subsectors in 2019
- $\Delta_{COVID-19}$: structural and behavioral impact from COVID-19 pandemic [%]

The income elasticity of useful demand is calculated from the average of the projection between 2020 and 2025 of the SSP2 baseline. SSP2 serves as the reference scenario for this study because it is designed to extend historical trends.

$$\epsilon_d = \frac{\%\ change\ in\ useful\ demand}{\%\ change\ in\ income^3}$$

Therefore, the values resulting from the term $\left[(1 + \Delta_{GDP_n}) \cdot \epsilon_{d_n}\right]$ represent the impact of the estimated GDP shock on useful energy. The different resulting magnitudes representing both the GDP impacts and the structural or behavioral impacts can be seen in *Supplementary Figures 4 and 5* in Supplementary Note 5.

2.3.1 *Structural and behavioral changes triggered by the pandemic*

To quantify structural and behavioral changes under each of the different post-pandemic recovery narratives (summarized description in main manuscript) that match the scale of the qualitative analysis performed in Section 2.2.2, we focused on surveys that capture the potential for maintained structural and behavioral changes and that identify shares of the population that changed their habits and lifestyles during the pandemic. Empirical data from and 2020 estimates from Section 2.1.2 serve as the reference point. The next sections provide a detailed description and references by transport mode, after introducing the impacts of teleworking.

2.3.1.1 *The impacts of teleworking*

Teleworking is found to have the potential to reduce activity levels across all transport subsectors due to reduced commuting across all modes of transportation[19,44]. Studies about workforce habits during the pandemic (first half of 2020) and studies informing what shares of the workforce could potentially remain practicing teleworking (at least two days a week) in the near future were consulted, separating for different regions of

[3] Where income is GDP per capita [USD_{2005}/capita/yr].

the world where possible (eventually grouped into Global North and Global South for this case study).

Levels of teleworking as a result from the pandemic has been reported to be about 37% for the EU[45]. In the US, Global Workplace Analytics projects that up to 30% of workers could still be teleworking multiple days per week by 2022[46]. In addition, an IEA analysis based on work from the International Labour Organization (ILO) found a strong correlation between GDP per capita levels and the teleworking potential at national scale with differentiated energy implications[47,48], which we take into account in our analysis.

These possible impacts have been combined with information on average commute distance and times in developed countries[44,49,50,51] to quantify the impacts on public and private transport activities, for each of the scenario narratives of this study.

2.3.1.2 ***Passenger transport***

2.3.1.2.1 Road private transport

Post-pandemic shock and recovery for road passenger transport is assessed based on the interactions that both perceived health risks in public transport and the appreciation of air pollution reductions could have on transport demand shifts, informed by two surveys conducted during lockdowns[35,52]. For car-usage we collect data for both *during* and *after* strict lockdowns[9–11], reports of permanent structural changes that may remain in the mid-term used in the qualitative analysis. This data was combined with the qualitative scenario description to construct quantifications of the different narratives.

The potential for a rebound and increase in higher activity in *self-reliance* is based on examples in China and the US. For China, a survey of 1620 respondents showed that the share of journeys made by bus and metro was halved while private car use and sales increased[35]. In the US, car usage bounced back to January 2020 values already in June[9]. For the Global South, we assumed a lower potential to shift to private car use and thus a less pronounced shift towards increased trips by car (due to the lower affordability levels and car ownership).

Global North estimates for *green push* use data from UK Transport Statistics[19,44] about travel habits as a reference point. This data provides shares for different transport modes by trips, distance, and purpose of trips. We then applied coefficients of what we see as the largest feasible persistent reductions (based on home-office levels before the pandemic and its potential after the pandemic, and mode shift to public and non-motorized transport, see Section 2.3.1.1). This results in eventual assumptions of reductions in commuting (-35%), shopping (-30%), and leisure (-20%), whereas the share of trips for other reasons remains unchanged. On aggregate, we estimate a -20% persistent change. For the Global South, due to lower capacities for remote working, we assumed a slightly smaller change (-15%).

Supplementary Table 8. Assumptions on private cars and 2-wheelers activity levels for each recovery scenario, for the Global North and Global South. Values are changes compared to reference SSP2 projection in 2025.

	Smart Use	**Self-Reliance**	**Green Push**
Global North	-10%	15%	-20%
Global South	-5%	10%	-15%

For *smart use*, in which we assume predominantly bottom-up learning and no additional supporting infrastructures from governments, we assume the relative change to be half that of *green push*, which especially lowers the potential for increased public transport, while non-motorized travel still increases.

2.3.1.2.2 Rail

For *smart use*, slightly reduced commuting levels which would decrease activity, are mostly offset by an increase in domestic tourism. In effect, we assume no variation compared to reference projections by 2025. In the Global South, the net impact on the rail activity is assumed to be negative due to the lack of extensive rail networks that could facilitate increased domestic tourism.

For a *green push* scenario, while increased teleworking would reduce the number of trips (and passenger distance travelled), we assume that a significant share of the recovery does not rebound to ‘old normality’ levels of private-car trips, but rather to bus, tram, and metro in urban and suburban areas (30% of avoided private car trips), due to policies instruments disincentivizing urban travel by car. In addition, high-speed rail infrastructure investments and safety measures are assumed to be publicly prioritized, which, together with concurrent levies on short-distance flights, absorbs part of the transport needs. Again, in developing countries these effects are assumed to be lower due to lower digital capacities as well as generally lower institutional capacity.

For *self-reliance*, we gain use a UK survey, which shows that 27% of the rail commuters expect to be making less trips after the pandemic[52]. 50% of those said the reason is due to health concerns, the remaining cited either teleworking or a change in preference for other modes of transport as the reason to move away from commuting by rail. Assuming parts of these expected changes were to materialize, we estimate a 10% reduction compared to the reference SSP2 trajectory by 2025, with a limited effect of increased teleworking due to lacking additional institutional and governmental support (Section 2.2). For the Global South, we assume that the shift from rail to private is 5%.

Supplementary Table 9. Assumptions on rail public transport activity levels for each recovery scenario, for the Global North and Global South. Values are changes compared to reference SSP2 projection in 2025.

	Smart Use	Self-Reliance	Green Push
Global North	0%	-10%	15%
Global South	-10%	-5%	25%

2.3.1.2.3 Other public transport

Due to data limitations for many regions in terms of further sub-sectoral detail, we treat changes in urban rail, tram, metro, and bus on an aggregate level.

In *smart use*, reduced commuting levels due to teleworking and a minor modal shift towards micromobility decrease the overall activity for these modes, leading to negative % reductions compared to reference projections. For the Global South, the impact is bigger since the length of commuting trips is lower than the average in the Global North[49], making the shift to non-motorized transport more noticeable.

In the case of *green push*, the shift away for (sub)urban car use also leads to increased public transport for these modes, compensating the minor modal shift to micromobility in cities. The same reasoning for rail, based on digitalization levels, was also used here to differentiate between the Global South and the Global North.

For *self-reliance*, we assume the same effects as for rail, following the qualitative analysis in Section 2.2.

Supplementary Table 10. Assumptions on urban rail, tram, metro, and bus transport activity levels each recovery scenario, for the Global North and Global South. Values are changes compared to reference SSP2 projection in 2025.

	Smart Use	Self-Reliance	Green Push
Global North	-5%	-10%	10%
Global South	-10%	-5%	15%

2.3.1.2.4 Domestic and international aviation

With the share of business travelers accounting for about 12% of the total passengers[53], the effect that increased virtual conferencing can have on aviation is significant. Along with road transport changes, the levels of air travel are thus another important distinctive driver for the different recovery pathways.

Indeed, to estimate the potential impact on aviation from reductions of long-haul business trips, cumulative distributions of key operational variables in the global commercial aircraft fleet in 2015[54] and the European fleet in 2018[55] were consulted as a starting point. We split the number of flights between short medium and long haul[4] to allow for separate directed assumptions. Acknowledging that passenger aviation activity and emissions are highly skewed towards long-haul flights[54,55], the modal shift from short-haul flights to high-speed rail (both in *smart use* and *green push*) will not have a large impact on overall activity levels.

In the *smart use* scenario, for both regions we assumed a larger decrease in international aviation since, as found during the qualitative analysis, a reduction in long-haul flights is projected to result from lower levels of international tourism compared to reference trajectories, a behavioral change retained after the pandemic. In the case of domestic

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[4] Short haul are flights <1000km, medium haul up to 3000km and long haul more than 3000km.

aviation, the reduction refers to the share of short-haul flights that is substituted by teleworking and, when existing, by an increase of usage of national rail networks.

In the *self-reliance* scenario, we assumed that activity levels to move back to original levels, as previously described in the qualitive analysis.

In the *green push* scenario, a more pronounced persistence is explored. Here, we assume domestic aviation is reduced by 80% of the *short*-haul flights and 35% of the *medium* haul flights due to a combination of policy instruments and bottom-up learning, using amongst others the following specific measures:

- limiting and reducing airport capacity[55];
- increasing taxation[55,56];
- limiting short-haul flights as a condition for bailouts[57].

We assumed further that 20% of the long-haul flights for leisure can also be avoided. In terms of business trips, due to the social learning in videoconferencing for many business purposes, supported by additional policies, a persistent shift towards less international travel is enabled. We assumed totals of 42% (domestic flights) and 28% (international flights) compared to reference trajectories for both regions (Global North and Global South), thus cutting about a third of global aviation passenger-kilometers.

Supplementary Table 11. Assumptions on domestic and international aviation activity levels for each recovery scenario. Values are changes compared to reference SSP2 projection in 2025.

	Smart Use	**Self-Reliance**	**Green Push**
Aviation (dom.)	-10%	0%	-41%
Aviation (int.)	-15%	0%	-28%

2.3.1.2.5 Non-motorized transport and electric micromobility[5]

Non-motorized activity represented 1.67% of global urban mobility in 2015[58], ranging between <1% in the US to 3% in the European Economic Area and Turkey.

In the case of *smart use*, we used as a starting point for our assumptions a report describing exploring a scenario for potential structural change that may persist on the medium-term[59]. This scenario comes with a permanent 5-10% increase in pre-pandemic activity. In this scenario, benefits from reduced air pollution in urban areas are retained. Moreover, in this scenario we assume that the lockdown periods in several regions where only walks and outdoor sports close to the place of residence were allowed reinvigorates active mobility and thus sees strong increases compared to reference projections. In the Global South, the change was assumed to be equally strong.

The *green push* scenario comes with all changes described in the *smart use* scenario. In addition, we project measures such as those implemented in cities like Milan or Budapest[60,61] become widespread, facilitating additional shifts from car to more low carbon forms of transport. As mentioned in public-transport Sections 2.3.1.2.2 and 2.3.1.2.3, 30% of the avoided private trips is absorbed by those. For non-motorized transport, we assumed further 20% of the avoided trips to be replaced by non-motorized transport (leaving the remaining 50% decrease due to the effect of teleworking, see Section 2.3.1.2.1). This 20% includes short-distance trips that can be more easily replaced by non-motorized transport or micromobility, being equivalent to a strong growth of 150% in activity levels compared to projections[58], in the case of developed

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[5] *Electric micromobility* refers to a range of small, lightweight electric vehicles including e-bikes, electric scooters and electric skateboards.

economies. The impact was assumed to be lower in developing countries mostly because these means of transport are more saturated in urban areas than in most of developed economies, also due to limited capacity to scale up biking infrastructure in some highly congested cities.

Supplementary Table 12. Assumptions on non-motorized transport activity levels for each recovery scenario, for the Global North and Global South. Values are changes compared to 2015 levels from ITF[58].

	Smart Use	Self-Reliance	Green Push
Global North	20%	0%	150%
Global South	20%	0%	100%

2.3.1.3 *Freight transport*

2.3.1.3.1 Road freight transport

The surge in e-commerce during the pandemic (one of the drivers analyzed in the qualitative analysis in Section 2.2.1) has changed consumer behavior, with implications for freight demand[31,32].

The increase in on-demand deliveries is expected to enhance delivery efficiency and reduce transport costs due to higher load factors due to more directed trips[58]. This, together with rising delivery vehicle-kilometers because of package returns, could ultimately lead to an increase in *last-mile* road freight activity[58]. We considered these factors to assume road freight transport increases for the *smart use* and *self-reliance* scenarios. No effect from this factor was assumed for the Global South in *smart use*, due to a lower degree of digitalization in some of the economies belonging to that region (for more information, see *Supplementary Tables 6 and 7* in Section 2.2.2).

At the same time, policy could counterbalance the developments mentioned above by promoting the use of collection points, and for instance implementing distance-based charges[58] or otherwise levying returns. We assumed that trends in activity of these characteristics are present in the *green push* scenario, matching the reasoning of the qualitative analysis in Section 2.2.2.2. Here then, despite increased online purchases (30% less of private trips by cars and 2-wheelers due to online retail, see Section 2.3.1.2.1), the overall impact on activity levels is a 5% decrease for both regions.

Supplementary Table 13. Assumptions on road freight activity levels for each recovery scenario, for the Global North and Global South. Values are changes compared to reference SSP2 projection in 2025.

	Smart Use	**Self-Reliance**	**Green Push**
Global North	5%	5%	-5%
Global South	0%	5%	-5%

2.3.1.3.2 Rail freight

The same reasoning as in road freight transport for *smart use* and *self-reliance* due to lack of data availability for potential impacts. In the case of *green push*, we assumed that a share of the reduction in the activity of road freight transport shifts to rail freight (increasing the train fleet together with infrastructure investments), meaning that, when feasible, the preferred mean for transporting goods is this low-carbon alternative.

Supplementary Table 14. Assumptions on rail freight activity levels for each recovery scenario, for the Global North and Global South. Values are changes compared to reference SSP2 projection in 2025.

	Smart Use	**Self-Reliance**	**Green Push**
Global North	5%	5%	5%
Global South	0%	5%	5%

2.3.1.3.3 International freight shipping

The effects on international shipping for the different recovery trajectories have been derived from the level of international restrictions assumed in each of the narratives (which correlates with the total traffic of goods, in volume). This results in a positive contribution in *smart use* and *green push*, while no variation from SSP2 reference projections is assumed in the *self-reliance* scenario.

Supplementary Table 15. Assumptions on international shipping activity levels for each recovery scenario. Values are changes compared to reference SSP2 projection in 2025.

	Smart Use	**Self-Reliance**	**Green Push**
Int. Shipping	5%	0%	5%

2.3.1.3.4 International air cargo

Air cargo activity was assumed to be muted across all scenarios since approximately 50% of the world air cargo capacity is provided by passenger flights[62]. Even under the *self-reliance* scenario we project a reduction in spite of a recovery of the passenger aviation growth due to higher international restrictions (See qualitative analysis Section 2.2.2). In *green push*, where the recovery of passenger aviation is affected most strongly, a stronger impact on air cargo capacity (and consequently in its activity), was assumed.

Supplementary Table 16. Assumptions on international air cargo activity levels for each recovery scenario. Values are changes compared to reference SSP2 projection in 2025.

	Smart Use	**Self-Reliance**	**Green Push**
Int. air cargo	-5%	-5%	-10%

2.3.2 *Outcome of the quantitative analysis*

Supplementary Table 17. Overview of quantitative impact on activity levels for the different passenger transport subsectors for Global North and Global South. Values are changes compared to reference SSP2 trajectory in 2025.

	Passenger transport (Global North)			Passenger transport (Global South)		
	Smart Use	Self-Reliance	Green Push	Smart Use	Self-Reliance	Green Push
Mode	Impact on activity levels	Impact on activity levels	Impact on activity levels	Impact on activity levels	Impact on activity levels	Impact on activity levels
Rail	0%	-10%	15%	-10%	-5%	25%
Cars, 2-wheelers	-10%	15%	-20%	-5%	10%	-15%
Buses, Tram and Metro	-5%	-10%	10%	-10%	-5%	15%
Aviation	-10%	0%	-41%	-10%	0%	-41%
Aviation (int.)	-15%	0%	-28%	-15%	0%	-28%
Non-motorized transport	20%	0%	150%	15%	0%	100%

Supplementary Table 18. Overview of quantitative impact on activity levels for the different passenger transport subsectors for the Global North and Global South. Values are changes compared to reference SSP2 trajectory in 2025.

	Freight transport (Global North)			Freight transport (Global South)		
	Smart Use	Self-Reliance	Green Push	Smart Use	Self-Reliance	Green Push
Mode	Impact on activity levels	Impact on activity levels	Impact on activity levels	Impact on activity levels	Impact on activity levels	Impact on activity levels
Shipping (int.)	5%	0%	5%	5%	0%	5%
Rail	5%	5%	5%	0%	5%	5%
Road	5%	5%	-5%	0%	5%	-5%
Air Cargo	-5%	-5%	-10%	-5%	-5%	-10%

Supplementary Table 19. Overview of total useful energy reductions for each MESSAGEix-GLOBIOM region, for each scenario. Values are changes compared to SSP2 trajectory in 2025.

	Smart Use	Self-Reliance	Green Push
R11_AFR	-14%	-6%	-19%
R11_CPA	-6%	4%	-11%
R11_EEU	-11%	1%	-18%
R11_FSU	-8%	4%	-15%
R11_LAM	-11%	-2%	-16%
R11_MEA	-11%	-2%	-16%
R11_NAM	-7%	5%	-14%
R11_PAO	-9%	3%	-16%
R11_PAS	-12%	-3%	-17%
R11_SAS	-14%	-5%	-18%
R11_WEU	-12%	-1%	-19%
Global North	-9%	3%	-16%
Global South	-10%	-1%	-15%

3 Supplementary note 3. The industry end-use sector

Industrial production is not affected equally by disruptive events, such as the COVID-19 pandemic. Economic and demand-driven changes to industrial activity and material demand are varied across industrial subsectors, geographical regions, and other dimensions. The overall trends depend on the use of the commodities, and the types of secondary and tertiary industries they feed-in. For instance, according to McKinsey & Co.[63] demand for metals that are primarily used in industrial end-uses (e.g. aluminum, nickel, and zinc) is closely coupled with any GDP change. On the other hand, countercyclical metals (such as gold), commodities mostly associated with new industrial applications (for example, copper), or materials used for other unaffected end-uses, such as agriculture or people-centered activities (e.g. potash in agriculture production)are more resilient to economic downturns . Iron, steel, and thermal coal are likely to be hit harder in places where construction demand falls along with power requirements, in line with lower levels of economic activity.

To capture these dynamics, we assessed the impacts of the COVID-19 pandemic on the industry sector with a combination of bottom-up and macro-economic approach. The GDP shock on the industrial production was developed with the macro-economic impact model as described in Supplementary Note 6, and the current section describes and quantifies the changes on the energy service side. Industrial energy services were expressed in terms of demand for produced commodity (activity dimension), the energy intensity of industrial production (intensity dimension), i.e. the final or useful energy demand per tonne production, and changes in the share of electricity and thermal energy (structure dimension) due to industrial restructuring as a result of supply chain changes and repurposing. Then the industrial demand estimate was coupled with the SSP2 - based GDP shock adjusted projection.

3.1 Data collection for the base year and for 2020 demand shock

The changes in individual lifestyles, institutional, social and commercial settings had a direct impact on industry: factories and manufacturing facilities were closed due to shortage of workforce (as a result of lockdown measures, health problems or because of access problems due to travel restrictions), and curtailment of raw materials (including problems with transportation and logistics)[64,65]. At the same time, activity in industry was impacted indirectly (as the upstream effects) as a result of changed demand for products in other sectors, for example a reduction in automobile sales, a slowdown of the construction and building renovation industries, and a change in shopping patterns (moving to online services) needing more packaging.

To estimate the COVID-19 impacts in 2020, first we defined the base-year industrial activities and energy use in the year 2019. Because of up-to-date statistics availability issues for the year 2019, we extrapolated activity based on several data sources and approaches. The energy service changes in industry were assessed at regional level, on the 5 regional aggregation level (see Supplementary Note 1), which were then subsequently aggregated to two global regions: Global North and Global South.

