COVID-19 impacts on energy demand can help reduce long-term mitigation challenge

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Abstract: The COVID-19 pandemic caused radical temporary breaks with past energy use trends. However, how a post-pandemic recovery will impact the longer-term energy transition is unclear. Here, we present a set of global COVID-19 shock-and-recovery scenarios that systematically explore the demand-side effect on final energy and GHG emissions. Our pathways project final energy demand reductions of 12 to 40 EJ/yr by 2025 and cumulative CO2 emissions reductions by 2030 of 28 to 53 GtCO2, depending on the depth and duration of the economic downturn and demand-side changes. Recovering from the pandemic with low energy demand practices - embedded in new patterns of travel, work, consumption, and production – reduces climate mitigation challenges. A low energy demand recovery reduces carbon prices for a 1.5°C consistent pathway by 19%, lowers energy supply investments until 2030 by 2.1 trillion USD, and lessens pressure on the upscaling of renewable energy technologies.

Introduction paragraph

The on-going COVID-19 pandemic is having a far-reaching impact on society. The effect of lockdown measures to contain the spread of the virus, which include reduced business activities and job losses, travel restrictions and increased border control, have affected the economy as well as people's daily lives[1]. Economic activity, manufacturing, production and trade are down[2]. Likewise, people have had to temporarily change their lifestyles in drastic ways, with reduced mobility, social distancing and home working affecting society's demand for energy on a daily basis[1,3]. These changes have led to immediate observable effects on air quality, energy demand, and greenhouse gas emissions, with several studies estimating the impact of initial lockdowns on reducing global CO_2 emissions[3–5]. Whilst the global drop in greenhouse gas emissions in 2020 is expected to be the largest on record in a single year[5], temporary short-term reductions will not avert global temperature to rise unless they are followed by long-term structural changes in energy systems[3,6].

We set out to assess the effects of these drastic near-term changes on the medium to longer term. This is challenging, because it requires a holistic treatment of both temporary and structural socioeconomic changes that together define a set of alternative future pathways[7,8]. Recent studies in this new field have mostly assessed the observed impacts of lockdown measures in some western countries on the energy sector and CO2 emissions[4] and have tried to project trends for the coming decades following the 2020 shock[3,7]. Other studies[8,9] have modelled links between current economic recessions and future projections of CO2 emissions but only at the country level, or without considering explicit persisting demand-side changes with feedbacks in an integrated energy-economy analysis. At the time of writing, however, the pandemic continues to have very different repercussions across countries worldwide, with new infection waves and associated lockdown measures compounding the initial impact and making future projections more challenging. Meanwhile, governments have also proposed and implemented major fiscal stimulus packages to help recover the economy from this on-going crisis, and an increase is expected in policies that support decarbonization efforts in energy and transport[10]. This has created a widely-discussed opportunity for a ‘green’ and climate-positive recovery towards a net-zero emissions future[11]. However, in part due to the complexity of socially driven change, previous research in energy-economy modelling has focussed little on assessing the potential effect of demand-side policies on decreasing climate mitigation challenges[12,13].

We contribute the first global scenario study of how the near-term COVID-19 shock and alternative medium-term recovery pathways affect long-term outcomes for energy and climate including the achievability of Paris Climate Agreement targets. We combine a detailed bottom-up assessment of energy demand changes induced by lockdowns with macro-economic modelling of sectorial changes driven by economic factors. We use the MESSAGEix-GLOBIOM Integrated Assessment Model (IAM)[14] to capture global economy, energy, and climate dynamics in the medium to long-term, and include heterogeneity among countries in terms of response to the COVID-19 emergency. We systematically explore the large uncertainties by using a combination of a distinct set of recovery pathways (through our scenario design) and modelling the regionally heterogeneous economic response that explores a range of possible durations and intensities of the pandemic (through our GDP sensitivity analysis). This integrated assessment of shock, recovery, and long-term outcomes shows the conditions under which COVID-19 can have the strongest implications for climate change mitigation.

Energy demand drop in 2020 and alternative recovery pathways

Lockdowns have had major impacts on energy-related activity, including international travel, commuting, use of office space, e-commerce, and ICT usage[15]. In turn, this has affected the buildings, transport and industrial end-use sectors. We set out to understand the implications of these changes for sectoral energy demand as well as for structural changes regarding the energy services that are used in each sector (see Methods and Supplementary Note 1-5). We assess the direct impact of lockdown measures in the first half of 2020 on activity measures, including use of residential and commercial floorspace, use of electric appliances, travel (by mode), and industrial output. We find that global energy demand in 2020 is 33-34 EJ lower than without a pandemic, with 37% of reductions attributable to industry and 63% to transport. In contrast, the building sector shows a small increase in demand of 1.8 EJ, as residential energy demand growth has offset reductions in commercial energy use[16,17]. As a result of these observed changes, we estimate total CO2 emissions in 2020 being around 5 Gton lower, or 9% compared to 2019. This provides an independent estimate within the range of earlier estimates[3,4] with different methods, albeit a slightly bigger reduction than the most comprehensive estimate available[18].

How these observed near-term impacts on energy-related activity play out over the medium-term to 2025 is highly uncertain. Two principal uncertainties are whether or not recovery pathways will seek a return to pre-pandemic ‘normality’, and to what extent recovery pathways will be driven by top-down policy or by bottom-up emergent social learning. We construct and analyze four scenarios to explore this uncertainty space systematically (Table 1 and Figure 1). Each scenario is characterized by a distinctive storyline that we then translated into detailed assumptions about activity and structural changes in each end-use sector over the period 2021-2025 (following the approach of ref. [19]).

The *restore* and *self-reliance* scenarios describe recovery pathways back towards pre-pandemic conditions, but *self-reliance* comes with a greater emphasis on individual choice and national isolation as opposed to cooperative economic and social integration. *Restore* largely sees a return to pre-pandemic energy-related activity and structure, whereas *self-reliance* implies increased use of private vehicles, and larger working and home office spaces (Table 1).

The *smart use* and *green push* scenarios describe recovery pathways towards new conditions shaped predominantly by either the bottom-up experiences and learning under lockdowns (*smart use*) or by top-down stimulation by policy efforts of national and local governments to 'build back better' (*green push*). *Smart use* sees positive experiences with enforced behavioral changes enduring over the medium-term. For example, continuation of experienced air pollution, health and wellbeing benefits of less carbon-intensive transport, less commuting, and more teleworking become embedded in new social patterns affecting energy-related activity in both buildings and transport sectors (Figure 1). *Green push* goes further by creating supporting structures that enable active travel and digital substitution for physical transport and efforts to reduce health risks in public transport, and directed downsizing of under-used retail and commercial buildings space.

