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

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Abstract: The COVID-19 pandemic caused radical temporary breaks with past energy use trends. How 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 effect of demand changes persisting. Our pathways project final energy demand reductions of 1 to 36 EJ/yr by 2025 and cumulative CO2 emissions reductions of 14 to 45 GtCO2 by 2030. Uncertainty ranges depend on the depth and duration of the economic downturn and demand-side changes. Recovering from the pandemic with energy-efficient 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 1.8 trillion USD, and softens the pressure to rapidly upscale renewable energy technologies.

Main text

Introduction paragraph

The ongoing COVID-19 pandemic has a far-reaching impact on society, with different repercussions across countries worldwide. The containment measures to limit the spread of the virus have resulted in reduced business activities, an increase in unemployment, travel restrictions, gathering limitations, and changes in manufacturing and trade, affecting both the economy and people's daily lives[1–3]. As a consequence, people have had to temporarily change their lifestyles drastically, leading to changes in society's demand for energy on a daily basis[1,4,5], leading to immediate observable effects on air quality, energy demand, and greenhouse gas emissions, with several studies estimating the impact of restrictions on global CO_2 emissions[4,6,7]. Although the global drop in greenhouse gas emissions in 2020 is very likely to be the largest on record in a single year[8], temporary short-term reductions will not avert global temperature rise unless they are followed by long-term structural changes in energy systems[4,9].

Governments have proposed and implemented major fiscal stimulus packages to help recover economies from this ongoing crisis. This has created a widely-discussed opportunity for a 'green' and climate-positive recovery towards a net-zero emissions future[10]. Recent research has shown that policy support for decarbonization efforts in energy and transport is expected to increase[11] and has identified policies for positive climate and economic recoveries[12]. However, in part due to the complexity of socially driven change, energy-economy modelling research has not yet focussed on assessing the potential impacts of demand-side effects on climate mitigation challenges[13,14].

In this study, we assess the potential effect of COVID-19 induced impacts on energy demand through recovery scenarios that vary the persistence of changes observed over the past year. We contribute a quantitative global analysis of how the near-term COVID-19 shock and alternative medium-term recovery pathways of demand-side changes could affect long-term energy demand. We find that enabling a low energy demand recovery can help reduce the costs of meeting Paris Climate Agreement targets.

An extreme event in a long-term model framework

Assessing the effects of drastic near-term changes over the medium to longer-term is challenging because it requires holistic treatment of both temporary and structural socioeconomic changes that together define a set of alternative future pathways[15,16]. Recent studies have mostly assessed the observed impacts of lockdown measures in some western countries on the energy sector and CO2 emissions[6] and have tried to project trends for the coming decades following the 2020 shock[4,15]. Some studies have focused on specific sectors like mobility[17] or the power[18] sector. Other studies[16,19] have modelled links between current economic recessions and future projections of CO2 emissions but only at the country level. Such studies do not explicitlyconsider different levels of persisting demand-side changes with feedbacks in an integrated energy-economy analysis.

Here, we combine a detailed bottom-up assessment of reported changes of energy services and energy demand in 2020 with macro-economic modelling of sectorial changes driven by economic factors. First, we compare activity levels and energy service use intensities during the 2020 shock with historical data in three key sectors: transport, buildings, and industry. Our focus is on social, behavior, business-model and infrastructure changes associated with COVID-19 restrictions. We then systematically evaluate medium-term uncertainties through a scenario design that illustrates distinct recovery pathways. These include regionally heterogeneous economic responses of varying intensities (through a GDP sensitivity analysis).

We construct possible recovery scenarios that either seize opportunities towards a new normality or revert back to energy system structures that existed before the pandemic. Each of the energy pathways is illustrated with a set of assumptions consistent with the persistence of activity and structural changes (Table 1 and Figure 1). We use the MESSAGEix-GLOBIOM Integrated Assessment Model (IAM)[20] to capture global economy, energy, and climate dynamics and feedbacks in the medium to long-term, including regionally heterogeneous responses to the COVID-19 emergency. 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 and other pandemic measures have had major impacts on energy-related activity, mostly on international travel, commuting, use of space, e-commerce, and use of technologies[21]. In turn, this has affected energy demand in 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 types and amounts of energy services consumed in each sector (see Methods and Supplementary Note 1-5). We assess the direct impact of COVID-19 on the use of residential and commercial floorspace, use of electric appliances, travel (by mode), and industrial output. We find global final energy demand in 2020 to be about 25 EJ (6%) lower than it would have been without the pandemic. 9 EJ of reductions are attributable to industry (6% sectoral reduction) and 20 EJ to transport (17% reduction). In contrast, the buildings sector shows a small increase in demand of 5 EJ (3% increase), as growth in residential energy use growth has been only partially offset by reductions in commercial and public building energy use (Figure 2a-c)[22,23]. As a result of these observed changes, we estimate total CO2 emissions in 2020 to be around 7% or 3 Gton lower than they would have been without the pandemic (Figure 2d). This provides an independent estimate within the range of earlier estimates[4,6,8].