The impact analysis of COVID-19 was based on five main commodities, which were analyzed and quantified, following the decomposition method of Grubler et al.[66] and

IIASA[67]: iron and steel, aluminum, cement, pulp and paper, and chemical and petrochemicals (Supplementary Table 20). We started from the base-year (2020) data on the total energy service levels reported by Grubler et al.[66] at two global regions, building on the GEA Efficiency Scenario[68], the 2-Degree Scenario (2DS) of the IEA's Energy Technology Perspectives (ETP)[6], the material efficiency literature (such as[69]), and the traditional industrial (process) energy efficiency literature[70].

Supplementary Table 20. Base year (2019) material production on a five-regional level based on Grubler et al.[66] and IIASA[67], in million metric tons.

Industry subsector	OECD+EU	REF	ASIA	LAM	MAF
Iron and steel	510	130	931	59	41
Aluminum	38	4	64	3	17
Cement	486	137	3013	180	359
Pulp and paper	229	11	134	18	8
Chemical and petrochemical	214	45	275	17	25

In order to estimate the intensity change, expressed in tonnes of materials produced per energy unit, the energy intensities as reported by ETP[6] were adopted. The fuel intensity was based on the ratio of electrical and thermal energy demand obtained from ETP[6], defined at two-region level for OECD and non-OECD regions for the five materials, and adapted to the analytical five regions basing REF, ASIA, LAM and MAF MESSAGEix-GLOBIOM regions on non-OECD data (Supplementary Table 21).

Supplementary Table 21. The ratio of electric and thermal energy demand for the five considered sub-sectors of industry, on a 2-regional level. Based on ref[6].

Industry subsector	OECD		non-OECD	
	electricity	thermal	electricity	thermal
Iron and steel	17%	83%	12%	88%
Non-ferrous materials (aluminum)	54%	46%	54%	46%
Cement	13%	87%	11%	89%
Paper	0,4%	100%	28,6%	71%
Chemical and petrochemical	9%	91%	11%	89%

The fuel intensity of producing the five material groups in the five MESSAGEix-GLOBIOM regions were defined for electric and thermal energy based on data in Supplementary Table 20 and Supplementary Table 21 (Supplementary Table 22).

Supplementary Table 22. Production intensity in energy per material produced, separately for electric and thermal energy. Based on refs[6,67].

Industry subsector	Thermal energy intensity (EJ_{heat}/bn metric tons)	Electricity energy intensity (EJ_{el}/bn metric tons)
Iron and steel	1.7	11.8
Non-ferrous metals	27.8	23.5
Cement	0.3	2.4
Paper and pulp	1.4	13.5
Petrochemicals	4.6	39.1

Non-energy uses (feedstocks) are described separately, using reference data from ETP[6] and Grubler et al.[66].

3.1.1 *Formulation of the COVID-19 direct shock in 2020*

The sub-sectoral activity (ACT) levels, i.e. material production of commodity types for 2020 were identified with the formula below to produce total material production based on commodity-specific and region-specific year-on-year change:

$$ACT_{2020_n} = ACT_{2019_n} + \sum_{m,n} ACT_{2019_{m,n}} * S_{m,n} * \Delta_{m,n} \quad \forall m, n \tag{3.1}$$

Where:

- ACT_{2020_n} is the aggregated activity level of industrial material demand in 2020;
- n: index for nodes (regions);
- m: sub-sectors (steel, cement, petrochemical, etc.) ;
- S: share of industrial subsector activities, i.e. relative commodity production in 2019;
- $\Delta_{m,n}$: year-on-year (YoY) % variation in sub-sectoral activity level in 2020 compared to 2019 (in % of million metric tons);

3.1.2 *Outcome of the demand shock analysis in 2020*

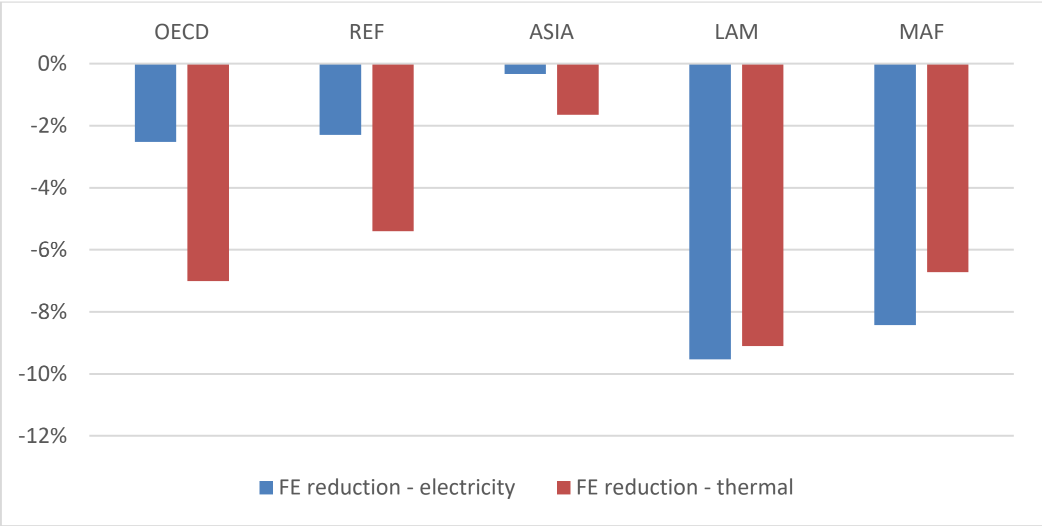
Reduction and repurposing impact of the pandemic during the year 2020 were collected from the (very sparse) peer-reviewed literature, industry working papers, and industry stakeholder reports.

Using the above formula (3.1), the base-year material distribution (Supplementary Table 20) and the share of electric and thermal demand, we estimate the below values for material production in 2020 (Supplementary Table 23).

Supplementary Table 23. Estimated material production for 2020 on a five-regional level (million metric tons).

Industry subsector	OECD+EU	REF	ASIA	LAM	MAF
Iron and steel	427	123	909	50	38
Non-ferrous metals	38	4	65	3	17
Cement	457	130	2910	180	359
Pulp and paper	218	11	127	18	8
Chemical and petrochemical	193	41	268	16	23

The energy demand reduction is depicted in the *Supplementary Figure 3* below.



Supplementary Figure 3. Final energy demand reduction between 2019 to 2020 (YoY) in industry thermal and specific electricity.

3.1.3 ***Observations in 2020***

The change in production levels varies sharply across commodities and regions. Some countries (such as Australia) have gone through limited levels of industrial lockdowns, others (such as South Africa) have witnessed severe measures, with a strong knock-on effect on mining sites. Data was collected on observed factory and mining closures, reduction or change in raw material or production volumes, stay-at-home measures for workers, repurposing changes, reduction in secondary industry demands, etc. expressed in YoY% change in 2020 compared to 2019.

The impact of the pandemic was differentiated in terms of the disruption on commodities across geographical regions[71].

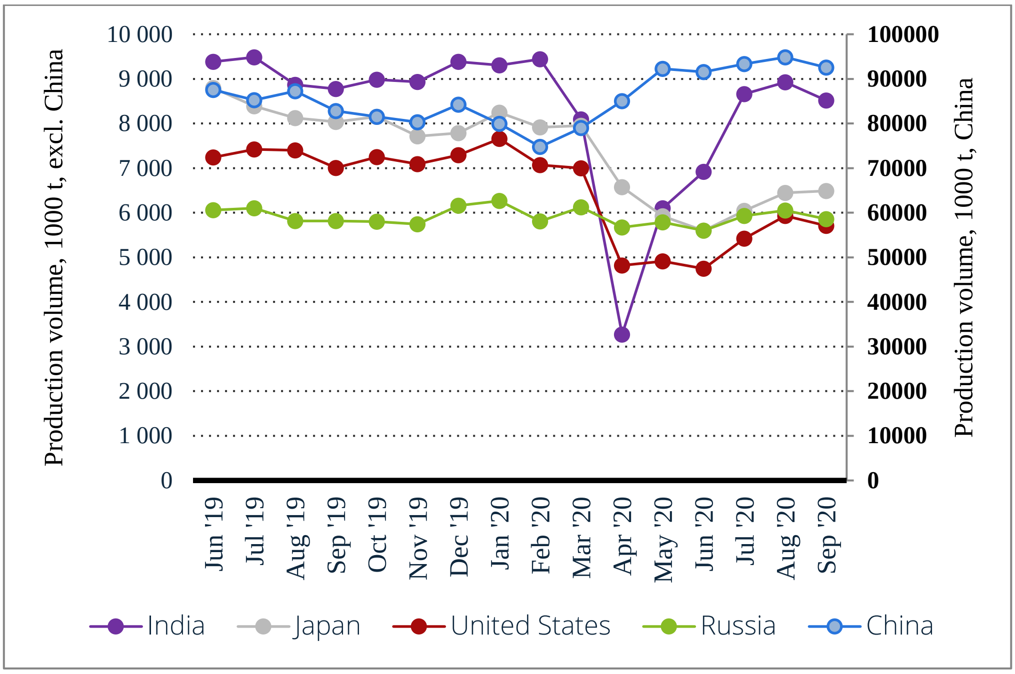
Data and information are collected for the five regions on the five commodity types are reviewed here.

Steel and iron ore market

Steel makes up the second largest amount across the commodity types, and is among the industries most affected by the pandemic[63,72]. Drivers of material and industrial activity reduction in the iron and steel sectors have been reported as[72,73]:

- Reduced demand mainly due to the drop in uptake by secondary industries;
- Lack of workers due to lockdowns and stay-at-home orders;
- Disruption of supply chains;
- Liquidity issues due to reduced demand.

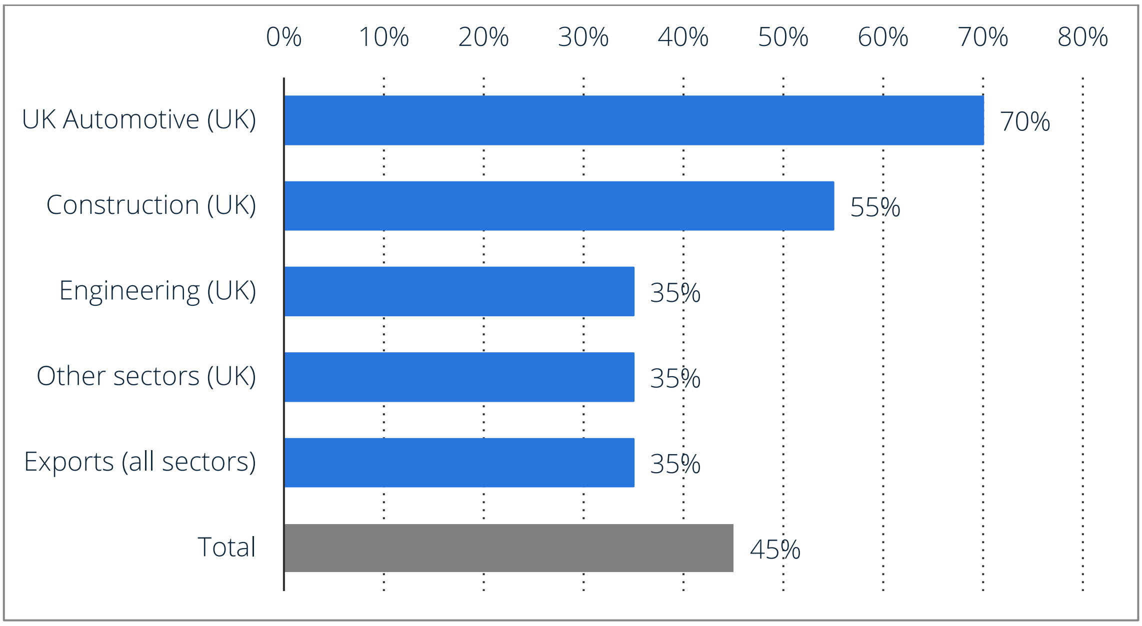
The annual drop in global level demand for finished steel is forecast to be around 2.4-4.3% in 2020 on top of 2019 [72,74], driven by reduced consumption of manufactured products, construction activities, and other consumable goods [75], including a rebound in the second half of the year following easing of restrictions, yet not enough to offset early losses in consumption[76], and is expected to decline throughout 2020 and then slowly recover in 2021[77]. Global steel production is prognosed to decline by 2.8% YoY[74].



Supplementary Figure 4. Crude steel production in selected countries[77] for the period from June 2019 to September 2020. Note that the scaling for China is on the second axis with a multiplier of 10.

Global North:

In the Global North, the pandemic impacts largely the consumer and service sectors, and the direct impact on manufacturing is moderate. Europe and North America are the second and third largest producers (after China), which explains the largest knock-on effects in these regions. The automotive industry closures, as well as significant demand reductions also have affected industry activity. For example, most of the US-based blast furnaces were idled because of reduced steel demand due to the pandemic; however, they reopened in the second half of 2020[76].



Supplementary Figure 5. Year-on-year (YoY) percentage reduction in steel orders in the United Kingdom (UK) in 2020 compared to 2019[78].

Global South:

China's output continued to grow in 2020 (by 4 percent YoY) due to initiatives aimed at boosting investments[74].

Disruptions in supply chain, massive dislocations of spending, and spillovers from job losses and economic downturn have characterized the sector in 2020. In India, the harsh lockdown of industrial operations, supply chain disruption, the slowing down of the uptake sector (construction) have caused the key disruptions[79]. According to market analyses[72], the production of steel was not cut fast enough during the beginning of 2020 to match the reduction in orders, thus prices were drastically falling. This resulted in a longer-term effect, causing liquidity concerns. In several regions small mills faced difficulties in financially covering their idle status. Consequently, mills of smaller sizes and those with a lower efficiency, especially in Africa, the Middle East and Asia outside China started to sell their inventory at extremely low prices to raise cash. In Latin America, the industry had low resilience to disruptions because of the previously existing vulnerabilities. Supply chain knock-on effects have been observed as well.

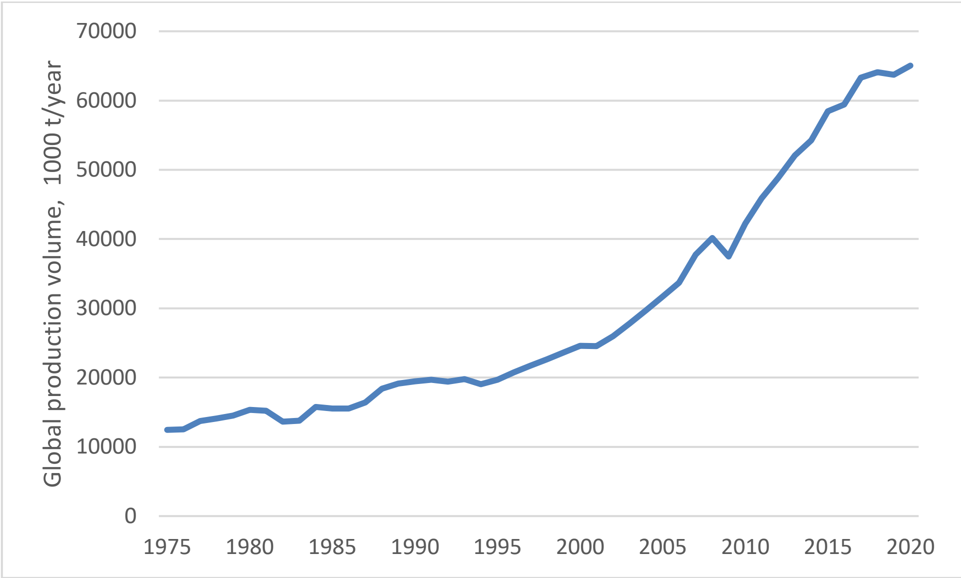
Steel-dependent industries not paid by their customers, such as construction companies, component manufacturers and mines, were faced with liquidity issues, in turn affecting income of steel manufacturers. As a result, some parts of the industry are negatively impacted by this crisis, simply because the cashflow dries up[72].

In terms of factors for increased activity, steel producers started to redirect towards packaging for e.g. alcohol in hand sanitizers, finding new growing markets[72].

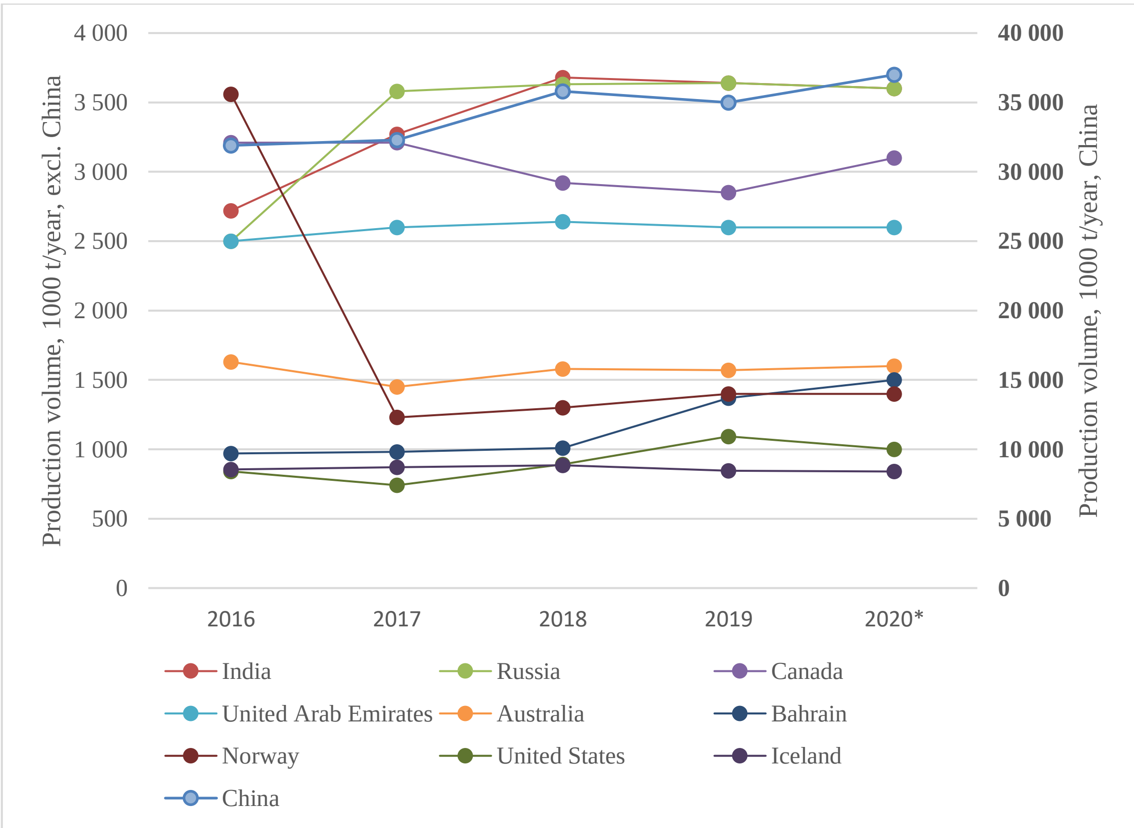
The above studies and data were used to estimate YoY change in iron and steel production for five global regions 2020 is shown in Supplementary Table 24.

Non-ferrous metals market, exemplified by aluminum

Aluminum is the most widely used non-ferrous metal, and it is used in construction (56%), transportation (10%), industrial equipment (17%), metal products (17%) as well as the packaging industry, and many more. Global aluminum production has been steadily growing in the past (Supplementary Figure 6), with a halt in the financial crisis of 2008-2009, and the impact of the year 2020 seems to be limited due to resilience (as shown in Supplementary Figure 7).