Table 1 summarizes the main elements of each scenario narrative, and how they are translated into structural changes in transport (modal shares), buildings (domestic-commercial-retail shares), and industry (production of different materials, Supplementary Notes 1-5 for full details). Industrial energy demand, which is strongly linked to macroeconomic recovery, shows activity levels in 2025 still lower than those in 2019. Economic uncertainty around GDP decline and recovery is further explored through performing a sensitivity analysis with regional detail (Supplementary Note 6). Figure 1 shows how each scenario narrative is operationalized into aggregated energy-related indicators, with the *restore* scenario serving as a reference point for change relative to pre-pandemic conditions.

These bottom-up assessments of activity and structural change related to energy end-use result in four distinct, plausible energy recovery pathways. Depending on the scenario, global energy demand will surpass 2019 levels between 2022 and 2024. The *smart use* and *green push* scenarios delay the rebound in energy-demand growth to a greater extent by aligning demand recovery with sustainability goals.

Global CO2 emissions follow a similar trend, returning to pre-pandemic levels in 3 to 6 years depending on the recovery pathway, with a cumulative carbon reduction of 28-53 GtCO2 by 2030 compared to a counterfactual scenario without a pandemic. Pre-pandemic, it was already clear that limited climate action was inconsistent with the Paris Agreement's goal of holding global warming well below 2°C and pursuing to limit it to 1.5°C [20]. The presented scenarios do not revert this trend, meaning that carbon budgets will still be depleted fast without additional ambitious climate policies (Figure 2d). The large economic uncertainty during the recovery has strong consequences for emission trends: rapid recoveries from economic recessions could more than offset emission reductions from activity and structural changes (grey shaded area in Figure 2d). Yet, also in the case of very strong reductions in global GDP, cumulative CO2 emissions will not lead to staying within the carbon budgets consistent with Paris Agreement

Goals. At most, it delays their depletion by 3 to 6 years (for 1.5°C and 2°C, respectively) compared to a scenario without the pandemic (Figure 2e). This emphasises the continued importance of stringent and sustained climate policies alongside or as part of the economic recovery.

At the sectoral level, transport and industry see largest short-term emission reductions (1.3 GtCO2 and 0.7 GtCO2 in 2020, respectively). Following our regionally heterogeneous narrative, the strongest CO2 reductions are found in the Global North, with growing energy and emission trends in the Global South dominating the COVID-19 demand change effect. In the absence of additional decarbonization efforts, the gap between our projected post-pandemic energy pathways and those consistent global climate targets continues to widen (Figure 2a-d).

Table 1: Scenario narratives and sectoral differences in structural change in 2025 compared to 2019 levels. Values are global aggregation of the estimation for the two macro-region Global North and Global South, please see **Supplementary Notes 1-5** for further details.

	Transport	**Buildings**	**Industry**
Restore	Return to pre-pandemic levels. Shares of private transport, vehicle ownership, and international aviation activity are restored.	Return to pre-pandemic trends of private and public space usage in terms of demand levels, intensity, and location	Production levels follow economic activity. Although there are repurposing and efficiency changes, the overall structure returns to pre-COVID-19 pattern.
Self-reliance	Concerns about infection risks remain for a longer time. An increase in more private transport is combined with more teleworking, leading to a strongly muted overall increase in public transit (+5% in 2025 compared to 2019 levels) while car usage surges (+25%). Air travel is high (+13%). Freight activity nearly fully recovers, just prevented from reaching counterfactual projections by the persistence of the economic shock.	Transformation in the location of office work, administration, services, and shopping continue the trends during the lockdowns. However, because of concerns about hygiene and persistent social distancing behavior, total floorspace per capita increases (+7% globally). While home office and online services increase, these also lead to increased shares of idle but temperature-controlled space.	Return to pre-pandemic production structures with strong emphasis on diversification of resources, shortening supply chains, and localizing production and services to reduce risk of disruption. Contraction due to economic recession.
Smart use	During-pandemic teleworking levels are partially persistent. The reduction in use of light duty vehicles (car commuting +5%) and public transport (+8%) compared to pre-pandemic structures remains slightly muted too. Online retailing reduces overall freight activity due to better utilization of delivery vehicle capacities. Aviation does not recover due to reduced international tourism (-2%).	Transformed space use for work, leisure, administration, and services becomes the norm, increasing the intensity of home space use, but limited change in the Global South (+4% intensity). Minimal decrease of non-residential space to cut idle space (-15% space per capita), thus compensating the residential effect.	Overall process and material efficiency heritage from the pandemic. Increase in production of paper (+7%) and chemicals (+11%) from moderate online and digital lifestyle growth. Reduction in mobility, and low level of efficiency improvements (i.e. renovation) of buildings impact iron and steel production (-12%), aluminum (-19%) and cement (-5%).
Green push	The large reduction in commuting trips and long-distance travel is highly persistent (-15% aviation). Especially in urban areas, policies are implemented to prevent high levels of transport by car to return (-5%). Transport needs are instead fulfilled by rail (+33%) and road public transport (+25%) in part enabled by lower actual and perceived health risks compared to other scenarios.	Increase of energy demand (+4%) in homes from an increased relocation of work, administration, services, and more energy-related activities (cooking, crafting, entertainment) can be fully compensated by space reductions and efficiency gains in non-residential buildings (-15% per capita) due to reduced time in the workplace because of partial teleworking, reorganization of public space, persistent business model changes that emerged during the pandemic (0% overall).	Increased efficiency in industries as a heritage of the pandemic (where industries worked under labor and raw material shortage). Rebalancing between local production and imports. Lower mobility and building activity leads to reductions in iron and steel (-16%), aluminum (-21%) and cement (-8%); Increase in online shopping, digitalization, dematerialization, and repurposing increases paper (+7%) and chemical (+6%) industries.

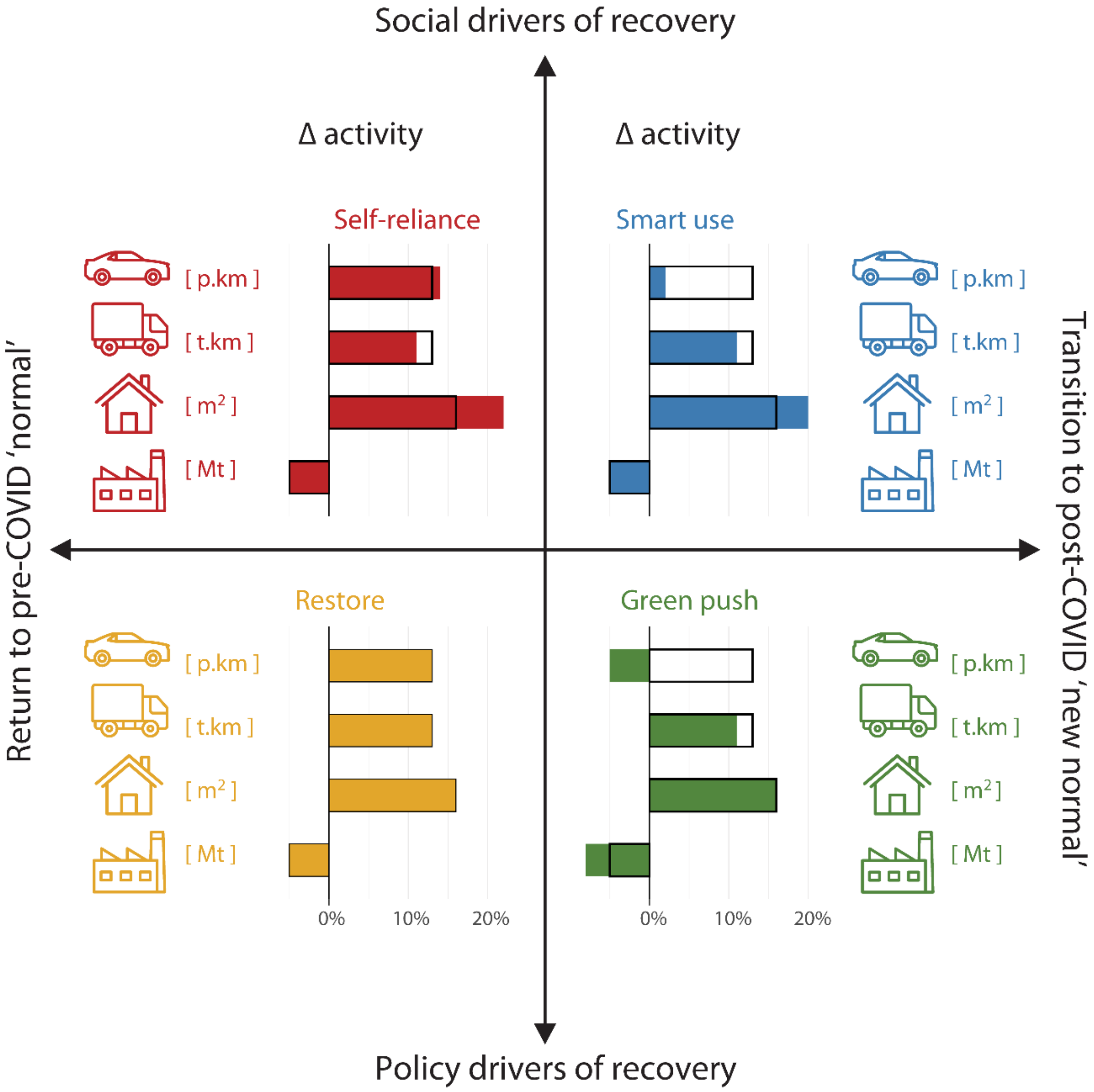

Figure 1: Changes in energy-related activity between 2019 and 2025 in transport (passenger, freight), buildings, and industrial sectors under four different recovery pathways. The black outline boxes indicate the 2019-2025 change in the *restore* scenario and serve as a common reference point for the *self-reliance*, *smart use*, and *green push* scenarios.