Supplementary Figure 6. Global annual primary aluminum production (in 1000 metric tonnes per year), based on ref. [80].



Supplementary Figure 7. Annual production of aluminum in key producing countries (in 1000 metric tonnes per year), based on ref.[81]. Note that the scaling for China is on the second axis with a multiplier of 10.

Global North:

In the Global North, some level of aluminum demand reduction was seen for a short period due to the lockdowns, disruptions of supply chains on the production side, while a slow-down of uptake and demand, mainly related to residential constructions and renovations[82]. For other non-ferrous metals, there is a larger impact in 2020, with prices down at their lowest since 2016 for copper, aluminum, zinc.

Global South:

China's aluminum material shortages were mainly due to the difficulties in transportation. At the same time, India experienced major disruptions (-60% of production in worst moments). However, these have been compensated by the end of 2020. The long-term drivers of aluminum growth remain after COVID-19 and the opportunities are greater[83].

The above studies and data were used to estimate YoY change in non-ferrous metal production for five global regions 2020 is shown in Supplementary Table 24.

Cement and concrete industry

Cement (including concrete) is the second-most-utilized product in the world after potable water[84]. The world consumes over 4 billion metric tons of cement annually[6,66]. The sector has a strong interlinkage with the global economy due to its long and diverse supply chain and it contributes 5.4% of global GDP and 7.7% of global employment[84]. The industry's revenue was down for most producers in 2020 compared to 2019, due to the secondary impacts from the drop in construction activity. There were large regional differences between how countries implemented different lockdowns, how markets responded and how they bounced back afterwards. Generally, the financial effects of this were felt in the first half of 2020 with recovery in the second[85].

Pacific Asia is the largest producer in the global cement and concrete market, accounting for 36% of the market in 2019. North America produced 23% of the global cement and concrete output, while Africa is the smallest region in the global cement and concrete product market[86].

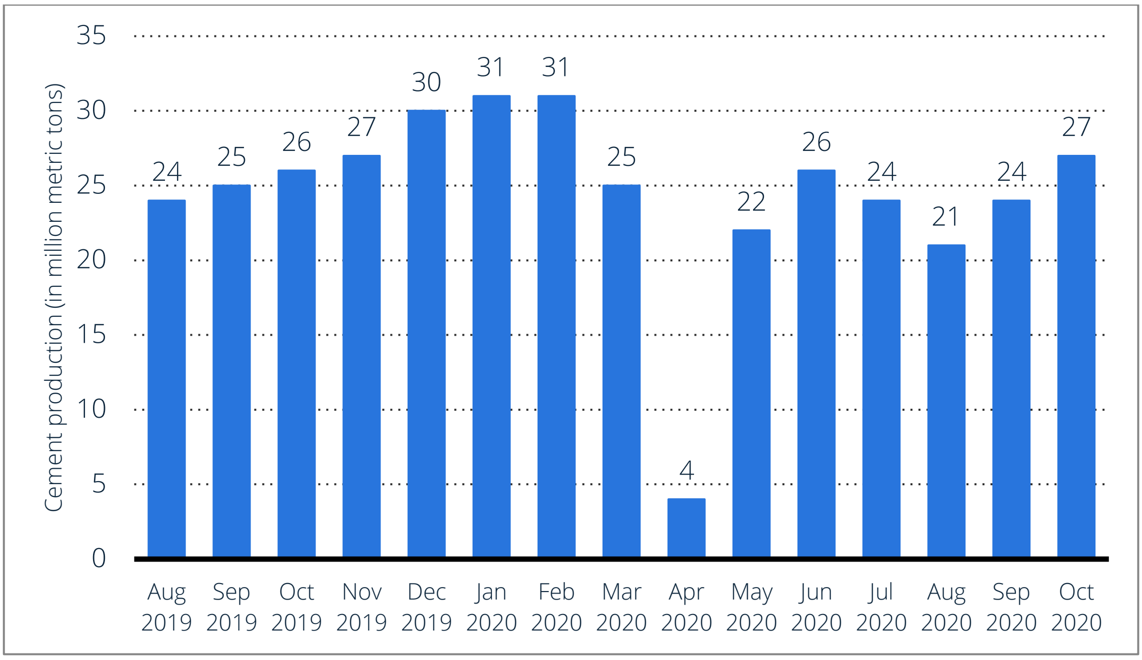
Demand was changing differently in different regions, as reported by IFC[84].How companies were able to supply still running construction projects is very different, because of the constraints on the supply chains and workforces, or even direct lockdown measures. Some countries allowed construction works to continue during lockdowns (considering these as emergency services), others did not.

Global North:

In the UK, direct impacts of lockdowns have affected construction sites and production sites in 2020, but a recovery outside hard lockdowns somewhat compensated reduced activity [87]. In Europe and North America, the effects were varied due to different responses during the pandemic[85].

Global South:

With a globalized cement market, a drop in demand in one region could impact the entire global market, with primarily Asian production being affected due to its large share[88]. India is an exception, as it has a strong local/national market, which in turn has been affected by the lockdowns and uncertainties of the pandemic and its measures much more locally[87,89,90]. Despite a hard shut down for a month during March-April 2020, regional markets largely recovered. One company, UltraTech Cement reported in January 2021, “Recovery from the Covid-19 led disruption of the economy has been rapid. This has been fuelled by quicker demand stabilization, supply side restoration and greater cost efficiencies." Apparently, rural residential housing had driven growth and government-infrastructure projects had helped[85].



Supplementary Figure 8. Quantity of cement produced in India between August 2019 and October 2020[89,90].

The above studies and data were used to estimate YoY change in cement production for five global regions 2020 is shown in Supplementary Table 24.

Paper and pulp industry

The paper and pulp industry was hit depending on the product shares in different regions. For instance, a slight increase in demand for packaging and sanitary and household products was paired with a sharp decrease in graphics and printed products, reflecting the new lifestyles, including teleworking and home schooling[91,92]. The production sites (mills) have a high potential for these repurposing opportunities, and repurposing and e-commerce are taking place.

Printing paper and board production decreased by 5.0% in 2020 on a global scale, compared to the previous year, according to preliminary figures, which has been taken into account in our estimates. On the other hand, the demand for packaging paper grew in 2020 especially due to materials used for transport packaging and corrugated boxes, driven by online commerce boom, inducing a production growth of 2.1%[92]. Similarly, the production output for sanitary and household paper increased by 1.9% compared to 2019.

Global North:

Analyses of the 2020 impact in Europe have been used for the Global North[92,93]. The production of packaging paper and materials have increased by 2.1% compared to 2019. Within this category, case materials – mainly used for transport packaging and corrugated boxes – even achieved an increase of 3.3%, while other grades (e.g. retail packaging) remained unchanged. At the same time, graphic grades production reduced by 18%, such as newsprint and printing papers decreased by 20.5% and 18.4% respectively. The pandemic accelerated a previously running structural decline. To reflect the changes, mills in Europe have been permanently shut down, and repurposing of machines has taken place.

Global South:

The downward trend in printed and board materials was only partially compensated by an increase in packaging and home products. China, India, and Korea recorded paper production decline ranging between -2% and -17%[92]. The Unites States, as the largest exporter to China, was also affected[91].

The above studies and data were used to estimate YoY change in paper and pulp production for five global regions 2020 is shown in Supplementary Table 24.

Chemicals and petrochemicals

Demand destruction for the products has led to an oversupply situation, which was already looming before the pandemic disruptions. The chemical industry has been affected by the combination of a general macroeconomic impact and a demand structure change[94].

Global North:

The automotive, transportation and consumer products sectors are amongst the hardest hit end-markets on the short-term, with demand for chemicals falling by up to 30% during the lockdown periods[94], which is moderated with the lifting of lockdown stringency over the course of 2020.

Global South:

Available analyses of China and India suggest that the petrochemicals sector in India has been considered as hard-hit in 2020, driven by secondary impacts from the construction and automotive industries. On the other hand, some essential industries, such as packaging and healthcare have limited some of the reduction. Demand growth of key polymers in India is expected to deteriorate in 2020 to around 1%, after an average growth of around 5% in recent times[95].

The above studies and data were used to estimate YoY change in paper and pulp production for five global regions 2020 is shown in Supplementary Table 24.

Overview of 2020 regional impacts

The impact of the pandemic between 2020 and 2019 is summarized in Supplementary Table 24 for the five analytical regions, and aggregated for the two global regions, Global North and Global South.

Supplementary Table 24. Overview of changes in material demand in 2020, compared to 2019 across the five global regions. References to support these assumptions are included in the text.

Region	Steel and iron	Non-ferrous metals	Cement	Paper and pulp	Chemicals and petrochemicals
OECD+EU	-16%	0%	-6%	-5%	-10%
REF	-5%	-1%	-5%	0%	-10%
ASIA	-2%	2%	-3%	-5%	-3%
LAM	-16%	-6%	0%	0%	-6%
MAF	-8%	3%	0%	0%	-6%
Global North	-14%	0%	-6%	-5%	-10%
Global South	-3%	2%	-3%	-4%	-3%

3.2 Recovery drivers in the analysis for the industry sector

Based on experiences of previous disruptions (financial crises, pandemics, wars), the industry sector typically goes through a four-phase recovery trajectory[63], which we use to inform the modelling of the medium-term response to the COVID-19 pandemic. We describe these phases below in short.

A price shock sets in during the first few weeks (phase one). This happened for instance during the financial crisis of 2008-2009, when commodity prices fell. In phase two, a demand shock rolls-out in combination with the price shock, that typically lasts for three months to two years. The drop in secondary industry demands, and end-use sector demands interrupts the uptake of produced materials. We have described this above in Supplementary Note 3.1.

In phase three, which is assumed here as the first part of the post-COVID-19 medium-term (see Figure 1) a new supply–demand equilibrium establishes. This period takes typically one to three years, when producers respond to new supply-and-demand dynamics. Facilities with higher costs, e.g due to low energy efficiency are closed or shut down, and the average stock performance may grow slightly. Market adaptation during the first and second phases change trade flows, which can lead to divergent price trajectories, which are partially fueled through government recovery support that alter end-use sector responses. Finally, in phase four the demand recovers and transitions into a new normal (one to five years). Global recovery is usually led by the larger economies and prices rebound as shortages begin to appear, new investment and projects start to address additional demand.

We distinguish a combination of drivers on the near to medium-term (until 2025 and beyond), based on direct and upstream impact on the overall industrial activity levels (million tonnes produced), on the structural changes due to varied change in the different industry sub-sectors, and a primary energy intensity change as a result of the fuel intensity of different sectors in different regions, mapping also to the MESSAGEix-GLOBIOM sectors of electric and heat demand.

The following **direct drivers** influence energy demand in industry primarily:

- **Manufacturing activity**: Factories, sites, mines, etc. reduce or change the level of output on the experiences or economic impact of the pandemic period.
- **Raw material availability**: One of the key attributes for seamless production is the availability of raw material, but interruptions have been affected not only mining, but also transportation and logistics, due to the lockdown restrictions and transportation closures (mainly air traffic). For example, China depends on important aluminum, which dropped and blocked the industry. A change after the pandemic can be the change of sourcing, or diversifying, so called glocalization.

- **Take-up sectors** (secondary, tertiary and quaternary sectors): In case of a halt in downstream industry sectors, as it was the case with construction and automobile production, take up slows down. The automotive industry is considered to be most hit by the pandemic[96], and expected to be impacted on a medium-term. Metal-consuming end-users reduced their input demands drastically in 2020, leading the iron and steel sector into a prolonged reduction in capacity and cost structure — and that could translate into possible staff reductions and related measures[73].
- **Oil prices**: Prices have been extremely volatile causing disruptions and uncertainty. For example, steel and iron industry in the REF region has been greatly limited on these terms[96].
- **Labor markets**: A lot of sites in India had to reduce operations because as a result of the hard lockdown workers had to leave the area to go home[96]. Workforce is already a concern in Europe and Asia, and has later become one in other regions, especially Africa.
- **Repurposing**: Facilities have changed production during the lockdown and can be expected to further change on the post-COVID-19 period.

As an example, the demand for paper and pulp is foreseen to go through a restructuring in production. The amount of paper produced is expected to increase in the medium-term post COVID-19 period, driven by new products (mostly disposable paper cups, paper plates, napkins, tissue papers, glasses, etc.), and due to a growing share of online shopping as a consequence of health risk assessments. A COVID-independent trend though, is the impact on biodegradable packaging with paper is due to the imposition of bans on “Single Use Polythenes” (disposable plastics) in many countries including India[97].

A selection of **upstream drivers** is shown below to demonstrate indirect impacts on industry as a result of changes in the buildings sector or the transport sector:

- **Automatization and digitalization**: Certain industries have been prepared to develop fast into a more modernized, automatized production cycle, which could give them an advantage (e.g. cement factories[88]).
- **Construction and renovation changes**: At the start of the pandemic, construction works halted as a result of wide-scale lockdowns. However, in the post-COVID-19 period, an increase of construction has been assumed in the *green push* scenario:
  - inducing increase in industrial activity;
  - a potential recycling dominance in the industry *green push* scenario;
  - the pandemic also has kick-back effect on the construction sector in underlining the importance of the quality and operational costs of our buildings.
- **Individual mobility changes**:
  - the assumed persistence of reduction
  - mobility mode shifts, in particular to non-motorized transport

3.2.1 *Mapping to the different narratives*

As illustrated in Supplementary Figure 1 in Supplementary Note 1**,** an analysis of the drivers of changes related to COVID-19 that affect energy services in the industry was conducted using COVID-19 specific literature, and demand-side literature on institutional and social change. We distinguish two sets of drivers as described above: direct and upstream. We map these onto the alternative recovery pathways as have summarized in Supplementary Table 25.

Supplementary Table 25. Overview of key qualitative drivers for the industrial sector in the three COVID shock-and-recovery scenarios.

DIRECT DRIVERS	Smart Use	Self-Reliance	Green Push
Manufacturing activity and repurposing	Some persistent production repurposing. *Reduced* activity due to process and material efficiencies inherited from the lockdown.	Production levels and structures and facility management aimed to return to normal, but with extended purposes resulting from foreseeing new pandemics.	Process and material efficiencies, experimented with during the lockdown are assessed and extended.
Raw material availability	Raw materials are available, but transportation costs and risks of export availability are priced.	Acquisition of raw materials is preferred from local sources, nationalization and protectionism, focus on local storage.	Focus on raw material efficiencies and balance between transportation and local solutions in light of sustainability
Take-up sectors (secondary and tertiary sectors)	Digitalization and efficiency-uptakes influence demand in primary sectors.	Falling export markets, protection of home production and sales.	Further increases in digitalization and efficiency. Learning extended to circular economy improvements.
Labor markets	Labor market reorganization with reduced primary and secondary sector workers.	Return to previous situation due to economic and social support.	Financial and social support to adjust the job market to a greener industry.
UPSTREAM DRIVERS			
Digitalization and automatization	Moderate impact from online shopping, such more packaging, more freight transport. More digital tools to manufacture.	Duplication of digital and offline solutions, increased hygiene.	Further enhancement of digitalization impacts with policies towards efficiency changes.
Individual mobility changes	Reduced overall transport demand and shift towards non-motorized transport impacts automobile production.	Concerns about hygiene and distancing, individual transport modes are preferred, increasing car demand, and thus relevant raw material demand.	Improved operational and business efficiency solutions due to decrease in communing as a result of increased teleworking and online services and administrations. Decreased level of international transport. These imply fewer cars and other vehicles, thus less embodied materials.
Individual mobility changes	Reduced overall transport demand and shift towards non-motorized transport impacts automobile production.	Concerns about hygiene and distancing, individual transport modes are preferred, increasing car demand, and thus relevant raw material demand.	Improved operational and business efficiency solutions due to decrease in communing as a result of increased teleworking and online services and administrations. Decreased level of international transport. These imply fewer cars and other vehicles, thus less embodied materials.
Construction and renovation changes	The *smart use* scenario does not imply changes in the building stock and construction rates. The rate of small renovations increase, but the impact is insignificant.	The *self-reliance* scenario does not imply changes in a medium term, though distancing may mean a need for more residential floorspace. On this time horizon, the two subsectors compensate each other.	Although there is an increased demand for residential floorspace due to the increased time spent at home, the idle floorspace in the non-residential sector is reduced, but shrinking offices and shops. These can be repurposed, which implies renovations in the Global North and constructions in the Global South.

3.4.2. Outcome of medium-term recovery

The drivers and levers discussed above lead to the persistent restructuring of some industries. Therefore, the combined impact of GDP changes and structural changes in demand in the energy system result alternative post-pandemic recovery pathways. We calculate the energy demand changes from the qualitative changes in each scenario using the following formalization:

$$UE_{COV_{n,s,f,t}} = EI_{SSP2_{n,t}} \times GDP_{COV_{n,t}} \times \sum_{m,t} \frac{UE_{2019,n,f} \times \left[F_{m,n,f} \times S_{m,n,f} \cdot \left(1 + \Delta_{COV_{m,n,s,f}}\right)\right]}{UE_{2019,n,f}} \quad \forall n, \forall s \qquad (3.2)$$

Where:

- n: index for nodes (regions);
- m: sub-sectors (steel, cement, petrochemical, etc.) ;
- t: in a given year t during the post-COVID period (2021-2025) ;
- s, f: index for *Scenarios* and *Fuel types (electricity vs. thermal)*, respectively
- S: share of industrial subsector activity, i.e. relative commodity production in 2019;
- F_m: fuel ratio (electricity, thermal) for the production of the given material *m*
- UE_{COV}: industry useful energy $[GWa/yr]$
- EI_{SSP2}: energy intensity in time *t* in SSP2 $\left[\frac{GWa}{billion\ USD_{2005}}\right]$
- $GDP_{COVn,t}$: GDP at Market Exchange Rates in year t during the post-COVID period $[bnUSD_{2005}/yr]$
- Δ_{COV}: structural and behavioral impact from COVID-19 pandemic [%]

Although the *smart use* scenario is described by the GDP shock (as estimated by the macro-economic analysis – see Supplementary Note 6) there is a large set of bottom-up events that influence or in effect create the economic recession impact on industry, which are reflected in the and *self-reliance and* a climate-centered restructuring and contraction of certain industries in the *green push* scenario. Key trends were reviewed above in Supplementary Note 3.2.1.

Supplementary Table 26. Global North activity (million metric tons production) change from 2019 to 2025 for the five industry subsectors.

Industry subsector	smart use	green push	self-reliance
Iron and steel	0%	-10%	8%
Aluminum	0%	-10%	2%
Cement	0%	-5%	5%
Pulp and paper	0%	-10%	2%
Chemical and petrochemical	0%	-3%	3%

Supplementary Table 27. Global South activity (million metric tons production) change from 2019 to 2025 for the five industry subsectors.

Industry subsector	smart use	green push	self-reliance
Iron and steel	0%	-2%	-4%
Aluminum	0%	0%	2%
Cement	0%	-3%	5%
Pulp and paper	0%	-10%	2%
Chemical and petrochemical	0%	-5%	3%

3.4.3. Feedstocks

We applied a simplified approach for the projections on non-combusted use of fuels, i.e. feedstocks for petrochemicals, bitumen and fertilizers. From a supply perspective, the share of feedstocks is small (around 5% in 2018[98]), and its share will depend largely on the expansion of recycling, which is not clearly influenced by the lifestyle and business changes due to the pandemic in our assumptions.

Thus, the impact of the pandemic on feedstocks is assumed to be driven by the GDP changes during the 2020 shock and the post-pandemic recovery scenarios.