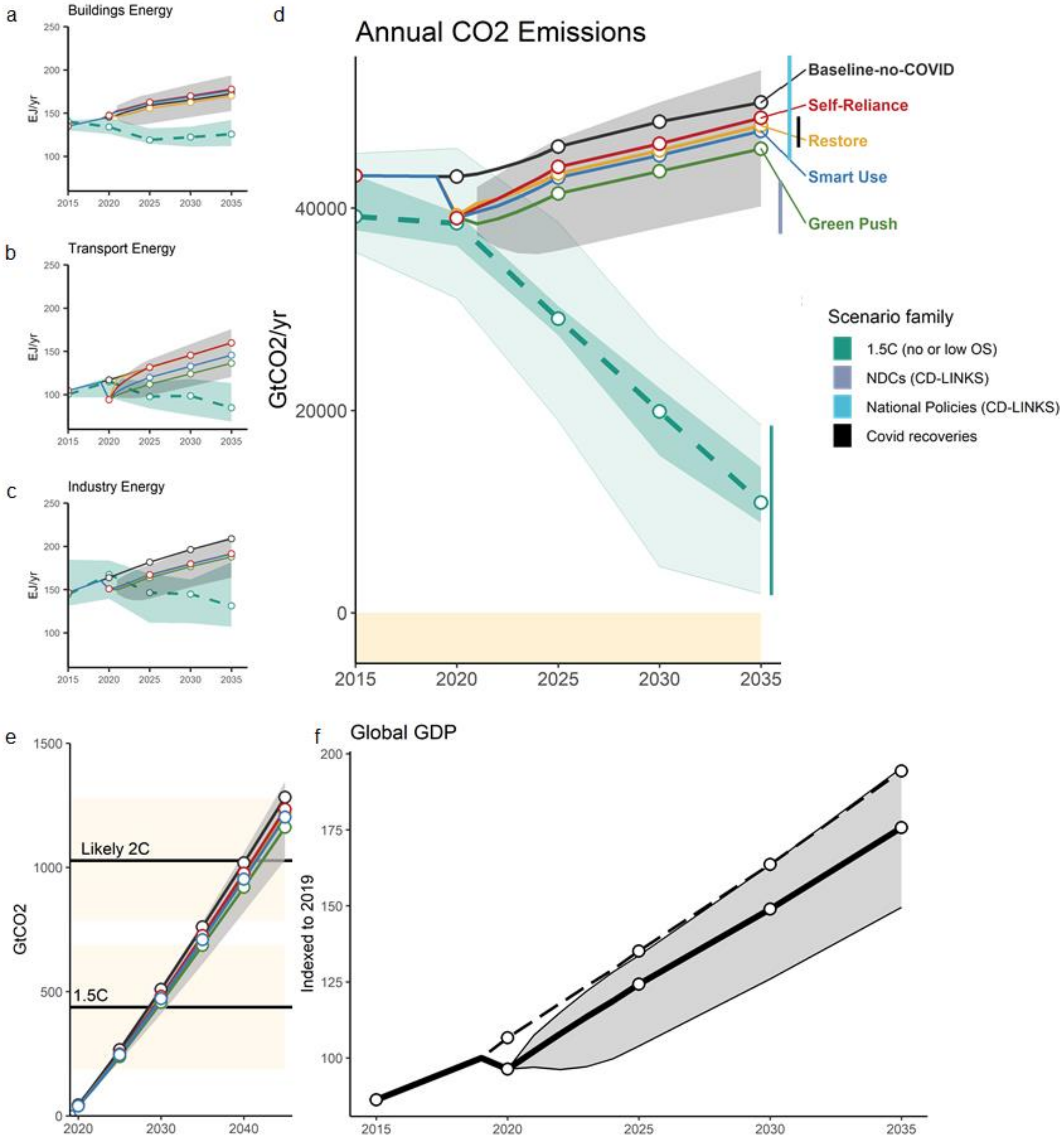

Figure 2: Energy, CO2, and GDP pathways under alternative COVID-19 recovery scenarios. Final Energy use for the buildings (a), transport (b), industry (c) sectors. Total annual CO2 emissions (d). Cumulative CO2 emissions starting from 2019, with global CO2 budgets visualized as reported in SR15 (e). Global GDP (market exchange rates) indexed to 2019 levels for our marker scenarios (bold), the pre-pandemic prediction (dashed line) and uncertainty range (f). Grey shading shows the sensitivity range considering GDP uncertainty (a-f).

Energy transition challenges under alternative recovery scenarios

Cost-effective energy transition scenarios that limit warming to 1.5°C or 2°C that were simulated prior to the COVID-19 shock required average CO2 emission reductions of 4.1% and 2.4% per year for the next two decades (2021-2040), for limiting warming to 1.5°C and below 2°C, respectively. Combining climate policies with the above-mentioned post-pandemic recovery pathways, we find that the overall reduction in CO2 emissions in 2020 due to the pandemic reduces the 2021-2040 average decarbonization rate slightly to 3.8-3.9% and 2.0-2.1%, for 1.5°C and below 2°C, respectively. The differences between the alternative marker recovery scenarios are very small. However, we find these minor changes to have very clear and substantial implications on the transition costs, resulting from a strong response to energy demand changes of a system that is stretched.

The post-recovery (2025-2040) decarbonization pace for our 1.5°C climate scenario (see Supplementary Figure 10 for regional detail) characterizes emissions reduction challenge in the most aggregated form. Particularly, a scenario with the most pronounced carbon emissions reductions from transport during the recovery (*green push*) has a lower mitigation challenge in the 2025-2040 period than a scenario seeing increased private vehicle use (*self-reliance*), requiring a 3.0% lower annual reduction. Also compared to a scenario that restores pre-pandemic energy system structures (*restore*) the required pace of reduction is reduced by 2.6%. Breaking down post-2025 decarbonization by sector we observe similar effects. The decarbonization pace in transport is 6.3% lower in *green push* compared to both *self-reliance* and *restore*. For industrial processes, CO2 reduction rates are 3.0% lower in *green push* versus *self-reliance*, and 2.5% versus *restore*. The persistence of space use transformation (Supplementary Note 4) towards increased home office and online solutions for services, shopping, entertainment, coupled with reduced non-residential space reduces the 2025-2040

CO2 abatement challenge for the built environment by 6.4% (*green push* versus *restore*) to stay below 1.5°C.

Pathways that aim to stabilize global temperatures around 1.5°C require considerable energy investments. A green recovery *green push* could reduce annual energy investments required until 2030 by more than 11% compared to *restore*, reducing total required energy transition cost in the coming decade by over 2.1 trillion US dollars (or 2.0% instead of 2.3% of GDP in 2030). In contrast, a *self-reliance* recovery, with higher energy demand, shows increased mitigation costs by 0.65 trillion. If the post-COVID-19 recovery fails to embed low-carbon activity and structural change, economic incentives to transform the system must be markedly stronger. Regional results show largest economic benefits between opposite energy recovery pathways in the *Global North*, due to the larger impact of COVID-19 on energy and emissions compared to the *Global South*. The net mitigation cost from carbon pricing by 2030 to meet the 1.5C target is 4.9% higher for *self-reliance* compared to *restore*, while *green push* is 19% lower than *restore*.

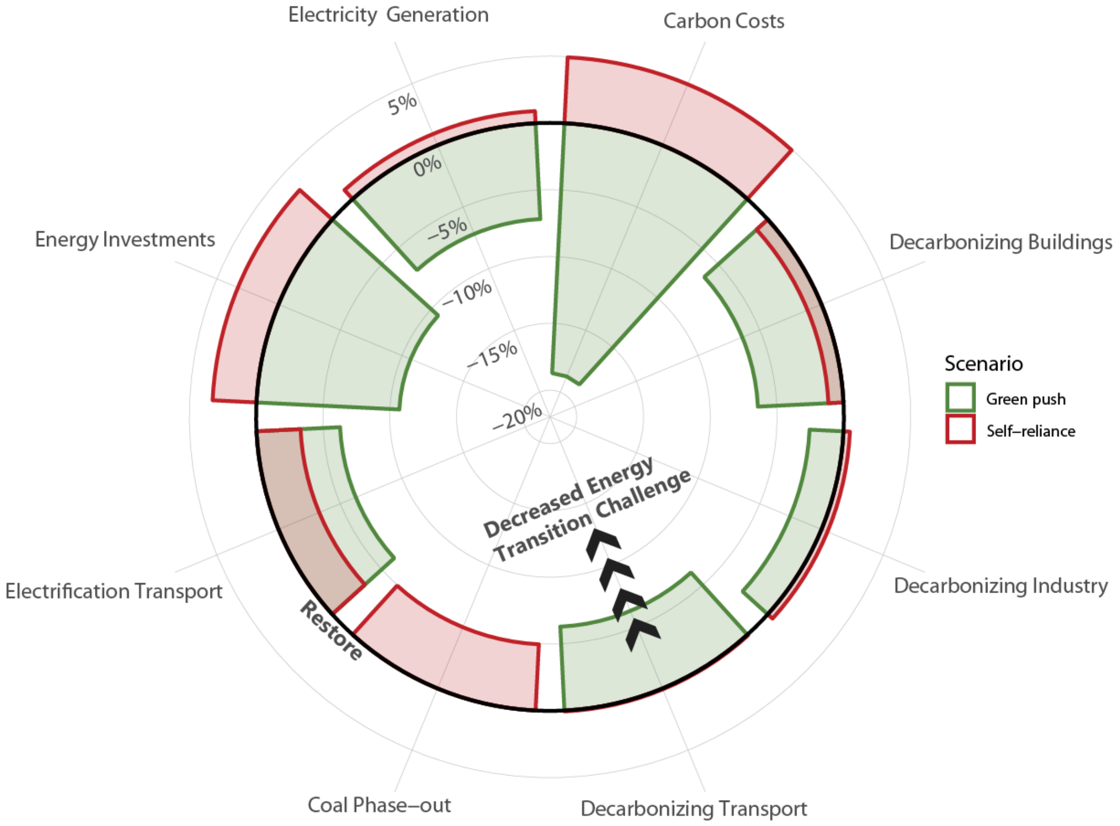

Figure 3: Alternative medium-term recovery pathways affect the size of the energy transition challenge. Each wedge shows the % variation in mitigation effort required in the Green Push (green) and Self-Reliance (red) scenarios relative to the Restore scenario (black circle). Electricity generation: the 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 its reference scenario with similar without climate mitigation. Coal Phase-out: cumulative coal energy production capacity in 2020-2030. Electrification Transport: share of electricity of transport energy in 2030. Energy Investments: cumulative energy supply investments 2020-2030.

The higher near-term transport energy demand and CO2 emissions force transport electrification to be faster under the *restore* and *self-reliance* scenarios compared to the other scenarios under a 1.5°C climate target. Electricity in transport in 2030 accounts for 10.6 EJ/yr in the *restore* scenario (10.1% of total sectoral final energy), while in the *green push* scenario it is only 8.7 EJ/yr. These noteworthy differences highlight a large electrification challenge for transport, especially when comparing to the electrification values in 2019, namely 1.7 EJ/yr (1.55% of transport energy). Failing to push for a green recovery that includes modal shift would however increase this challenge in the order of 10.6 trillion EV-kilometers extra per year by 2030 or about an extra 6.6 times the 2019 global electricity demand from EVs[21].

A transformation to a low-carbon energy system requires a strong energy generation transformation as well. The higher the global energy demand, the faster renewables need to increase if emissions are to be reduced. Consequently, the share of electricity coming from wind and solar installations in 2030 could be 0.5 percentage points higher (*self-reliance*) or 3.6 percentage points lower (*green push*) compared to a *restore* scenario. Regardless of the recovery pathway, the transitional challenges remain large, with values indicating for 2030 a wind and solar electricity share of between 47% and 51%, compared to 2019 values of 8%, but well lower than the value by 2030 in the no-COVID-19 baseline scenario (56%).

Another defining challenge of the energy transition is the required speed of the phase out of coal-fired power plants. In the very near term, due to lower energy demand the modelled coal capacity for electricity reduces faster under a *green push* and slower under a *self-reliance* pathway, which provides more electricity from coal next to having higher renewables capacity. All presented scenarios with ambitious climate mitigation strategies towards 1.5°C see no recovery of the primary energy coming from coal after the steep reduction during the pandemic, persisting the reduction observed in 2020[22]. In 2030, global coal capacity has reduced to 534-555 GW under our four alternative recovery scenarios, compared to an installed capacity of 1621 GW in 2019. The total installed capacity in the next decade is in our modelled pathways is 5% higher under the *self-reliance* scenario, whereas the *restore* and *green push* values are not distinguishable.

Medium-term green recovery yields mitigation benefits towards net-zero

Most scenarios that aim to limit global warming to 1.5°C show global net-zero CO2 emissions around 2050[23]. Such a decrease requires fast and continued emissions reduction including the decarbonization of energy systems. The pre-pandemic global emission level of about 42 GtCO2/yr[18], which was still trending upwards, would leave less than 10 years before closing the door on limiting temperature increase to 1.5°C [20,24].

Our study confirms that the direct effect of the COVID-19 pandemic lockdowns on global emissions is negligible in the context of this challenge. In addition, we show that the effects of the persistence of activity changes alone (28-53 GtCO2 less by 2030 compared to scenarios pre-COVID-19) is not nearly sufficient to meet emissions reductions targets, which require more fundamental changes in the energy system. This finding still stands when accounting for economic uncertainty, even considering a very long economic downturn paired with lower emissions.

However, we find that because of the urgent need for strong CO2 emission reductions, even relatively small differences in post-pandemic energy demand create substantial changes in terms of required mitigation efforts and costs. For our 1.5°C scenarios by 2030, a low energy demand recovery (*green-push*) reduces the need for electricity in transport by 1.9 EJ/yr, the transition challenge for electricity generation from solar and wind by 4 percentage points, and the total required energy investments in the next decade by 2.1 trillion compared to a case in which demand quickly jumps back to pre-pandemic levels (*restore).* These comparative differences between scenarios are robust for different climate mitigation goals. Considering both 1.5°C and 2°C as temperature stabilization targets by the end of the century, we find similar all-round benefits for the green-push scenario (See Figure 3 and Supplementary Figures 7-10, and 13 for comparison with the wider scenario literature).

Insights for an energy demand recovery

To be able to devise the policies that lead to a recovery that reduces mitigation challenges, it is important to understand to what extent different behavioural changes drive emissions or enable emissions reductions. In this article, we not only acknowledge, but also quantify the large uncertainty in energy consumption and the economy to estimate the impacts on CO2 emissions related to the COVID-19 pandemic. This is done by assessing detailed bottom-up activity recovery scenarios while accounting for interactions with a wide range of macro-economic projections.

While there is no magic bullet to meet the challenge of ensuring a transition that averts climate change beyond internationally agreed safe levels, we show that devising a strategy to guide the post-pandemic activity recovery to less carbon intense energy services is an important piece of the puzzle. Specifically, policies that support increased working from home and teleconferencing to reduce flying and commuting can have strong effects when combined with optimization of office space, just like increased safety in public transport that would reduce concerns about infection risks. The insights from this study need to be integrated with insights on the application and direction of fiscal stimulus packages and supply side measures in order to form a coherent holistic policy for a green recovery.

Methods

MESSAGEix-GLOBIOM: a model for energy and price-induced demand changes

We use the MESSAGEix-GLOBIOM Integrated Assessment Model (IAM)[25] to assess the implications of different COVID-19 scenarios on the energy system and derived indicators such as greenhouse gas emissions and energy investment needs[26].