4 Supplementary Note 4. The buildings end-use sector

4.1 Data collection for the base year and for 2020 demand shock

We carry out the core of the bottom-up analysis for the buildings sector at two-region granularity: Global North and Global South (see Supplementary Note 1), with information coming from regionally heterogeneous sources. For certain indicators (digitalisation, teleworking, home schooling), less developed regions and the emerging countries (in particular China and India) in the Global South are differentiated. These regions differ in the set of pandemic response measures, the recovery plans, the building stock characteristics, and the level of resilience in terms of absorbing lifestyle change shocks and taking up new models on a longer-term, which sets them a different recovery pathway.

The starting point for our Activity-Structure-Intensity (ASI) assessment of changes in the pandemic year 2020 is the 2020 base-year data of the Low Energy Demand (LED) scenario[59], for which activity (total floorspace, m^2), energy intensity (final energy per m^2) and per capita intensity (final energy per cap) are interpolated to 2019 (shown in Supplementary Table 28).

Supplementary Table 28. Decomposition of drivers of thermal (upper part of the table) and electric (lower part of the table) energy demand in the LED scenario in 2020[66].

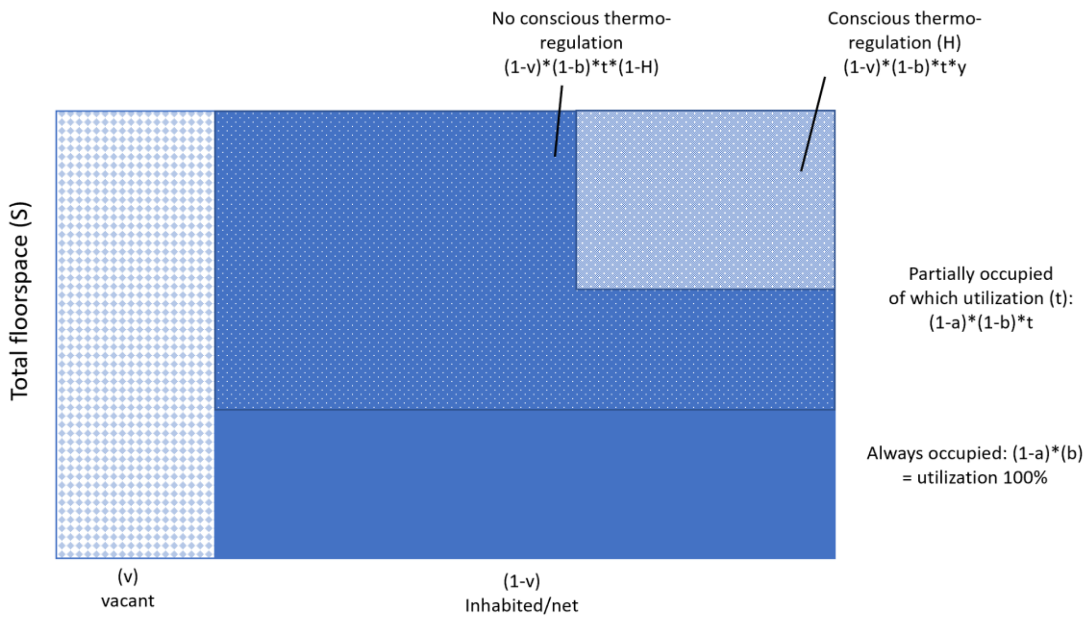
Thermal energy demand		drivers			energy demand			
		popu-lation	floor-space	floorspace/capita	useful energy demand	final energy demand	total useful energy demand	total final energy demand
		billion	*billion m^2*	*m^2/capita*	*MJ/m^2*	*MJ/m^2*	*EJ/yr*	*EJ/yr*
Residential buildings	Global North	1.5	44	30	634	673	28	30
	Global South	6.2	134	22	120	294	16	39
Non-residential buildings	Global North	1.5	24	16	538	571	13	13
	Global South	6.2	39	6	180	443	7	17
Electric energy demand		**drivers**			**energy demand**			
		popu-lation	units	units/capita	useful energy demand	final energy demand	total useful energy demand	total final energy demand
		billion	*billion*		*MJ/unit*	*MJ/unit*	*EJ/yr*	*EJ/yr*
All buildings	Global North	1,5	38	25	365	468	14	18
	Global South	6,2	67	11	142	272	10	18

Note: Global totals may not add up to the sum of regional values due to independent rounding.

4.1.1 *Formulation of the COVID-19 direct shock in 2020*

However, for the measure of activity in the current study, we diverge from the traditional use of total floorspace, because it does not accurately capture the short-term impact of changed occupancy and utilization, as was also highlighted by others[99]. Instead, we work more directly on utilization levels of living and non-residential space to better capture energy demand changes. We estimate the baseline of the use factor of total floorspace in the residential and the non-residential buildings sectors, which we call floorspace-degree-days (m^2DD). The COVID-19 pandemic has had little immediate and short-term impact on total floorspace, i.e. people are not moving to larger homes, or from the rural areas to cities in large. Significant differences are observed in people staying at home, with more homes being used for longer times, and non-residential buildings have become more empty or even abandoned or repurposed. To assess the change of these factors, we start from the utilization rate of buildings before the pandemic.

Supplementary Figure 9 depicts the factors that we evaluate in determining the changes in the use of building floorspaces, and explained in Equation 4.1. below.



Supplementary Figure 9. Factors of the utilization level of the total floorspace.

$$S.DD_n^T = S_n^T(1 - v)(1 - (1 - b) \times t \times H) \quad (4.1)$$

Where:

- *S.DD:* utilized thermo-regulated floorspace, i.e., used floorspace multiplied by its amount of heating and/or cooling;
- *n:* index for nodes (regions);

- T: year;
- S: traditionally used activity: total floorspace;
- v: vacancy ratio in the total floorspace;
- b: ratio of floorspace, which is used by somebody or it is thermo-regulated despite of vacancy 24/7 (including idle use due to e.g. expectation of possible office use);
- t: hours per day spent at home
- H: ratio of households that habitually adjust temperature when they leave home

Based on the above, inhabited space is expressed as $S \cdot (1 - v)$, utilized "space.time" is $S \cdot (1 - v) \cdot b + S \cdot (1 - v) \cdot (1 - b) \cdot t$. From this occupied and utilized space definition we can derive the size of thermo-regulated (heated and cooled) areas. Note that we do not use heating/cooling degree days to determine the actual heating/cooling demand, but to indicate the ratio of floorspace in residential and in non-residential buildings that are thermo-regulated for a certain (locally relevant) period of the year. This allows us to determine the relative change in the pandemic.

4.1.2 *Outcome of the demand shock analysis in 2020*

The level of inhabitancy and its change are determined using vacancy studies. For residential buildings, we calculate with an average of 20% and 5% of vacancy, in the Global North and the Global South respectively (Supplementary Table 29). The EU reports rates ranging from 2.5% in Poland to 35.3% in Greece[100] in line with other sources[101] and US data (12%) (OECD[102]), (for a review see Huuhka[103]). OECD[102] and Statista also report vacancy rates in the Global North, where Brazil, Colombia and Costa Rica show between 5-8% vacancy rates.

For non-residential buildings, we estimate vacancy rates at 8% and 12% of the total non-residential floorspace for Global North and Global South respectively, based on

Statista's worldwide survey of selected cities[104]. Vacancies result from uninhabited dwelling, e.g. in unpopular rural areas, second homes, relocation, lack of tenants.

Of the inhabited floorspace, 40% of the homes are occupied practically all the time in the Global North, mainly inhabited by elderly (ca. 20% of the population being above 65 years old in the OECD)[105], and by families with very small children or people working from home, estimated to be another 20%[106] of the households in the Global North. Utilization rates are estimated to be 50% for households that leave their homes. In a similar logic, 70% of the Global South homes are occupied by the residents 7/24, based on UN data[107].

To determine the same factors for non-residential buildings, we have assumed that hospitals, social housing units, elderly homes, student dormitories, emergency services hotels and restaurants are used 7/24. Based on buildings typology[108] 25% of the tertiary building space fall in these categories in Europe, which is used as a reference for Global North, and about 20% in the Global South. The utilization rate of non-constantly open buildings is high (70%, 50% in the Global North and South respectively).

The last factor is the ratio the part of the building space that is consciously (manually or with intelligent systems) thermo-regulated[109] in the function of time[110].

Supplementary Table 29. Non-pandemic baseline values of the components of our floorspace.degree-days calculation which is subsequently used for determining the impact of the pandemic on residential and commercial energy demand, for the Global North and the Global South.

subsector	region	**total floorspace (billion m2)**	**vacancy rate (v)**	**Ratio of full occupancy floorspace (b)**	**utilization rate of non-constantly occupied space (t)**
residential	Global North	44	20%	40%	50%
	Global South	134	5%	70%	30%
non-residential	Global North	24	8%	25%	70%
	Global South	39	12%	20%	50%

The aforementioned factors used to determine the floorspace-degree-days are summarized in Supplementary Table 29, with the resulting floorspace-degree-days and energy variables in Supplementary Table 30.

Supplementary Table 30. Floorspace-degree-days variables and energy variables in the two buildings subsectors for the Global North and the Global South.

subsector	region	utilized floorspace. time	m2.DD	final energy (EJ)	final energy/capita (kWh)	final energy/m2 (kWh)
residential	Global North	25	29	30	6	188
	Global South	101	114	39	2	81
non-residential	Global North	17	18	13	3	156
	Global South	21	23	17	1	122

4.2.1. Outcome from the 2020 analysis

The drivers: We assumed three dimensions of impacts based on the factors that determine the variable floorspace-degree-days: (1) change in total space due to repurposing as a secondary effect, (2) change in the occupancy and utilization factors of floorspace respectively in the two sub-sectors, and (3) the energy intensity of space demand in terms of thermal and electric energy demand, as a result of using the space differently.

(1) As a result of the pandemic, no change in the total floorspace is evident. While a suburban drift has been systematically recorded, because service and city workers, students, tourists and visitors have voided city centers, moving outside at least temporarily, and businesses, services, factories have shut down for shorter or longer periods, the overall direct impact on the rate of construction or demolition is largely uncertain and influenced by many forces. Although construction projects have halted (see in Supplementary Note 3.1.3.), these were mainly infrastructure projects, and with limited impact on the overall buildings sector. Repurposing of floorspace, especially in

the retail sector changing from offline to online services, is reflected in our utilization rate factors, and not in the total floorspace.

We assume the pandemic has not led to significant technological efficiency change in this sector. The intensity is assumed to be unchanged in terms of final energy/floorspace.degree-days, which in turn does result in a 4% increase of intensity of total floorspace at global level (5% in the Global North and 1% in the Global South).

(2) The overall occupancy rate of residential floorspace increases around the globe, as well as the utilization rate (i.e. the share of time spent at home by residents that leave their homes regularly). In the homes, appliances are also used more and more often, with a lot of new appliances (ICT equipment, cooking and gardening equipment). At the same time, the thermal comforting of non-residential spaces does not decrease proportionately to the reduction of occupancy reduction, and thus to a level that would compensate the increase in the residential sector. Several studies have shown that buildings and facilities with low utilization rates during 2020 continued to consume energy close to pre-pandemic levels, and in average an energy load reduction of 20-30% is not in parse with the occupancy reduction of around 80%[111]. There are various factors that limited energy savings during low-occupancy periods. Offices are kept on heating/cooling, although used by employees, who may stay at home or visit the workplace only occasionally, the schools offer emergency care, and thus only a small portion can decrease the thermal control. This may also happen because of contractual facility management arrangements that set fix office hour requirements. It was shown that about 30-50% of the load in schools and universities may be consumed by idle use. Additionally, employees working from home have been using remote services, office computers, servers and other loads[111,112]. This means that while teleworking reduces transport activity levels due to reduced commuting [19,44], the impacts are rather the

opposite in the level of use of buildings. People working and studying from home have a larger floorarea footprint and demand more energy per capita, when considering both their homes and the still running workplaces, without policies or measures to counteract these.

It is important to recognize that for many teleworking is not an option. An IEA analysis based on work from the International Labour Organization (ILO) found a strong correlation between GDP per capita levels and the teleworking potential at national scale with differentiated energy implications[47,48], which we take into account in our analysis both for buildings and transport. Evidence from Brazil shows both the large differences between the Global South, and the regional and sectoral differences within countries[113].

In the EU about 37% could work from home during lockdowns[45], that is 50% of the employed population[114], while in Japan, where the government did initially not enforce a widespread lockdown, the share was only around 10%[115].

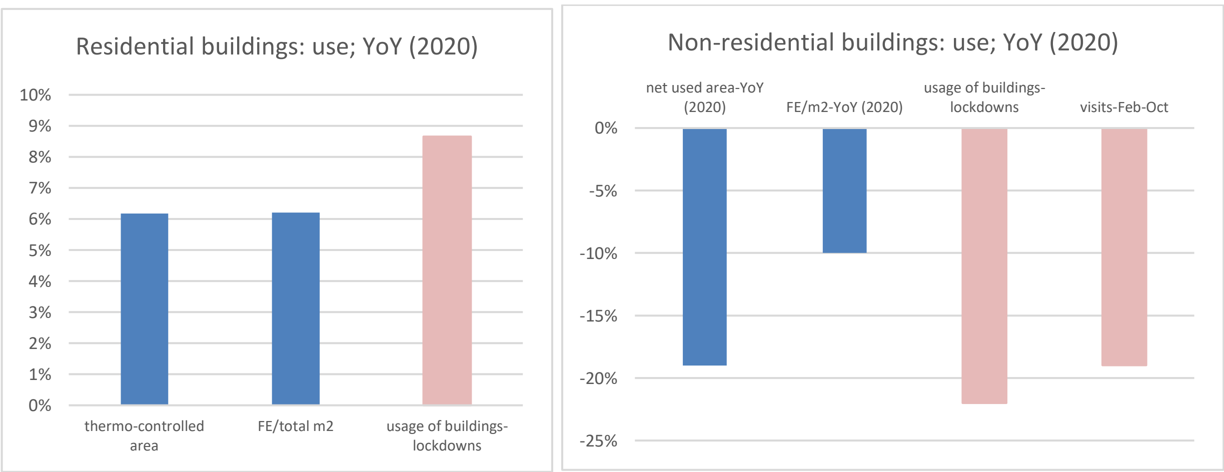
Possibilities to work in different places correlates with socio-economic status in the country[116]. In particular in developing countries lockdown measures have not had the same effect on increasing working from home since more people work in informal sectors and other jobs that do not allow for remote online working, and infrastructures to facilitate remote working are often not available .

Bulb Energy and other electricity providers reported a profile shift, whereas 21% less electricity was consumed at 7:30 in the mornings in the UK than before the pandemic, while about 30% increase at midday[117]. Energy demand boomed for ICT services. For example, Akamai's web traffic monitor showed 50% more web traffic than average during lockdowns[118,119].

Online shopping, entertainment and socializing increased by around 50%. Over half (52%) of US and UK consumers turned to online shopping as a result of COVID-19[120]. Similar results were shown for 70% of consumers in South Korea, 67% in Brazil, Spain (42%), Germany (41%), Russia (39%), and France (36%).

Impact: In 2020, the impact on the total levels of activity (floorspace) is assumed to be zero, and calculated to be +2% of floorspace.degree-days at a global level using the equation 4.1. On the other hand, region and country-specific stringency of pandemic containment measures critically transformed the way space is used. A larger impact is observed in the Global North due to the dominance of hard lockdown combined with incentives to stay-at-home, while typically less comprehensive and curfew-based measures in the Global South[121].

Assuming no technological efficiency improvement during 2020, we estimate the final energy of the total building stock to grow by 6% in the Global North, and 2% in the Global South (*Supplementary Table 31*). In comparison to literature, we find that the IEA[47] estimated similar impacts in 2020, with the difference of considering a shorter and more affected period (until October 2020) (***Error! Reference source not found.***).



Supplementary Figure 10. Comparison of bottom-up estimated data of year-on-year impact of the pandemic in 2020 in the use of residential (panel a) and non-residential (panel b) buildings calculated by this study (blue) and by IEA (pink)[47].

We calculated the change in utilization of floorspace (i.e. our measure of floorspace.degree-days) as a 6% growth of residential floorspace utilization, coupled with a 10% drop of non-residential floorspace utilization. Using these data, the energy intensity increased by 4% globally, corresponding to +6% in the residential sector and a decrease by 1% in the non-residential sector.

Supplementary Table 31. Change of activity and energy demand indicators in the buildings sector from 2019 to 2020. YoY is year on year.

		YoY Δ total floorspace	YoY Δ utilized floorspace	YoY Δ m2.dd floorspace	Δ FE (EJ)	Δ FE/floorspace (MJ/m2)
residential	Global North	0%	15,4%	7,9%	8,3%	7,9%
	Global South	0%	13,0%	5,7%	6,9%	5,7%
non-residential	Global North	0%	-14,4%	-11,4%	0,0%	-0,4%
	Global South	0%	-13,5%	-9,6%	-8,5%	-9,6%

4.3 Recovery elements (drivers) considered in the analysis for the buildings sector

We assessed the persistence of energy-related demand factors in the buildings sector, separately for thermal and electric demand. We start from the SSP2-based per capita activity trends in the medium (till 2025) term (based on ref. [66]), which are influenced by the persistence of the activity and intensity changes tested and experienced during the pandemic.

We considered three elements of thermal energy demand changes. First, the change in the intensity of residential floorspace utilization due to increased use of the homes, more teleworking, adoption of hybrid or digital solutions. For example, Global Workplace Analytics projects that up to 30% of workers could still be teleworking multiple days per week by 2022[46]. In combination with this, the intensity of non-residential floorspace utilization changes, due to the transfer of previously face-to-face and externally located solutions to the online space (i.e. to home), including administration, banking, retail and shopping, leisure, even health services, amount and place of travel and holidays. Finally, a longer term change can be the extension or contraction of total floorspace. The last factor (change in total floorspace compared to baseline values) only features in the *green push* scenario.

Residential electricity demand is affected by a change in the penetration and use of ICT equipment for work, school, leisure and services. There is also a penetration impact on new small appliances (depending on the scenario – see below) because of changes in cooking habits (eating at home as opposed to eating out), home activities (sports, repairs and gardening), and large appliances (e.g. due to stocking of frozen food). Because of changing home activities, the use intensity of the existing appliances also mirrors the changes in the lifestyles and businesses (Supplementary Table 32).

Supplementary Table 32. Activity and energy intensity related factors that drive energy demand changes in residential and non-residential buildings.

	Residential	Non-residential
Thermal energy	Intensity of presence at home: teleworking, unemployment, digital service use, online entertainment and administration solutions, online shopping.	Need for presence in offices, customer services, shopping and entertainment services, administration share in online and offline solutions. Retail change between frontal to back-end business models, latter based on delivery services.
Electrical energy related drivers	Intensity of use and penetration of small appliances for cooking, sports, repairs, and gardening, and large appliances e.g. for stocking and preservation. Penetration and use of ICT and related equipment	Use of small ICT for services further extends, besides banking, entertainment, also schooling, informing, awareness. Penetration and use of ICT and related equipment.

4.3.1. Mapping the different narratives

The recovery elements for the buildings sector are summarized in the table below along the drivers identified in the previous section. For the three scenarios *smart use*, *self-reliance* and *green push*, we assess the possible combinations of plausible ranges of these factors that fit well with the general narrative of each scenario.

Remote work: Clearly, the most obvious and ubiquitous change related to the use of buildings during the lockdowns, as well as during the follow-up periods has been the uptake of teleworking solutions. The learning from teleworking during the pandemic is expected to roll-out more work from home strategies in companies, mostly in the Global North, but for some socio-economic groups and certain professions also in the Global South. A number of governments have been giving out financial support for companies to enable dealing with the challenges of business closures, reducing office space use, etc. Dingel and Neiman[122] estimated the potential share of teleworking in different occupations, and suggested an average potential of 34% of US jobs. Similar estimates are collected by ILO[48].

In case of Argentina, teleworking potential lies between 26% and 29% of jobs, and between 20-34% for Uruguay[48], however the potential is insignificant for the African countries in average[123].