MESSAGEix-GLOBIOM is a process-based integrated assessment model that allows for a detailed representation of the technical-engineering, socio-economic, and biophysical processes in energy and land-use systems. It is a linear/mixed integer optimization model, aiming to satisfy exogenous and endogenous demands at least cost[27]. MESSAGEix-GLOBIOM consists of a linkage between the energy system model and MACRO, a macroeconomic model, which maximizes the intertemporal utility function of a single representative producer- consumer in each world region. The optimization result is a sequence of optimal savings, investment, and consumption decisions. The main variables of the MACRO model are the capital stock, available labor, and energy inputs, so that the model can describe the feedback of end-use prices on demand for energy services[26].

The linkage between energy and macroeconomic models is established through an iterative process. First, energy prices are calculated in MESSAGEix-GLOBIOM based on a reference exogenous energy demand data. Then, these energy prices are passed to MACRO, where energy demand is recalculated considering the impact of energy supply cost on a reference trajectory of GDP for each model region. In return, new energy demand data resulting from the MACRO solution are fed back to MESSAGEix-GLOBIOM, which influences the demand-supply balances resulting in new energy prices. The iteration of energy prices and energy demand between the two models continues until the output of the two models converges to a stable trajectory within a predefined tolerance (more details can be found in ref.[25]).

MESSAGEix-GLOBIOM has been widely used for analysis of GHG emission pathways under a range of climate and socio-economic futures[28,29], as well as in assessment of climate mitigation strategies including specific assessments of energy investment needs[30,31]. It has been one of the models informing global emission pathway analyses such as the reports of Intergovernmental Panel on Climate Change (IPCC)[23], Global Energy Assessment (GEA)[32], and the World in 2050[33]. The global model version defines a set of eleven macro-economic regions. The time horizon of the optimization framework goes from 2020 to 2100, with a non-regular distribution of time steps. For this analysis, the model was extended to include individual years between 2020 and 2025, five-year periods between 2025 and 2060, and ten-year periods between 2060 and 2100. The addition of the yearly periods (2021, 2022, 2023, and 2024) for this analysis, compared to previous versions, allows for a better focus on short-term dynamics, that are specifically important for the COVID-19 scenarios.

The socio-economic assumptions of MESSAGEix-GLOBIOM are based on the Shared Socioeconomic Pathways (SSPs)[29,34], a set of internally consistent narratives, and assumptions for main socio-economic drivers widely adopted and updated by the Integrated Assessment Modelling community[35]. SSP2 is adopted as the starting point for this analysis[28].

We represent both the impact of COVID-19 on the economy with drops in the GDP value for 2020, and a five-year recovery to ‘reference’ values of a no-COVID-19 scenario and we implement energy demand reductions as results of a bottom up sectoral assessment both for the year 2020 and for four recovery scenarios. The model is first calibrated to fix the GDP and energy demand values in 2020. Results of the calibration are two parameters, *gdp growth rate* and *autonomous energy efficiency improvements (AEEI)*, which respectively guarantee that the desired trend of GDP and energy demand in MACRO align with the exogenously defined values over time. Further details on the calibration process can be found in refs[25,26].

The different narratives for lifestyle and energy demand recovery share the same economic assumptions (both the GDP shock in 2020 and the recovery until 2025). However, each narrative has different assumptions for energy demand, meaning that, after calibration, each scenario will have slightly different *AEEI* values, namely different energy efficiency per economic output.

Bottom-up assessment of 2020 shock on energy demand

The disruptive effect of the COVID-19 pandemic had a direct impact on energy using activities[36,37]. It has impacted the structure and level of our mobility, how we use residential, public buildings and workspaces, and the production of goods and materials. The changes that we have taken into account are directly or indirectly induced by the COVID-19 containments measures, such as local and national lockdowns, distancing requirements, higher hygiene standards, as well as restricted international trade and travel[3,4]. These measures and new awareness induced unprecedented behavior, lifestyle, and business changes, while coming paired with a strong economic shock. Therefore, we assessed the energy demand shock using a bottom-up approach, independent from the economic downturn. We do this by assessing changes in activity and structure in three demand sectors: transport, buildings, and industry. In each of these sectors, we first collected observed demand shocks during the first part of the COVID-19 crisis (until July 2020) and use these, in combination with an assessment of sectoral impact studies, to extrapolate the energy demand change for the full year. We map the 2020 values in a year-on-year method onto 2019. Initial assessments from international organizations and governments estimated different short-term 2020 recovery trajectories, including the possibility of a second wave of COVID-19 cases and new lockdowns later in the year. We based our assessment of 2020 values on a cluster of impact estimates that are stronger but have relatively faster recovery paces, to reflect the tightening and loosening of restrictions following increasing and decreasing infection rates, taking the middle ground between optimistic quick one-wave recovery pathways and more pessimistic slow recovery scenarios. We then combined assessments of individual sub-sectoral activity reductions and aggregated them to estimate a total effect on global energy demand, extrapolated to the spatial resolution of the MESSAGEix-GLOBIOM Integrated Assessment Model (IAM)[38]. A detailed description of the estimation of the 2020 energy demand shocks can be found in Supplementary Notes 2, 3, and 4.

COVID-19 scenario framework

The recovery narratives in this study explore two principal uncertainties. First, whether recovery pathways will seek a return to pre-pandemic 'normality' or whether a greener, new normality will be pursued. Second, whether recovery pathways will be driven by dedicated policy effort or more by emergent social learning. The four scenarios in this study cover all quadrants in this scenario space following the overall narratives as summarized in Table 1. These narratives focus on persistent lifestyle, institutional and business model changes that drive energy demand and have an indirect impact on greenhouse gas emission through changes in the level and structure of energy use. The medium-term trends (2021-2025) use 2019 as a base year to compare changes to the "pre-COVID-19" normal. Detailed narratives and quantitative assumptions for the transport, industry and buildings sectors are described below and in Supplementary Notes 2, 3, and 4. The scenarios are independent of and do not include a quantification of the effects of the large-scale fiscal stimulus packages announced by many countries (see e.g. ref.[39]), which are likely to have additional effects on specific sectors (e.g. airline bailouts or increased investment in green mobility[10]. These scenarios as described here are considered baseline scenarios that do not include explicit climate policy assumptions. On the other hand, the *green push* scenario considers policies specifically aimed to strengthen lifestyle changes (teleworking) or business practice (online health consultations) that have benefits for climate mitigation. They are combined with carbon budgets to create combined COVID-19-recovery and climate mitigation scenarios (see Mitigation section of Methods).

GDP marker pathways, coupling, and sensitivities

Along with transformations in the energy sector and behaviour-induced energy demand, MESSAGEix-GLOBIOM-MACRO can also represent shocks at the macroeconomic level, by perturbing GDP. To be able to clearly represent the different dynamics between the initial shock and the long-term response of the COVID-19 pandemic, we model both the economic shock in 2020 and the level of persistence of this economic shock in the short and long run. Considering the highly unpredictable nature of the current crisis, we deploy a maximally transparent, general-purpose framework to model possible macroeconomic effects of the COVID-19 pandemic.

Assessing the impact of COVID-19 on the economy in 2020 has been a challenge for economists, including the major financial institutes and central banks[40]. Consequently, initial, very uncertain estimates have been updated over time (e.g. refs. [41,42]). We capture this uncertainty by collecting a range of estimates of widely used economic prospects (including public entities, central banks and private rating agencies, see Supplementary Note 6). Regional and national data from multiple sources is included to calculate the expected GDP shock for 2020 for the eleven modelled regions. From these sources, we estimate an average expected impact on the economy, as well as lower and higher estimates, being the 10th and

90th percentile of the sample respectively**.** Supplementary Table 36 reports the regional values by source and the final values adopted in the model.

To acknowledge that the impacts on GDP levels are not restricted and highly uncertain, we choose to systematically assess the sensitivity of the price-induced effect of a wide range of alternative GDP pathways. With a growth rate g, regional GDP levels developing follow $GDP_{r,t} = GDP_{r,t-1} \cdot \left(1 + g_{r,t}\right)$, where and r, t stand for region and year, respectively. For projecting 2021 GDP levels, we apply a regional one-year persistence parameter ρ following $GDP_{r,t} = GDP_{r,t-1} \cdot (1 + g_{r,t} - \rho_r \cdot \gamma_{r,t-1})$ similar to previous work[43], where γ represents an economic shock. The applied ρ values are calculated based on the difference in GDP prospects in World Bank and IMF prospects before and after the corona crisis (Supplementary Note 6). Subsequently, to include both the long-term effect of the economic shock and the dynamics of the underlying SSP2 scenario, we let the GDP growth levels converge back linearly to the underlying growth rate.

In the quantification of the recovery scenarios, we treat the economic recovery and the energy demand trajectories independently. We do so, because the nature of this crisis and its recovery are too uncertain to link any GDP trajectory explicitly with the energy scenarios. Therefore, the marker versions of all recovery scenarios follow the same GDP recovery trajectory, but we have added sensitivity runs based on varying the persistence parameter and the time it takes for growth rates to return to their originally projected values under SSP2.

Transport

We estimated the 2020 impacts on transport activity using a bottom-up assessment of the impact of the COVID-19 crisis on mobility, independent of the indirect effects of the GDP shock in 2020. The sharp decrease in transport activity in 2020 has mainly been driven by the lockdown restrictions, which imposed a close-to-total halting of mobility for non-essential services[36,44,45]. We assumed a moderate shock across the existing estimates for each region and 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 (See detailed assumptions in Supplementary Note 2).

We use developments in five main elements as starting point for the transport recovery scenarios: international tourism, commuting, business travel, online retail, use of mass transit and active mobility. In the *restore* scenario, no changes occur, and the recovery follows the patterns as foreseen under the SSP2 scenario. Under the *self-reliance* scenario both international tourism and business travel revert back to pre-COVID-19 levels, commuting returns to pre-COVID-19 levels as well but is mostly car-bound. Online retailing sees a lower increase than in the other narratives. The use of public transport is sharply reduced, and active transport modes revert back to pre-COVID-19 levels as well. In the *smart use* scenario, domestic tourism is rediscovered, and business trips are partially substituted by video conferencing. Partial teleworking remains common after the discovery of better work-life balance benefits and productiveness levels. Increased adoption of online retail leads to an increase of road freight activity and reduced shopping trips. The use of mass transit of reduced: short-distance trips are replaced by non-motorized transport, while partial teleworking reduces the need for commuting. Finally, active mobility modes increase slightly as levels of usage during the pandemic are retained, driven by increased health benefits and perceived reduction of pollution levels. In the *green push* scenario, international tourism is reduced, and low-carbon modes dominate domestic travel. Business travel is strongly muted due to common video conferencing and discouraging policies. Commuting level are reduced due to a high share of teleworking and online retail is increasing. Targeted incentives lead people back to mass transport options and investment active mode infrastructure together with disincentivizing use of private cars sharply increases the use of private transport modes.

These narratives were used to quantify transport sector energy demand under each scenario (see detailed description of the quantitative analysis and assumptions in Supplementary Note 2). We used the MESSAGEix-GLOBIOM SSP2 scenario as starting point and combined the GDP projections in combination with the bottom-up scenario analysis to determine relative changes in energy intensity of transport as the joint effect of economic recovery and sectoral structural change.

Industry and material production

For the quantification of industrial activity, we have used the level and intensity of material production as a proxy, both of which are directly impacted by the GDP shock. The pandemic changed total industrial production levels as well as production structures. Changes in individual lifestyles, institutional, social and commercial settings had a direct impact on industry[46,47], and activity in industry was impacted indirectly as a result of changed demand in products in other sectors.

We use developments in a handful of driving elements as starting point for the industrial recovery scenarios: manufacturing activity, raw material availability, upstream sectors, labour markets, digitalization, individual mobility changes, and construction and renovation changes. In the *restore* scenario, changes are driven by GDP, and recovery follows the patterns as foreseen under the SSP2 scenario. Under the *self-reliance* scenario activity levels, structures, and facility management aim to return to normal, but with extended purposes resulting from foreseeing new pandemics. Acquisition of raw materials is preferred from local sources, nationalization and protectionism, focus on local storage[48]. Falling export markets and protection of home production and sales determine the demand for manufacturing products, while labor markets return to a pre-pandemic situation. Under this scenario, there is a lot of duplication of digital and offline solutions and increased hygiene, driving up material demands. In *smart use*, production repurposing and reduced activity due to process and material efficiencies inherited from the lockdown determine the level of activity. Raw materials are available, but transportation costs and risks of export availability are priced in. Digitalisation and efficiency-uptakes influence demand in primary sectors and labour market reorganization reduces primary and secondary sector workers. Digitalization drives a moderate impact from online shopping, such more packaging, more freight transport and more demand for electronics. Reduced overall transport demand impacts automobile production. In the *green push* scenario, manufacturing activity is driven by a thorough drive to increased process and material efficiencies. There is a focus on raw material efficiencies and on the balance between transportation and local solutions in the light of sustainability. Upstream demand is driven by further increases in digitalization, efficiency and a focus on circular economy, while labour markets see financial and social support to adjust to a greener industry. There is further enhancement of digitalization impacts with policies towards efficiency improvements.