These potentials assume a high roll-out of teleworking in occupations for jobs that can be done remotely. We take a more conservative assumption for the average potentials in the *smart use* scenario for both global regions, with 16% and 2% in the Global North and Global South, respectively. This assumes that even jobs that can operate remotely, not all employees will prefer working from home due to family considerations, socializing, access to equipment and internet, etc. and thus will still go to the office, or job location. Furthermore, we also assume that on average no full-time remote working is rolled-out, but employees spend 50% of their working time at home and 50% in the job[124]. These organizational details imply that the floorspace demand is not reduced in the workplaces.

In summary, in the Global North, in the *green push* scenario, employees and employers are incentivized by rolling-out of home office solutions, supporting businesses to apply online and hybrid working solutions, support for online retail and administration (Supplementary Table 33). This can lead to a higher uptake of teleworking potential, through which there is an increase in electricity and thermal demand in the residential sector.

Supplementary Table 33. Assessed teleworking potential levels, related to two COVID shock-and-recovery narratives, based on the analysis in the text.

	Current potential (as in S*mart Use*)	Expanded potential (as in *Green Push*)
Global North	16%	30%
Global South	6%	10%

Digitalization: increased use of online services has been a megatrend across the globe for the last decades, and the pandemic has accelerated the trend. Sale of digital electronics was one of the fastest growing at the start of the pandemic. Certain product sales have temporarily increased by up to 1000% (printer consumables in France), to over +500% (webcams in the US), over 300% (printers, copy machines and fax machines in the EU), to +350% (monitors and modems), over +200 (educational software) in the US compared to the first four weeks of the year[120]. Similar trends have been reported from China and South Korea. Together, this constituted significant digital infrastructure development away from the baseline trend, which we have thus considered as a persistence change in our scenarios.

According to the International Telecommunication Union, differences in digitalization potentials vary greatly across regions of the Global South. We differentiate two subregions here: low and middle income countries and emerging economies (primarily China). This wide range is described by e.g. access to the internet ranging from under 10% in Eritrea, Congo, Nigeria, Chad, and Somalia to over 95%, for example, in Saudi Arabia, United Arab Emirates. In Panamá, which is considered to be the median country, only 58% of the public have access to internet. This suggests that rolling-out digital solutions just based on the experiences and practices during the pandemic is not straightforward.

Localization: Exploration of the local natural and touristic destinations has been a popular alternative to long-distance travels and holidays. This type of holidays requires less non-residential floorspace due to day-trips and the use of – anyway existent – secondary homes. In the Global North, in *self-reliance* and *smart use*, people's behaviour and decisions are assumed to be not changed by the experiences of the pandemic, therefore activity in this respect is not assumed to be changed. People are looking forward to taking up holidays missed, with only little indication for shifted preferences toward low-carbon holidays on the medium-term[125]. In the Global South, similar trends exist, and thus our assumptions are mapped in the same way (see e.g. Bhaduri et al.[126] for India).

Health considerations: public spaces, including work places, entertainment and administration are expected to increase the floorspace per capita utilization. In case of the *smart use* scenario, a continuation of the current situation is expected, i.e. floorspace.degree-days are expected to be similar to those in 2020. In *self-reliance*, people are assumed to require more space both at home, so that they can work and stay more at home, as well as at work, at leisure activities, and while using services. This requires a reduction of crowdedness, thus either longer utilization times (e.g. public services, entertainment, such as theaters and movies), or larger spaces for the same amount of users.

Supplementary Table 34. Overview of key qualitative drivers for the buildings sector for the three COVID shock-and-recovery narratives across, comparing to SSP2 in the Global North.

Element	Smart Use	Self-Reliance	Green Push
Teleworking	*Small increase*: using the experiences during 2020, and tapping on the current potentials, teleworking schemes spread moderately.	*Sharp increase*: teleworking is driven by distancing and hygiene concerns.	*Sharp increase*: incentivized progress on experience, infrastructure development
Utilization rate of non-residential space	*Small increase*: due to some remaining health consideration, expectation of distancing, the space use per capita of 2020 persists, either implying larger space or longer use time (e.g. longer office hours in administration)	*Increase*: due to remaining health consideration, expectation of distancing, the space use per capita of 2020 further increases and persists, requiring larger offices and longer open hours.	*Decrease:* health considerations are solved differently, and a rational use of space is implemented at least to the level or pre-pandemic.
Idle space	*Increase*: due to duplication of working space (at home and in the office) due to delayed organizational adjustments, coupled with decreases in retail and service space.	*Increase*: due to duplication of working space (at home and in the office) due to hygiene and distancing concerned also linked with avoiding transportation, coupled with decreases in retail and service space	*Reduced*: the increase in remote working is coupled with organizational and infrastructural restructuring, thus removing vacant space.
Digital / offline ratio	*Increase*: learning by customers and providers allow for extending online solutions in many aspects of life. Due to the digital divide and lack of proper and quality infrastructure, the change is slow.	*Increase*: digital divide is widening, with higher income societies merging more into online solutions, while others lagging behind.	*Sharp increase*: learning by customers and providers allow for extending online solutions in many aspects of life.
Localization, tourism	*Limited change:* the rediscovery experience during lockdowns is overridden by aspirations to return to normal.	*Limited change:* the rediscovery experience during lockdowns is overridden by aspirations to return to normal.	*Reduce:* Local values increase by enhancing the experiences during the pandemic by incentivizing.

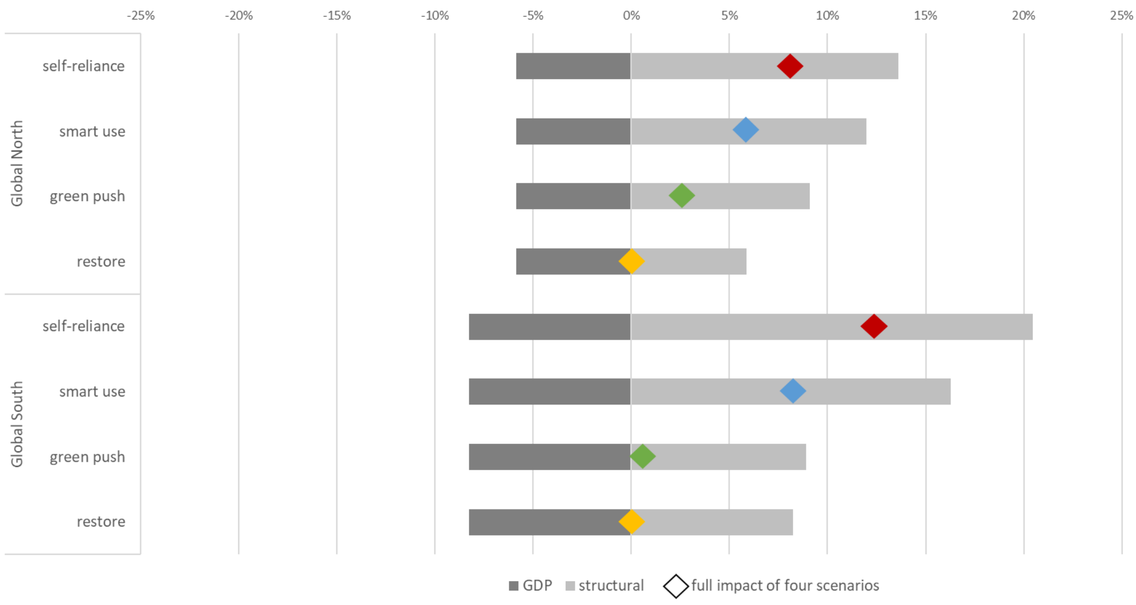
Supplementary Table 35. Overview of key qualitative drivers for the buildings sector for the three COVID shock-and-recovery narratives across, comparing to to SSP2 in the Global South.

Element	Smart Use	Self-Reliance	Green Push
Teleworking	*Limited change*: potentials are very low in most countries.	*Small increase*: teleworking potentials are too low to be impactful, yet there is limited uptake.	*Small increase*: incentivized progress to tap on the potential, but impact is limited.
Utilization rate of non-residential space	*Small increase*: due to health consideration, expectation of distancing, the space use per capita grows in public spaces.	*Increase*: due to remaining health consideration, expectation of distancing, the space use per capita of 2020 further increases and persists, requiring larger offices and longer open hours.	*Decrease*: health considerations are solved differently, and a rational use of space is implemented at least to the level or pre-pandemic.
Idle space	*Small increase*: Pandemic measures vary greatly from hard lockdown to curfew, which is directly linked to the amount of idle space. Dominance of informal jobs related to limited stay-at-home.	*Limited change*: Pandemic measures vary greatly from hard lockdown to curfew. Hygiene considerations emphasize extended distancing and using more space per capita, thus reducing vacant and idle space.	*No change*: Social system (built on a lot of informal jobs) limit the impact of optimizing space. Digital services continue to play a role on previous trends (minor inducement by the pandemic experience).
Digital / offline ratio	*Increase*: previous trends in towards dematerialization are up-taken, but not everywhere, as the digital divide is large: reducing time spent offline, and thus outside.	*Increase*: previous trends in towards dematerialization are up-taken, but not everywhere, as the digital divide is large: reducing time spent offline, and thus outside. Seen as solution for physical distancing.	*Increase*: The previous trends in the Global South towards leap-frogging in digitalization are enhanced with further increasing experiences. Efforts to take on the digital opportunity roll-into new services e.g. schooling, socializing, etc.
Localization, tourism	*No change:* largely a supply-side impact, i.e. visits from tourists restart, touristic places are reopened and turn back to normal.	*Limited increase:* in correlation with idle space reduction, largely a supply-side impact, i.e. visits from tourists restart, touristic places are reopened and require small increase in per capita space for distancing.	*Reduce:* Local values increase by enhancing the experiences during the pandemic by incentivizing.

The tables above summarize the directions and qualitative size of change in key drivers after 2020, as a result of persistence of the behavior, lifestyle, institutional and business model changes. These translate to a differentiated change in the Global North (+8% floorspace in 2025 compared to 2019), and in the Global South (+5% floorspace in 2025 compared to 2019) in the *self-reliance* scenario, +7% and +4% respectively in the *smart use* scenario. For the *green push* scenario we assume a full compensation of the growth in the residential sector with incentives for increased use efficiency.

4.3.2. Quantification

The impacts of the different demand-related drivers described above were combined to structural impacts. Per capita energy trends were mapped onto the energy structure values in order to create pathways until 2025 for the two global regions (Global North and Global South) for thermal and electric demand. The total useful energy demand was used a proxy to estimate the total energy demand for the whole buildings sector (Supplementary Figure 11). The combination of the impact from structural change and the economic shock were calculated to a full impact on the buildings sector energy demand change in 2025 compared to 2019.



Supplementary Figure 11. Change in total useful energy demand in the buildings sector in the four scenarios from 2019 to 2025 in the two global regions: Global North and Global South. The rate of impact of the economic shock and the demand change, i.e. structural changes are indicated as grey bars, and their combined impacts are shown as colored squares (red = self-reliance, blue = smart use, green = green push, yellow = restore).

5 Supplementary Note 5: End-use sectors comparison

Following the analysis in Supplementary Notes 2, 3 and 4, we illustratively compare the effects in the post pandemic narratives (*smart use*, *self-reliance* and *green push*) across sectors.

First, we juxtapose relative activity changes for the Global North and Global South regions across pathways and sectors for illustrative indicators in *Supplementary Figure 12*. Second, *Supplementary Figures 14 and 15* show the contributions to the energy demand changes the from both a reduced economic activity (GDP effects) and structural and behavioral changes across the three different end-use sectors.

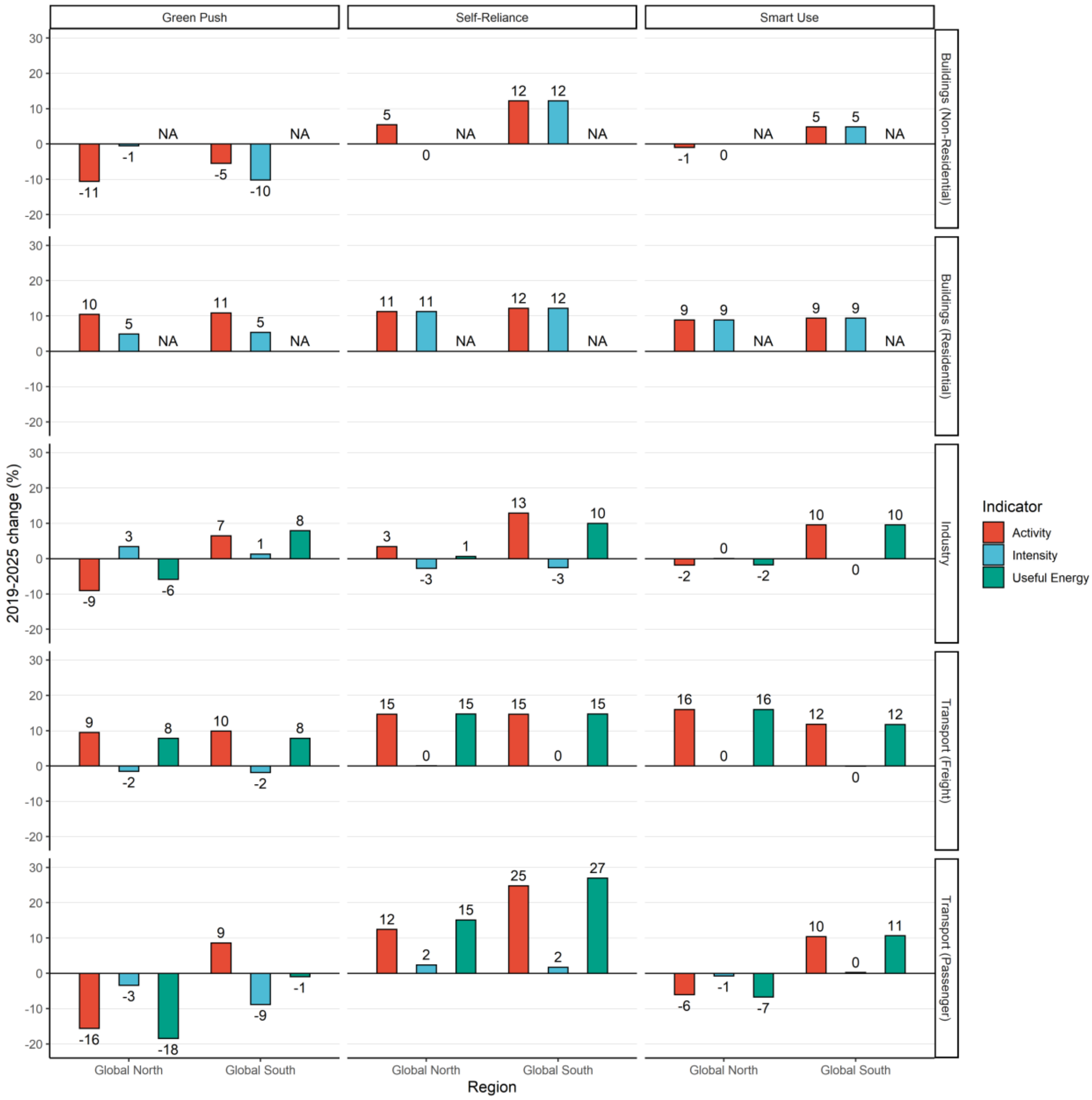
5.1 Activity changes across sectors

Supplementary Figure 12 provides information on the relative change in 2025 compared to 2019 for the indicators: activity, useful energy and energy intensity (useful energy per unit of activity). *Supplementary Figure 13* shows the resulting useful energy pathways that serve as model input.

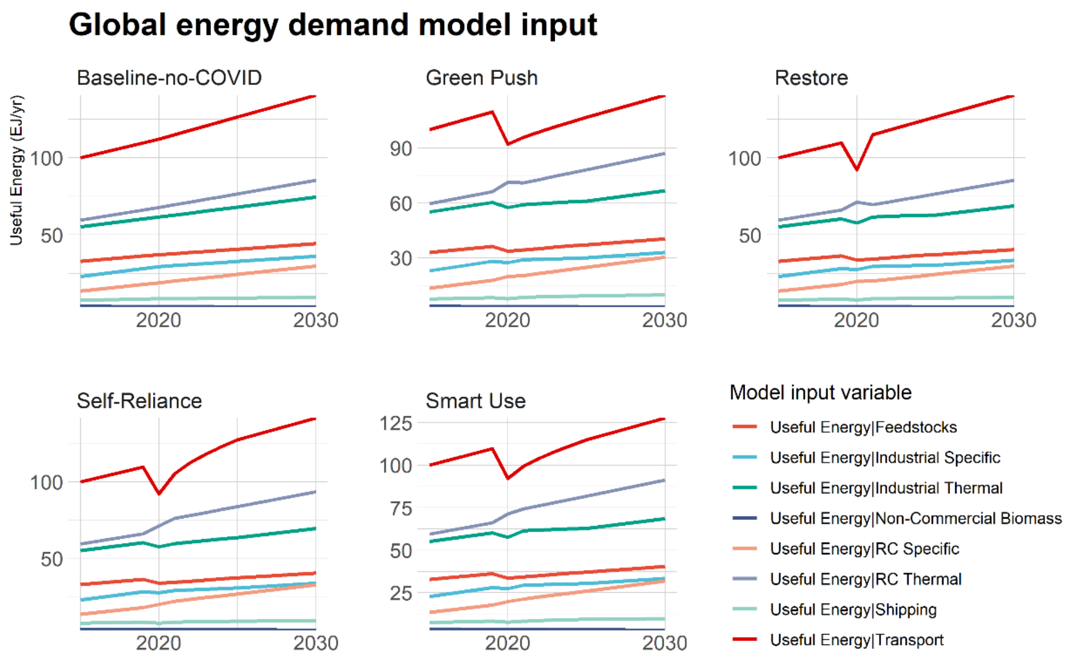
The relative intensity variations across scenarios are small for passenger mobility and negligible in the case of freight transport. This is because the bottom-up estimation of the 2025 levels of activity and structure (see Supplementary Note 2) were not including drivers or impacts from policy measures that would make the intensity per unit of activity for the individual transport modes better off than reference, across all scenarios. That is to say, neither including impacts from policies endorsing higher adoption of vehicles having better tank-to-wheel efficiencies compared to traditional ICEs (i.e. EVs or FCEVs) nor assessing the social acceptance of shared mobility (which would in turn increase the occupancy levels of vehicles, decreasing their energy intensity over passenger kilometer). However, in the case of passenger transport in *green push*, energy intensity variations are well appreciable as a consequence of the sharp restructuration of the transport subsectors, where avoided car trips and modal shift to less energy intensive mass transit are pronounced. In regards of activity, it can be seen that the relative increase (compared to 2019) in the case of self-reliance is substantial, due to the combination of the reference SSP2 growth with the structural change from the bottom-up analysis. This is more pronounced in the Global South since activity levels grow much faster in the 2019-2025 compared with high-income countries in the same period.

The industry sector's activity level is closely coupled with the economic trends persisting after the pandemic, with slight demand-driven elasticities in the *self-reliance* and the *green push* scenarios. The observed activity and useful energy changes are smaller than in the transport sector, moderating an internal growth in the SSP2 reference scenario. Activity (material output) grows most in the Global South in the *self-reliance* scenario, while in the green push scenario demonstrates that the changes experienced during the pandemic can induce a reduction. Less mobility, changes in the utilization of buildings, shortening of supply chains, motivation of the population to trust the health system again can lead to a minimal activity decrease, though only in the Global North,

The energy demand of the buildings sector grows more than other sectors. The main driver of this change is the endogenous SSP2 development between 2020 and 2025, explaining about 60-80% of the change depending on the region and subsector. Accordingly, the pandemic induced changes in activity (expressed in floorspace.degree-days here) has an energy demand that almost, but not quite compensates the savings in the transport sector. The final energy per m2 intensity indicator grows between 10% in the Global North and over 30% in the Global South driven by the change in the utilization rate of space, meaning higher energy demand both for thermal and electric fuels because of being at home more, using more appliances, heating and cooling for longer times and larger spaces, while the decrease of the same in the non-residential sector is less pronounced.



Supplementary Figure 12. Sub-sectoral, regional relative activity, intensity, and useful energy change for 2025 values compared to 2019 values, within each scenario that has structural change in its narrative. Activity units are: tonne-kilometer for freight transport, passenger-kilometer for transport-passenger, meter squared-degree days (m2.DD) for buildings, and million tonnes (Mt) production for industry. Intensity is activity per unit useful energy, except for Buildings, where the relative intensity change is calculated as activity per unit final energy for residential and non-residential, with useful energy changes only calculated as an aggregated model input.

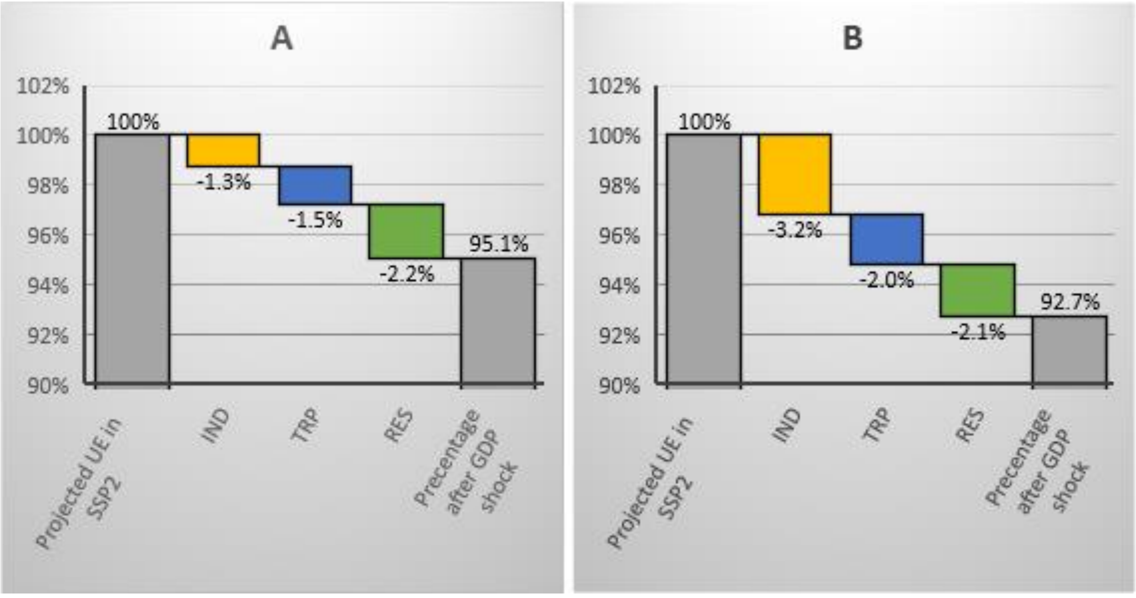


Supplementary Figure 13. Global useful energy demand for each pathway without additional climate policies, representing aggregated model input for a selected timeframe (2015-2030).

5.2 Energy use and GDP effect across sectors

This study used a set of simple elasticities for each of the end-use sectors to calculate the GDP[6] impact (Δ_{GDP}) on useful energy demand. *Supplementary Figure 14* illustrates this heuristic for an isolated GDP effect for each of the three end-use sectors. The waterfall charts A and B use SSP2 estimates in 2025 as the reference point (Index = 100%). In our analysis, the end-use sector most sensitive to the GDP shock is the buildings sector in the Global North (A, -2.16%), and the industry sector in the Global South (B, -3.15%), with the difference in industry impact coming from the regionally different GDP projections.

[6] GDP estimates were calculated using our macroeconomic impact model (see Supplementary Note 6).



Supplementary Figure 14. Impact of the main estimate of GDP changes in 2025 on useful energy demand for the three end-use sectors in the Global North (A) and Global South (B), represented as % compared to SSP2 2025 useful energy projections. IND, TRP, and RES stand for industry, transport and buildings end-use sectors, respectively.

The aggregated impact on the three subsectors lead to aggregated useful energy levels in 2025 that are 95.10% (Global North) and 92.76% (Global South) of SSP2 levels.

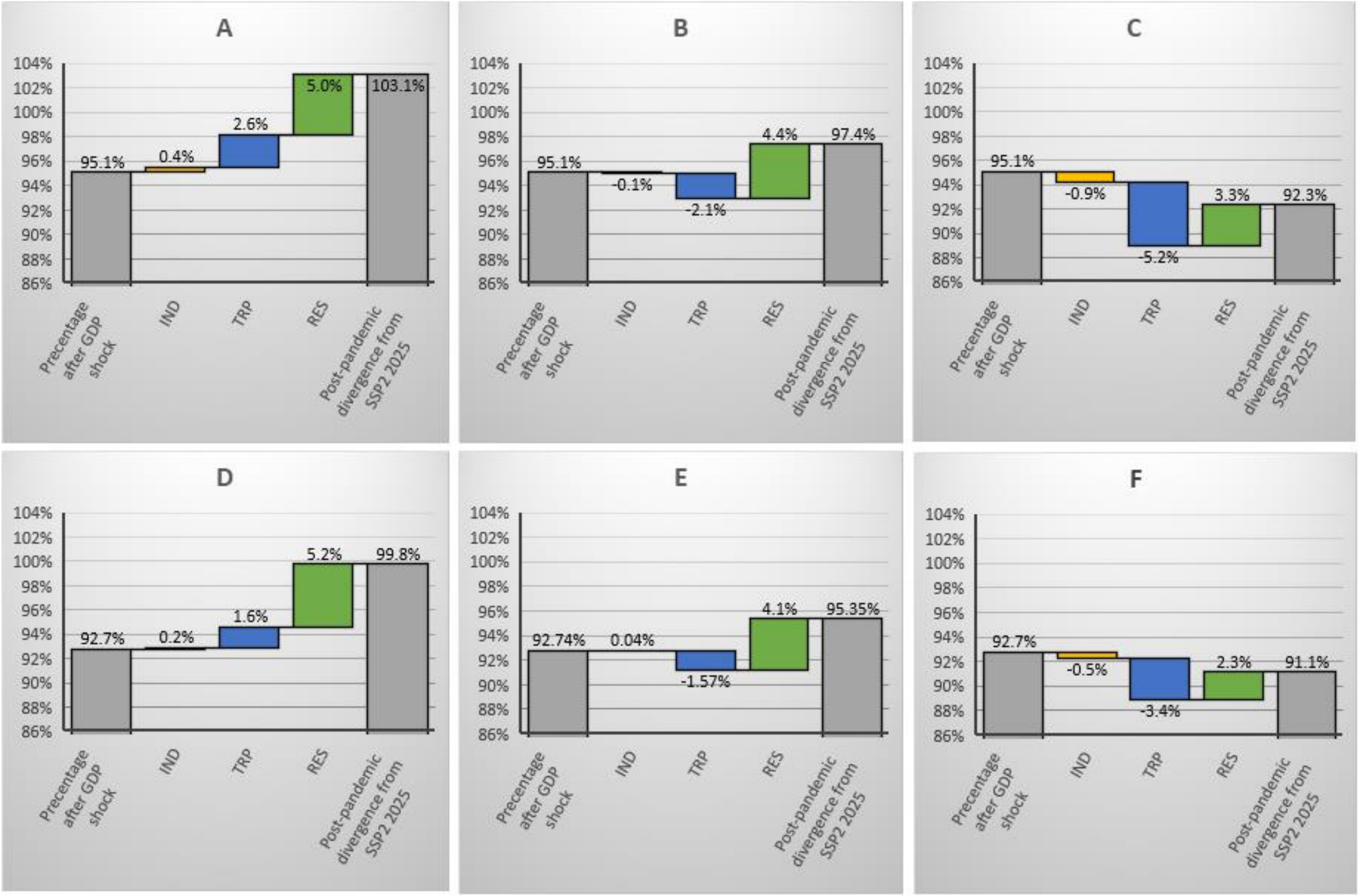
Supplementary Figure 15 uses these two values as a starting point to show the additional impact from demand-related (structural and behavioral) changes calculated as described in Supplementary Notes 2, 3, and 4, for Transport, Industry and Buildings respectively.

In *self-reliance* (A, D), the structural and behavioral changes lead to useful energy values above the SSP2 reference trajectory for the Global North region, completely offsetting the energy demand reduction impacts from the GDP shock. This means that the energy consumption per capita is higher than in the SSP2 reference scenario or in other post-pandemic scenarios in this study.

For *self-reliance* (A, D) and *smart use* (B, E), respectively, there is no aggregate impact in our scenarios for the Industry sector due to the assumption of economic activity being tied to industrial activity here (see Supplementary Note 3). In *green push* (C, F) structural changes are assumed for industry, leading to a further reduction (Supplementary Note 3).

The Residential and Commercial Buildings sector always increases useful energy levels in each of the pathways on the short and medium term due to higher residential energy use tied to more working from home not being fully compensated by reductions in office energy use (with the starkest lack of reductions in *self-reliance* (B, E) than in the other two scenarios). However, for *green push* (C, F), energy efficiency policies (including better use of office spaces) offset parts of this increase.

For Transport, the largest drop in useful energy levels is projected in *green push* (C, F), due to the higher teleworking rates (and consequent lower mobility levels) in this scenario.

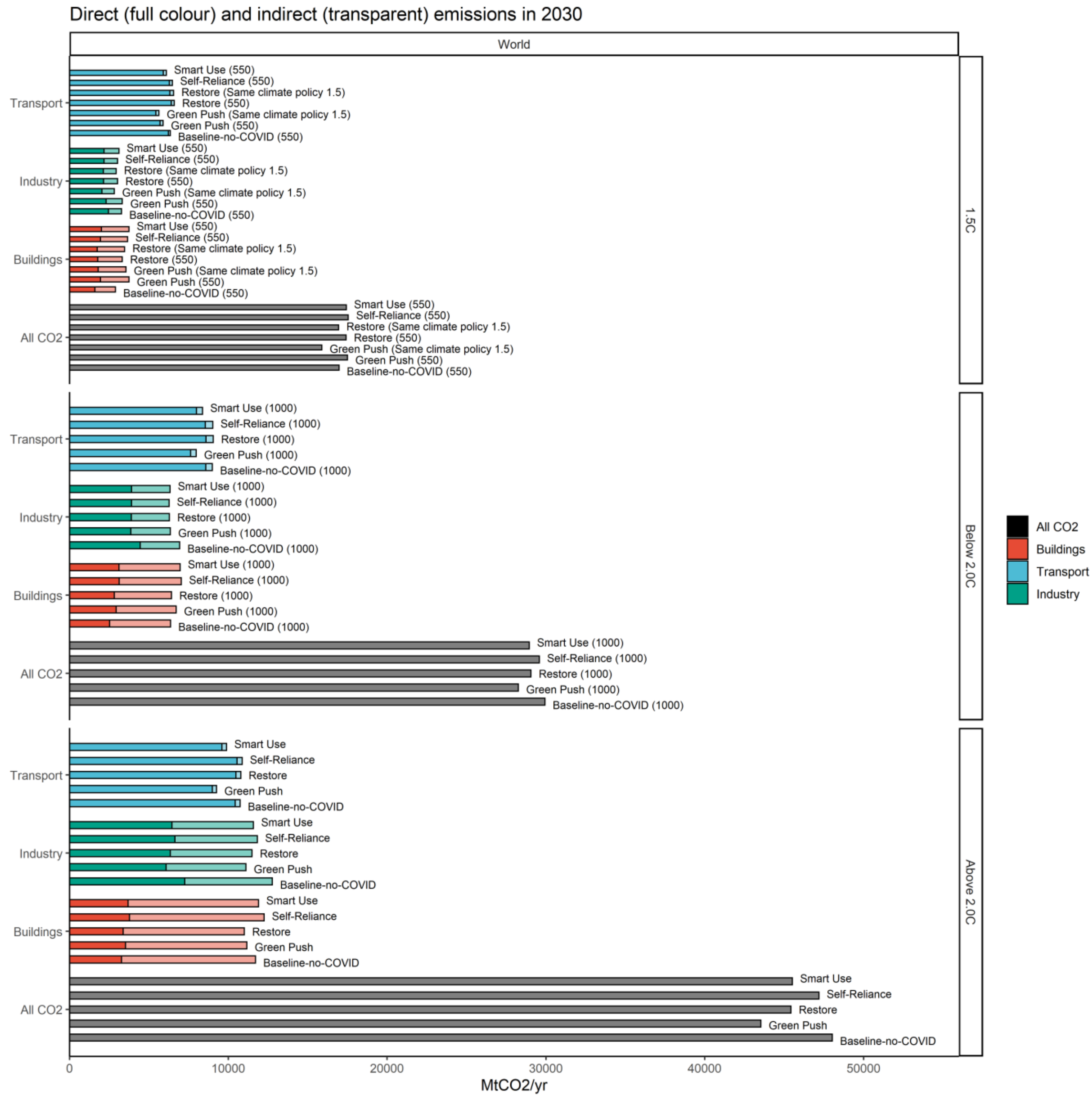


Supplementary Figure 15. Impact of behavioral/lifestyle and structural changes in the Global North (A-B-C) and Global South (D-E-F), in the *self-reliance* (A, D), *smart use* (B, E) and *green push* (C, F) scenarios. IND, TRP and RES stand for industry, transport and buildings end-use sectors, respectively.

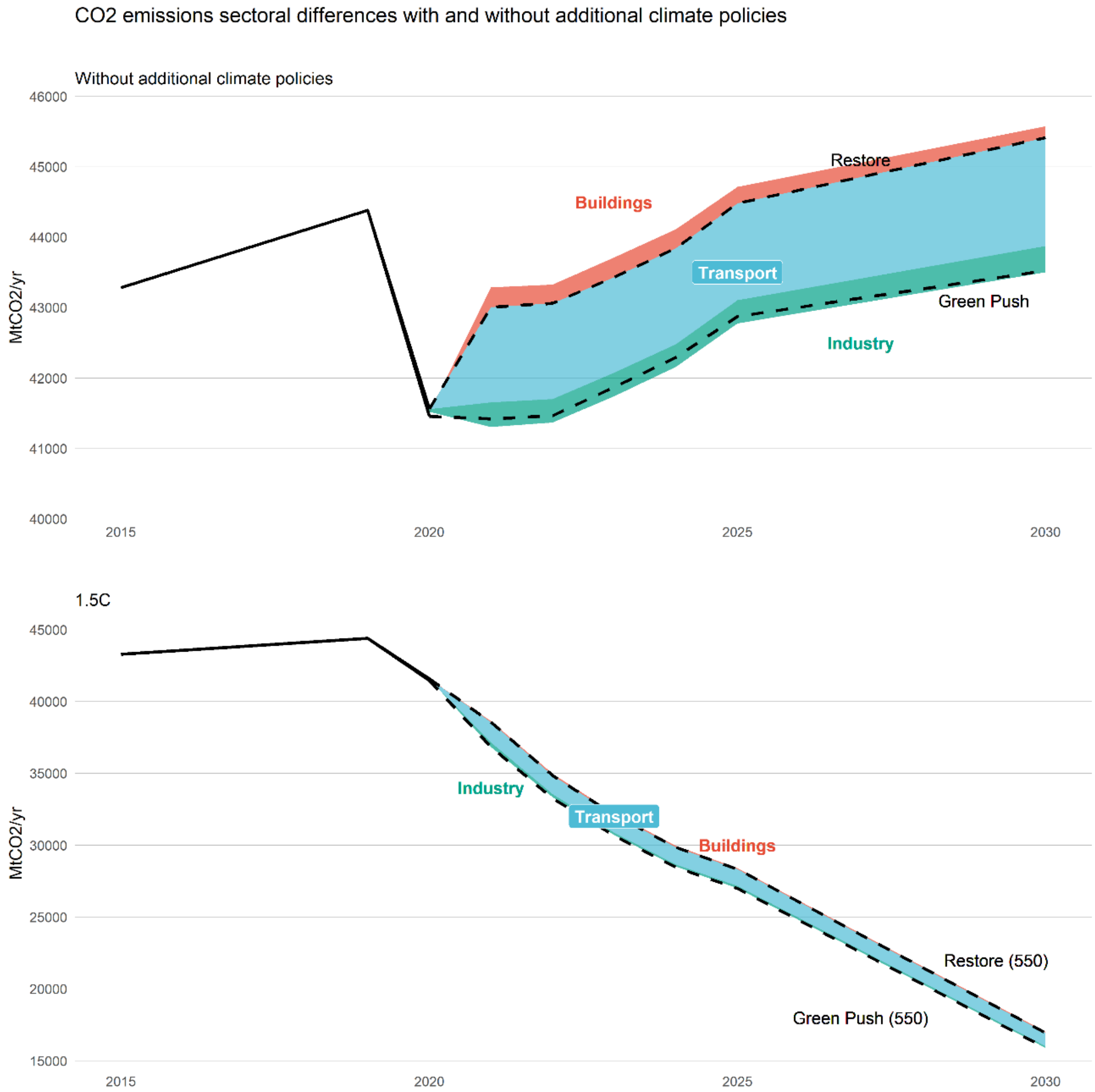
5.3 End-use sector emissions reduction including upstream emissions

Supplementary Figure 16 and *Supplementary Figure 17* compare CO2 emissions from the three end-use sectors, for the *green push* and *restore* scenarios. These include both (i) direct CO2 emissions at the end-use side, e.g., emissions from burning fossil fuels in industrial processes and in small-scale technologies in buildings, and (ii) indirect, upstream CO2 emissions of the end-use sectors. For the calculation of the latter, we derive upstream emission factors for each energy commodity, such as electricity, district heating, and fuels. For example, the emission factor of electricity delivered to the end-use sectors is estimated by dividing total CO2 emissions of the electricity sector by total electricity demand at the final level for each scenario. This emission factor (tonne CO_2 / MJ) is then multiplied by the final use of electricity (MJ) in each demand sector to determine respective supply-side related CO2 emissions of that sector.

The buildings sector sees the largest share of indirect emissions, transport the lowest (*Supplementary Figure 16*). Under a similarly stringent carbon pricing regime, the transport sector accounts for almost all the differences between the two scenarios (*Supplementary Figure 17*).



Supplementary Figure 16. Upstream indirect emissions and end-use related emissions for each pathway presented in this work for the main GDP pathway specification. Visualized results are separated by climate mitigation target and illustrate both the absolute and relative contributions of direct end-use and indirect upstream emissions by sector.



Supplementary Figure 17: Total (direct and indirect) CO2 emissions in the *restore* and *green push* scenarios. The difference between the two scenarios is highlighted with different colors for the end-use sectors: blue for transport, red for buildings and green for industry. Upper panel shows the scenario without, and the lower panel with additional climate policies, with 1.5C using 1.5C consistent fixed carbon price mitigation pathways with suffix (550) to indicate the carbon budget in GtCO2.

6. Supplementary Note 6. Macroeconomic impact model for GDP recovery pathways and sensitivity analysis

To estimate economic loss related to the COVID-19 pandemic we collect a number of GDP projections from financial public institutions, or rating agencies, we pooled them together, and updated throughout the year until October 2020. When available we collected national projection or macro-regional estimation that could be easily linked to the region delineation of the MESSAGEix-GLOBIOM model (11 macro-economic regions, see documentation[127]). For each source we aggregated with weighted averages to the MESSAGEix-GLOBIOM region scale and then we look at the distribution of the sample.