These narratives were used to quantify industry sector energy demand under each scenario (see details and assumptions in Supplementary Note 3). We used the MESSAGEix-GLOBIOM SSP2 scenario as starting point and combined the GDP projections in combination with the bottom-up scenario analysis to determine relative changes in energy intensity of industry as the joint effect of economic recovery and sectoral structural change.

Buildings

We use data on activity (floorspace) and energy intensity derived from the base-year information in ref. [19] as the starting point for two global regions, Global North and Global

South. We estimated the use factor of total space in the residential and the non-residential sectors in the base year (2019). This estimate is based on vacancy rates due to second homes, relocation, lack of tenants, etc. (using ref. [49]), as well as occupancy rates (space and time) in homes, offices, and retail (using refs. [50,51]**)**, in addition to assessing the additional energy demand for heating/cooling for longer occupancy[50,51]. We assumed changes in three dimensions: (1) change in total space due to additional construction, demolition or repurposing as a secondary effect, (2) change in the use factor of space respectively in the two sub-sectors, and (3) the energy intensity of space demand in terms of thermal and electric energy demand.

In 2020, the impact on the total levels of activity (floorspace) is considered to be zero. However, region and country specific stringency of pandemic measures critically transform the way buildings are used. A larger impact is observed in the Global North due to the dominance of hard lockdowns combined with incentives to stay-at-home, while typically less comprehensive and curfew-based measures are observed in the Global South[52].

We determine the consequences of the pandemic-induced space reorganisation in thermal and electric demand with a bottom-up approach also on the medium-term, reflecting in the level of persistence of the behavioural, infrastructural, and business model changes. The key drivers influencing behaviour and lifestyle change are relocation of work and education, new business models for entertainment, socialisation, administration, services, etc. There are important differences between the Global North and Global South, with emerging economies yet performing along a different trend. We describe these below for each scenario.

In the *restore* scenario, none of the changes experienced in 2020 persist and recovery follows the patterns as foreseen under the SSP2 scenario. The *self-reliance* scenario for buildings is characterized by extension of distancing measures due to persistence of higher hygiene distancing preference and fear of new pandemics. In the Global North teleworking persists at low levels, but leading to duplication of digital and offline solutions, and duplication of home offices and office buildings. Energy demand is high due to this duplication of buildings and a reversal of the sharing economy trends observed in past years. Homes are used intensively by being inhabited for more hours per day[17]. The emergence of secondary homes increases the average floor space per person. And the increased time spend at home increases energy demand for cooking, crafting, ICT usage and entertainment.

In the *smart use* scenario, the building sector is characterized by the transformation of building space for work, leisure, administration, and services. This increases the energy intensity of floorspace mainly due to higher use of residential buildings, which is not compensated by a similar reduction in commercial and public buildings because of increased idle floorspace. In spite of the limited teleworking potential in much of the Global South[53], a similar, though smaller change can be seen (+4% intensity), due to already high multi-purpose use of buildings. In the *green push* scenario, the increase of energy demand (+4%) in homes as result of the increased teleworking and other activities at home (cooking, crafting, entertainment) can be fully compensated by space reductions and efficiency gains in non-residential buildings (-15% per capita). This is achieved through a reduction of workspace for part-time teleworkers, reorganization of public space, and the persistence of business model changes that emerged during the pandemic. These counterbalancing trends result in an overall net-zero change in building energy demand in 2025 compared to 2019.

The above narratives were used to quantify the energy demand changes with bottom-up approach under each scenario and combined with the GDP projections based on the MESSAGEix-GLOBIOM SSP2 scenario, to determine relative changes in final energy intensity of the building sector as the joint effect of economic recovery and sectoral structural change. For more detailed information, see Supplementary Note 4.

Mitigation analysis

Besides middle-of-the-road reference scenarios, which do not assume any specific ambitious climate policies, we also considered scenarios that achieve the Paris Agreement goals. The goals of maintaining global temperature increase by 2100 below 2C or 1.5C have been frequently modelled in the IAM community by imposing global or regional carbon prices on GHG emissions throughout the decades. Another common approach in optimization models like MESSAGEix-GLOBIOM is to impose a cumulative carbon budget and let the model find economically optimal mitigation strategies. For this analysis we combined both these approaches, as described in ref. [54]) to produce scenarios that meet pre-defined carbon budgets (550 GtonCO2 and 1000 GtonCO2 for 1.5C and below 2C scenarios respectively) until reaching net-zero emissions by mid-century, while staying at net-zero CO2 emissions afterwards. These scenarios are modelled as a combination of carbon prices and constraints on emissions and are independent from the COVID-19 related assumptions. This scenario set-up allows us to combine climate mitigation targets with different post-pandemic recovery pathways compare be differences of these latter under different perspectives.

Data availability

All data sources used for this study are cited in the Supplementary Information. Data are also available from the corresponding author upon request. Model code has been published open source at https://github.com/iiasa/message_ix.

The results presented in this article explore only a small portion of the model outputs from our scenario analysis. The ENGAGE Scenario Explorer hosted by IIASA provides access to a database of all variables of interest, defined for each scenario and broken down to MESSAGE regions https://data.ene.iiasa.ac.at/engage/ .

The Scenario Explorer is a versatile open access tool to browse, visualize and download data and results. Users can freely create a private workspace where customized plots can be saved and shared.

Peer-Review: reviewers can access and visualize the scenario data developed in this study, please go to https://data.ene.iiasa.ac.at/engage/#/login, and log in with the following credentials:

Username: COV_review

Password: COV_password

For tutorials on how to use the scenario explorer, please visit https://software.ene.iiasa.ac.at/ixmp-server/tutorials.html

SR1.5 scenarios have been made available through refs. [55,56] at https://data.ene.iiasa.ac.at/iamc-1.5c-explorer/.

Author contributions

J.S.K. and A.V. coordinated the study, performed and analyzed the model runs, and made the visualizations. B.B. and F.L. performed the bottom-up energy activity and structural change analysis. F.L., B.B., J.S.K., A.V., B.v.R. designed and analyzed the energy demand pathways. B.Z. and O.F. contributed to modeling and scenario runs. J.R. and C.W. designed the scenario typology and mitigation pathway selection. K.R. conceived the study. All authors contributed to writing and reviewing the manuscript and analysis.

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Competing interests

The authors declare no competing interests.

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