As we assume a SSP2 baseline for our projections, we need to correct these the collected GDP drop values by a correction factor in order to only represent the COVID-19 shock. The correction factor for 2020 is calculated based on the economic forecast that the World Bank published in January 2020 their latest report before the economic downturn induced by the pandemic.

The low, medium, and high shock values are based on the 10th percentile, mean, and 90th percentile of the distribution of the collection of GDP projections and reported in Supplementary Table 36.

Supplementary Table 36: GDP change projection in percentages, with GDP annual growth rate for all MESSAGEix-GLOBIOM regions in 2020 after correcting for structural differences in historical baseline GDP projections in the model and the World Bank data. Sources: IMF[128], WB[129], OECD[130].

	REGION Sources	AFR	CPA	EEU	FSU	LAM	MEA	NAM	PAO	PAS	SAS	WEU
Compared to 2019	**IMF**	-2.6	1.7	-2.8	-3.4	-7.4	-3.6	-4.5	-5.1	-3.7	-8.0	-7.2
	WB	-3.7	-0.6	-6.4	-2.8	-6.9	-5.0	-3.6	-5.3	-6.1	-6.7	-7.4
	OECD		1.8			-6		-3.7	-5.3		-9.9	-7.5
	Correction factor	2.6	2.6	-0.2	1.7	2.5	1.8	0.8	0.6	0.1	0.3	0.5
Implemented in MESSAGE	**10 perc**	-1.0	2.4	-6.3	-1.6	-4.8	-3.1	-3.5	-4.7	-5.8	-9.2	-7.0
	90 perc	-0.1	4.3	-3.4	-1.1	-3.7	-1.9	-2.8	-4.6	-3.8	-6.7	-6.7
	mean	-0.6	3.5	-4.8	-1.4	-4.3	-2.5	-3.1	-4.6	-4.8	-7.9	-6.8

In the MESSAGEix-GLOBIOM-MACRO model, a 5-year timestep model (except for 2021-2025, which is annual), the new growth rate for 2020 is calculated as a function of the underlying regional scenario growth rates (G_{ssp2}) and the 1-year regional macroeconomic shock (γ) following: $g_{new_{2020}} = \left(\left(1 + G_{ssp2}\right)^{4} * (1+\gamma)\right)^{\frac{1}{5}} - 1.$

The calculation of the persistence factor, which represents the ratio of relative long-term damages over the damages during the shock, is calculated following:

$\rho = \frac{g_{cf} - g_{21_{new}}}{g_{cf} - g_{20_{new}}}$, where $g_{cf} = \frac{\left(1+g_{20_{old}}\right)\left(1+g_{21_{old}}\right)}{1+g_{20_{new}}} - 1$. We calculate regional and global persistence parameter using the discrepancy in economic projections of the World Bank (WB, January[131] and June 2020[132]) and the International Monetary Fund (IMF, January[133] and June[134] 2020) to estimate counterfactual (old) and actual (new) growth rates for 2020 and 2021. The global estimate of the World Bank suggests a one-year persistence factor of 0.42, whereas IMF yields 0.40. For the 11-region level aggregation of the MESSAGEix-GLOBIOM-MACRO, we find a regional minimum and maximum of 0.29 (CPA) to 0.53 (MEA) using the IMF reports, and 0.37 (WEU) to 0.69 (SAS) in the World Bank reports. For the marker scenarios, we take the mean of the two values at the regional level to reflect the differences most accurately in the persistence of the macroeconomic shock in different parts of the world, with consequent feedbacks in the energy system. For the GDP uncertainty analysis, we take a more generic approach and implement a globally consistent one-year persistence factor ranging from zero to one because regional uncertainties in the persistence of macroeconomic are not available nor straightforward to obtain.

Using these persistence factors, we project GDP in 2021 using $GDP_{r,t} = GDP_{r,t-1} \cdot (1 + g_{r,t} - \rho_r \cdot \gamma_{r,t-1})$, which yields the new growth rate as a function of the underlying scenario growth rates (G_{ssp2}), the regional macroeconomic deviation in 2020 (γ), and the mean of regional growth rate projections for 2020 ($g_{new_{2020}}$):

$$g_{new_{2021}} = \left(\frac{\left(\left(1 + G_{ssp2_{2020}}\right) * \left(1 + G_{ssp2_{2021}}\right)\right)}{1 + g_{new_{2020}}} - 1 \right) - \rho \left(\left(\frac{\left(\left(1 + G_{ssp2_{2020}}\right) * \left(1 + G_{ssp2_{2021}}\right)\right)}{1 + g_{new_{2020}}} - 1 \right) - \gamma \right)$$

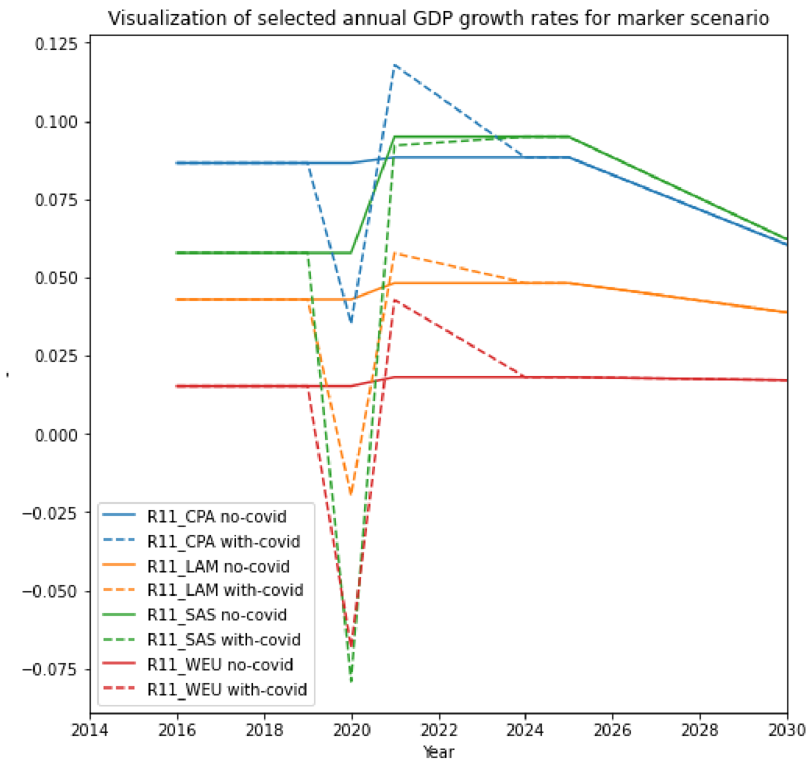
For the calculation of GDP after 2021, we need to assume the length of the effect. In the absence of more information on how regional economies will respond to this two-year deviation of the GDP underlying the assumed socio-economic scenario, we assume a smooth pathway in which GDP growth rates linearly converge to underlying regional growth rates. For marker scenarios we assume the length of the GDP growth effect T to be three years. In the economic uncertainty analysis, we vary this effect from 1 to 4 years. The economic growth rate in for $t \leq T$ subsequently follows

$g_{new_t} = G_{ssp2_T} + \left(g_{new_{2021}} - G_{ssp2_T}\right) \cdot \left(\frac{T-t}{T}\right)$. Please note that due to the constant GDP growth over the 2021-2025 period in the SSP2 scenario, $G_{ssp2_t} = G_{ssp2_T}$.

An illustration of the results GDP growth pathways is provided in *Supplementary Figure 18*. Maximum and minimum GDP pathways used to illustrate the GDP sensitivity in the main text use $\rho = 0.25$ and $\rho = 1$, both with $T = 4$.

Supplementary Table 37: rho values derived from economic outlooks. Specific regional values were used for the marker scenarios, more aggregate values (*) were not explicitly used in our analysis.

MESSAGE Region	ρ derived from World Bank	ρ derived from IMF	Average value used for marker
AFR	0.538	0.539	0.54
CPA	0.248	0.209	0.23
EEU	0.514	0.385	0.45
FSU	0.438	0.422	0.43
LAM	0.438	0.414	0.43
MEA	0.548	0.473	0.51
NAM	0.354	0.211	0.28
PAO	0.365	0.302	0.33
PAS	0.567	0.506	0.54
SAS	0.622	0.362	0.49
WEU	0.385	0.366	0.38
Global South*	0.4600	0.391	-
Global North*	0.387	0.313	-
World*	0.415	0.367	-

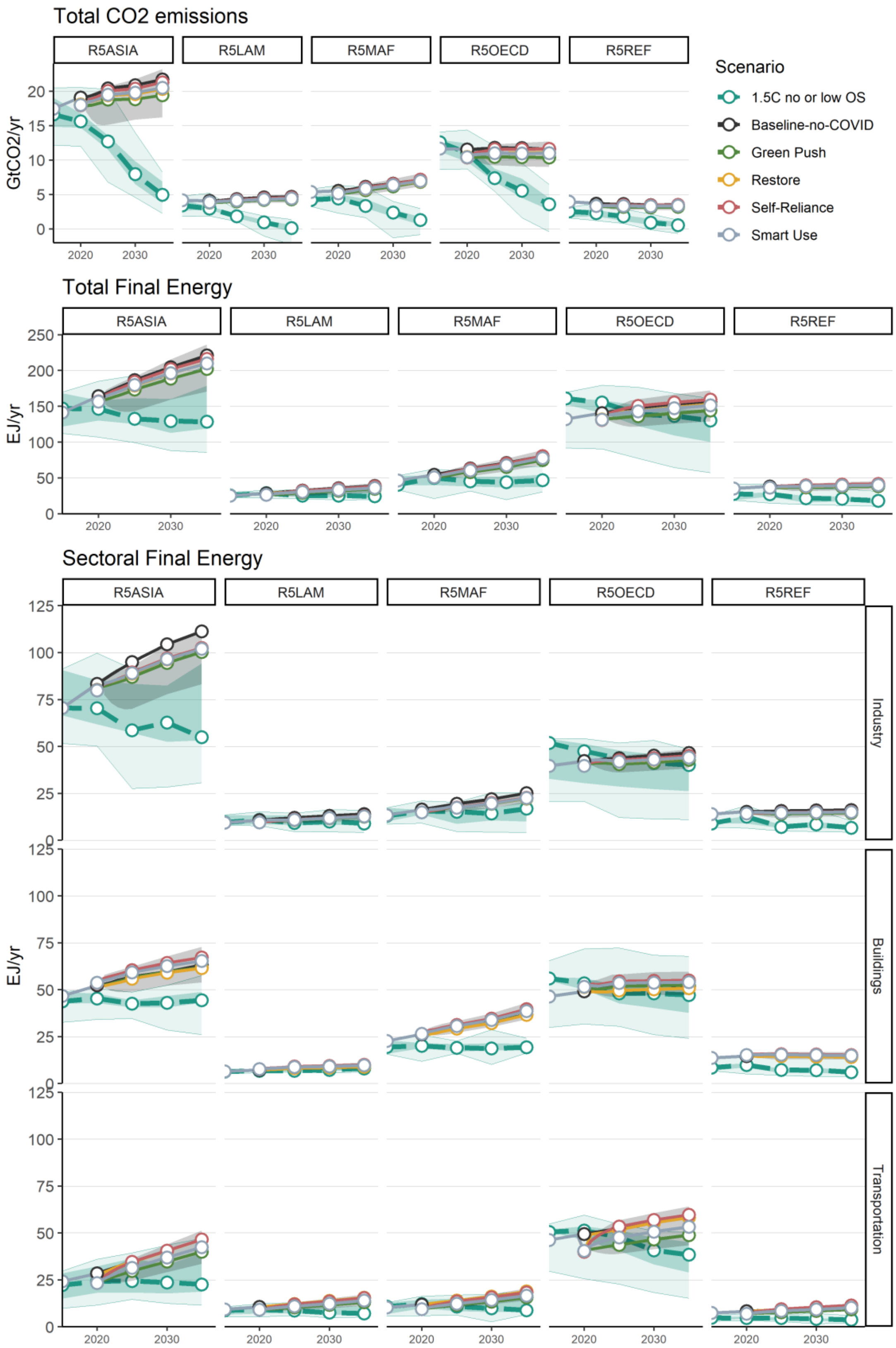


Supplementary Figure 18. Selected regional GDP growth in absolute year on year terms. Dashed lines present the marker scenario for a selected set of regions, whereas the solid lines represent the counterfactual year on year GDP growth for a baseline pathway without a pandemic. Note: GDP was modeled for all the 11 MESSAGE regions, of which four are shown here (see Supplementary Note 1).

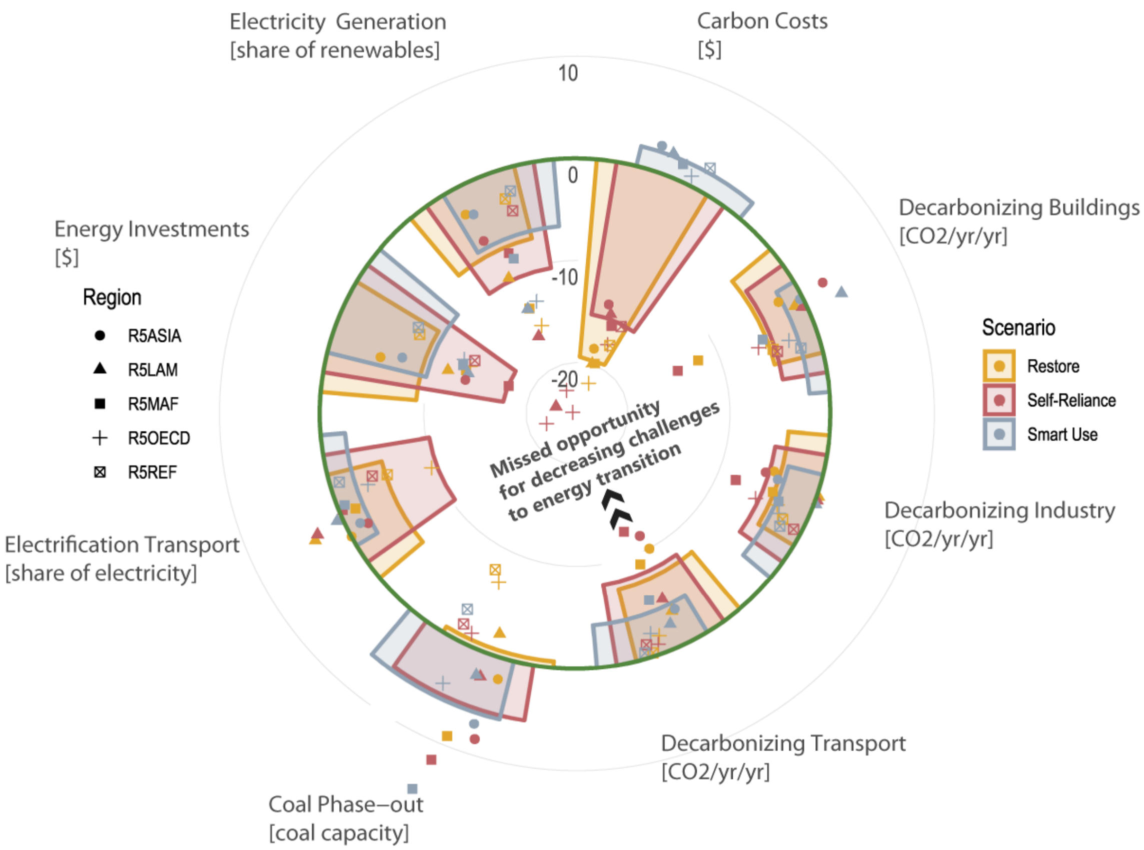
7. Supplementary Note 7. Additional Results

To enable further insights in the characteristics of our scenario set, we present a set of additional results. Additional figures:

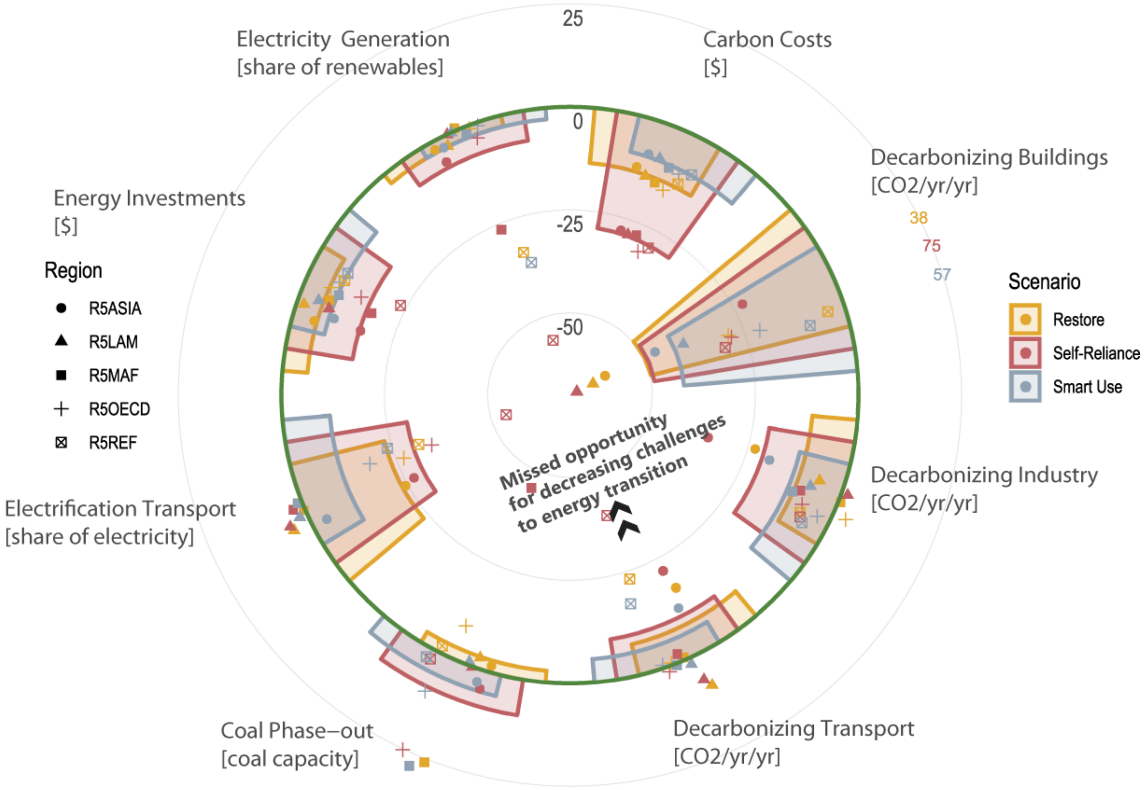
- Regional final energy demand and CO_2 pathways (Supplementary Figure 19);
- A replication of main text Figure 3 on a five-regional aggregation (Supplementary Figure 20);
- A replication of main text Figure 3 on a five-regional aggregation for a below 2C pathway instead of 1.5ºC (Supplementary Figure 21);
- Differences between scenarios at full model regional detail for a set of mitigation effort indicators for 1.5ºC (Supplementary Figure 22);
- Regional CO_2 emissions pathways for each region in for all marker scenarios (Supplementary Figure 23);
- Global emissions pathways for all marker scenarios for a selected set of greenhouse gases (Supplementary Figure 24);
- A selected set of variables in 2030 compared to the broader scenario literature from ref.[135] (Supplementary Figure 25);
- Regional absolute levels Cumulative energy investment from 2020 until 2030 for an alternative 1.5ºC scenarios in billion US$2010 (Supplementary Figure 26).



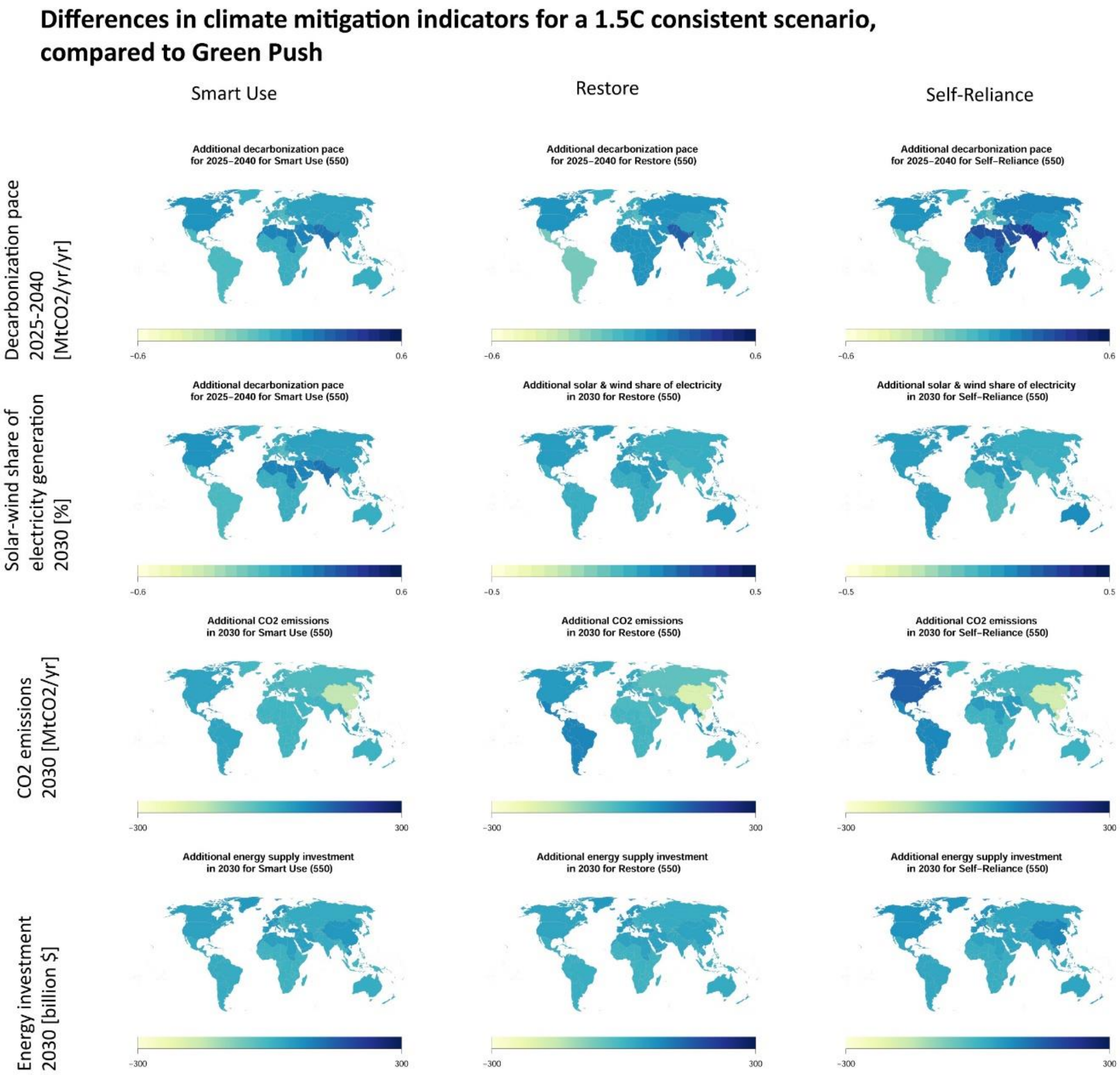
Supplementary Figure 19. Regional mid-term model output for the four COVID scenarios without additional climate policies compared with 1.5C compatible pathways from the IPCC Special Report on 1.5C database, using a 5-regional aggregation (see Supplementary Note 1).



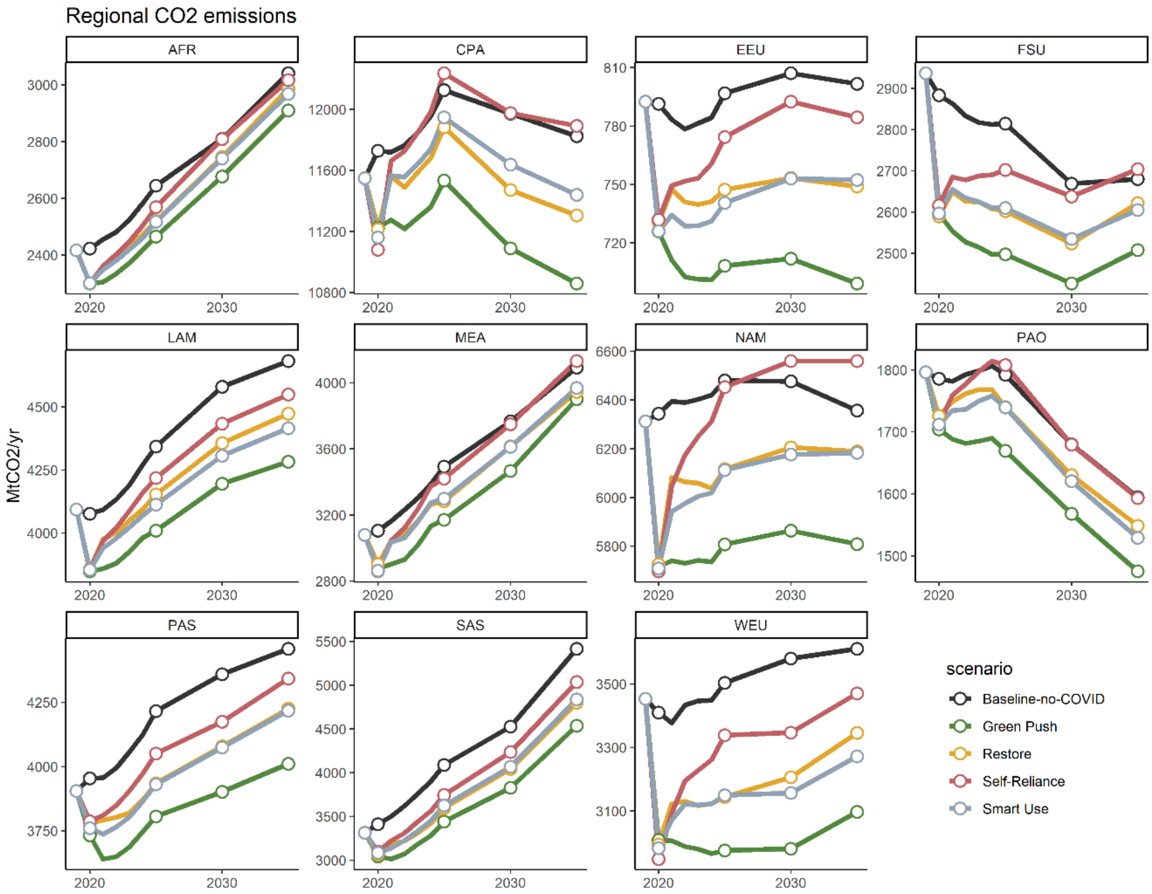
Supplementary Figure 20. Alternative medium-term recovery pathways affect the size of the energy transition challenge for limiting global warming to 1.5°C. Each wedge shows the % variation in a specific indicator of mitigation effort required in the *restore* (yellow), *self-reliance* (red), and *smart use* (grey) scenarios relative to the scenario with the lowest transition challenges (*green push*). Electricity generation: the share of solar and wind in electricity generation. Carbon costs: the net present value of the global carbon price multiplied by annual greenhouse gas emissions, for the period 2020-2030. Decarbonizing Buildings, Industry, and Transport: increase of post-recovery decarbonization pace in 2025-2040 compared to the reference scenario under the same climate target. Coal Phase-out: reduction in cumulative coal energy production capacity 2020-2030. Electrification Transport: share of electricity of transport energy in 2030. Energy Investments: cumulative energy supply investments 2020-2030.



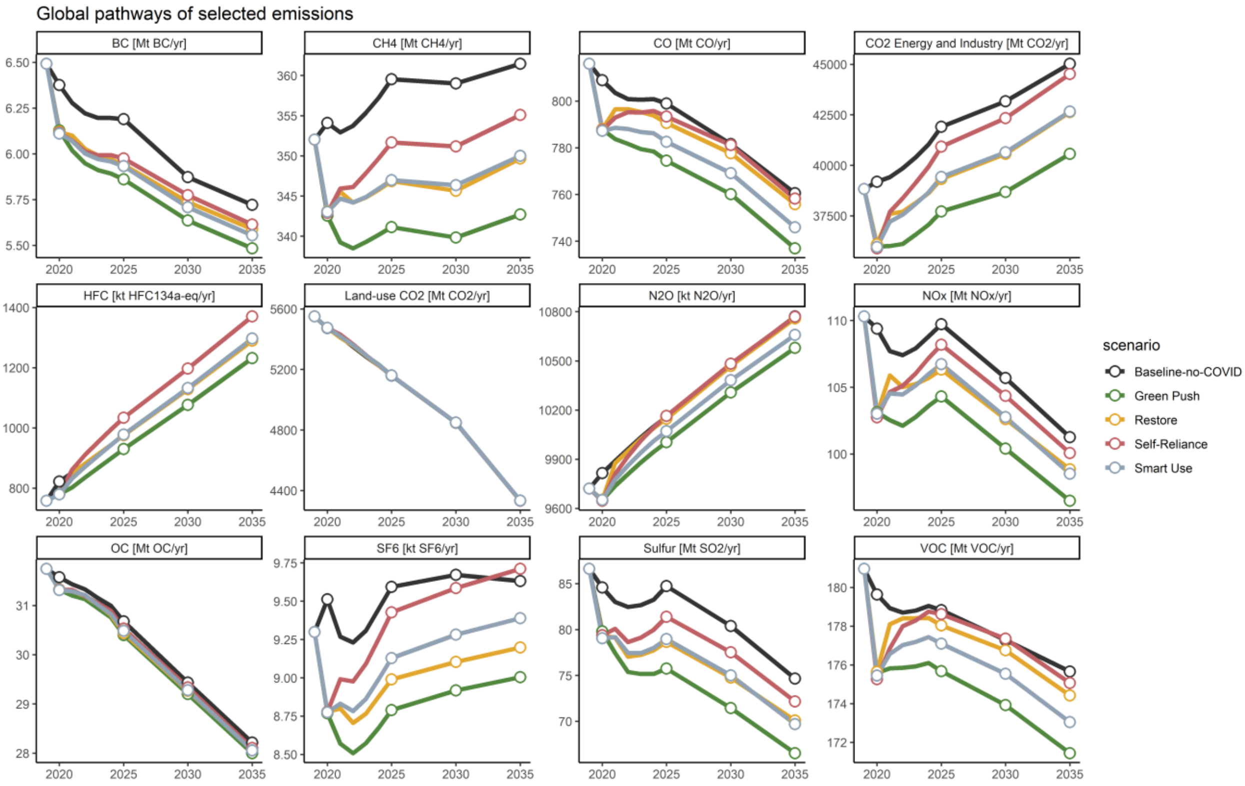
Supplementary Figure 21. Alternative medium-term recovery pathways affect the size of the energy transition challenge for limiting global warming to 2.0°C. Each wedge shows the % variation in a specific indicator of mitigation effort required in the *restore* (yellow), *self-reliance* (red), and *smart use* (grey) scenarios relative to the scenario with the lowest transition challenges (*green push*). Electricity generation: the share of solar and wind in electricity generation. Carbon costs: the net present value of the global carbon price multiplied by annual greenhouse gas emissions, for the period 2020-2030. Decarbonizing Buildings, Industry, and Transport: increase of post-recovery decarbonization pace in 2025-2040 compared to the reference scenario under the same climate target. Coal Phase-out: reduction in cumulative coal energy production capacity 2020-2030. Electrification Transport: share of electricity of transport energy in 2030. Energy Investments: cumulative energy supply investments 2020-2030.



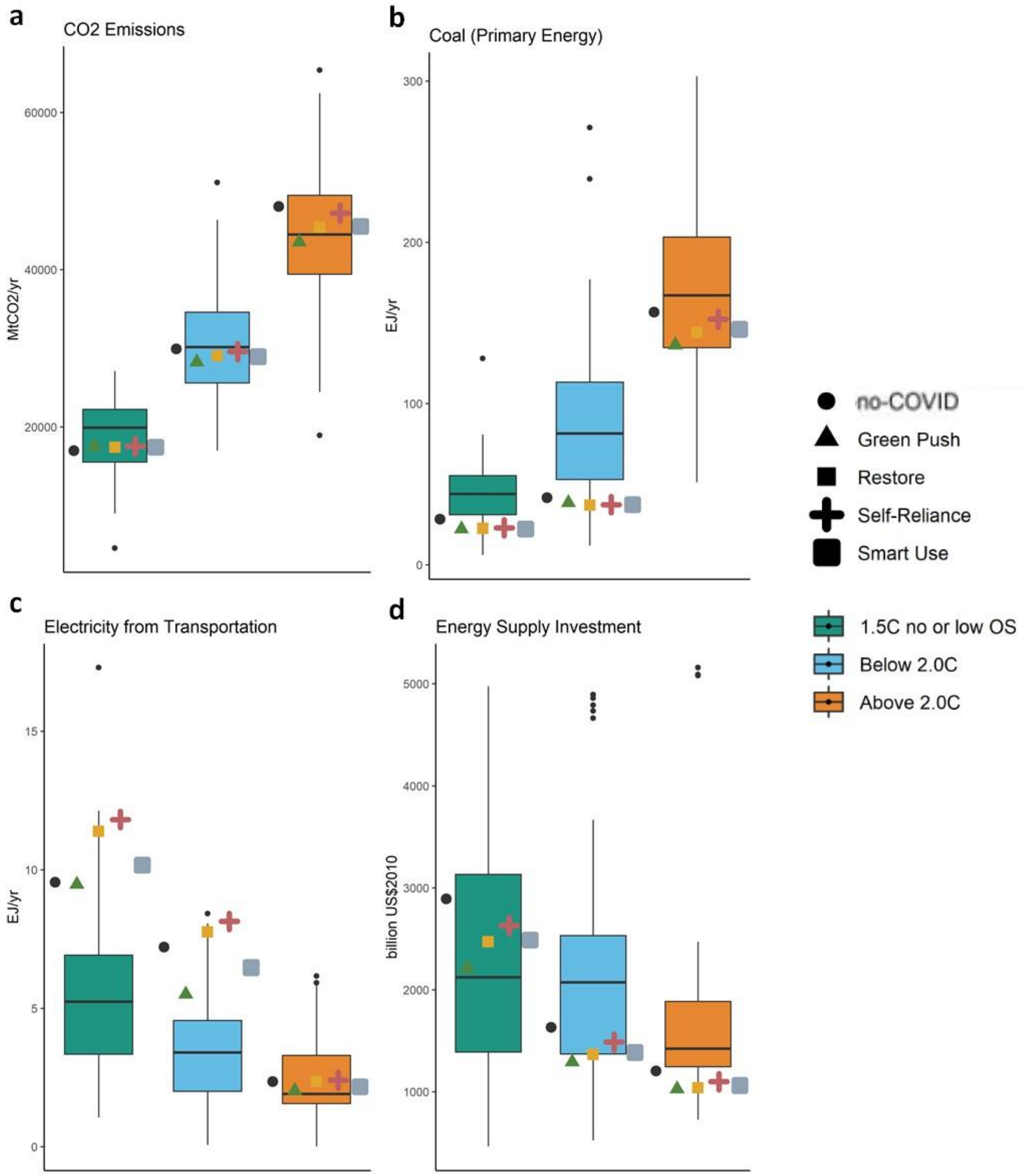
Supplementary Figure 22. Regional results comparing a *green push* scenario to alternative shock-and-recovery pathways that are consistent with a 1.5C target. For each figure, the indicated variable is subtracted by the value in the *green push* scenario.



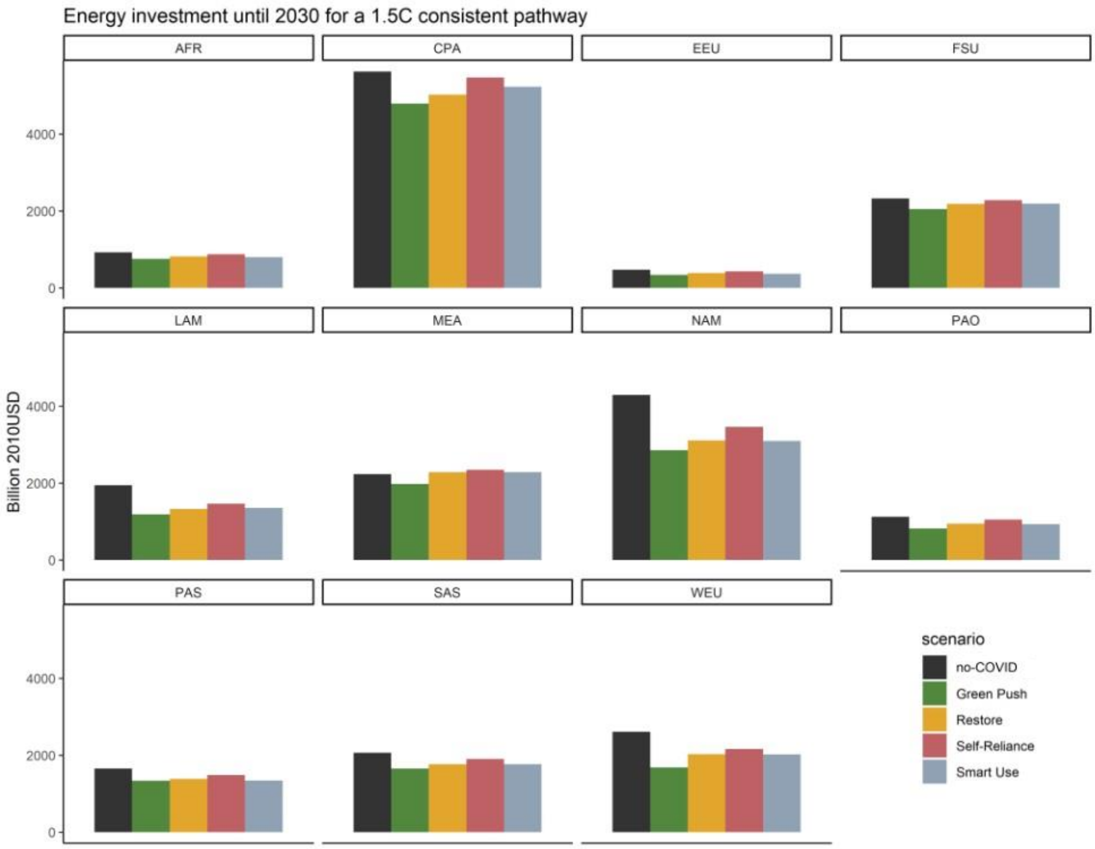
Supplementary Figure 23. CO2 Emissions pathways under alternative COVID-19 recovery scenarios for each of the modelled regions (see the regional definitions in Supplementary Note 1).



Supplementary Figure 24. Multiple global emissions pathways under alternative COVID-19 recovery scenarios with no additional climate policies, for a selected group of modelled greenhouse gases.



Supplementary Figure 25. COVID-19 scenarios in 2030 for both the non-mitigation and mitigation variants compared to the wider scenario literature data taken from the IPCC Special Report on 1.5 Degrees[135], OS=temperature overshoot. (a) CO2 emissions, (b) primary energy generation from coal, (c) electricity from transportation, and (d) energy supply investments. Upper and lower whiskers represent 1.5x the interquartile range, the box limits represent the upper and lower quartiles, the center line the median, and points are outliers.



Supplementary Figure 26. Cumulative energy investment from 2020 until 2030 for mitigation scenarios limiting temperature increase to 1.5ºC scenarios in billion US$2010.

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