How these observed near-term impacts on demand-related activity play out over the medium-term to 2025 is highly uncertain. We construct and analyze four scenarios to systematically explore this uncertainty space using a branching point design. The first branching point distinguishes recovery pathways that move towards restoring pre-pandemic ‘normality’ from pathways that seize opportunities towards a ‘new normality’ (Figure 1). The second branching point distinguishes pathways with weaker or stronger responses to the demand-side changes experienced during lockdowns.

Table 1 summarizes the main elements of of the four scenario narratives, along with the detailed assumptions about activity and structural changes in transport (modal shares), buildings (domestic-commercial-retail shares), and industry (production of different materials) over the period until 2025. The activity-structure-intensity methodology follows the approach of ref. [24] (Supplementary Notes 1-5 for full details). Economic uncertainty around GDP decline and recovery is further explored using sensitivity analysis with regional detail (Supplementary Note 6).

The *restore* and *self-reliance* scenarios describe recovery pathways characterized more strongly by path-dependence and system inertia. *Restore* sees a strong return to pre-pandemic energy-related activity and structure. S*elf-reliance* comes with an amplified emphasis on individualism and national isolation, with less cooperative economic and social integration. S*elf-reliance* implies increased use of private vehicles and larger working and home office spaces (Tables

Table 1).

The *smart use* and *green push* scenarios describe recovery pathways that learn from experiences during lockdowns. *Smart use* sees positive experiences with enforced behavioral changes enduring over the medium-term. For example, increased awareness of the impacts of air pollution, health and wellbeing benefits of less carbon-intensive transport, benefits of less commuting time, and more teleworking become embedded in new social patterns affecting energy-related activity in both buildings and transport sectors (Figure 1). *Green push* illustrates strong learning supported by structures that enable enduring changes in active travel, digital substitution for physical transport, efforts to reduce health risks in public transport, and directed downsizing of underused retail and commercial buildings space. These distinct scenario narratives focus on the first and second-order effects on the energy transition given the varying persistence of COVID-19 impacts on energy demand. It is not the aim of this study to assess the dynamic of implementing specific policies, which would deserve a separate dedicated effort that also explicitly explores governance contexts.

Depending on the scenario, global energy demand surpasses 2019 levels between 2021 and 2023, with global final energy demand in 2025 remaining 1-36 EJ/yr lower than a counterfactual no-pandemic scenario and with different sectoral dynamics (Figure 2a-c). The *green push* scenario is the only scenario to delay the rebound in energy demand considerably. Notably, *smart use* still sees a rebound of energy due to higher energy demand.

The range of final energy outcomes for the buildings and industry sectors across our four COVID-19 shock-and-recovery scenarios is relatively small compared to the full uncertainty range in future forecasts. In contrast the range in transport final energy in 2025 due to COVID-19 recovery assumptions is almost four times as large as the the projection uncertainties across five different IAM pathways simulating national policies without a pandemic (after harmonizing in 2020) (Figure 2e). To get a sense of the magnitude of this change, transport energy demand reductions in *green push* by 2025 relative to a counterfactual *no-Covid* scenario are equivalent to a 12% reduction in global passenger transport activity (holding constant modal shares and fuel efficiencies). Alternatively, similar levels of energy demand reductions could have been achieved by shifting 18% of private transport activity to public transport, or by electrifying approximately a third of global private road transport activity (if change were globally uniform).

Global CO2 emissions follow a similar trend, but pre-pandemic levels are reached between 2023-2033 depending more strongly on the recovery pathway (Figure 2e). The cumulative carbon reduction is 14-45 GtCO2 by 2030 compared to a counterfactual scenario without a pandemic. This reduction is attributable to the energy demand reductions in industry and transport, with the latter accounting for most of the variation between scenarios. Pre-pandemic, it was already clear that current climate action is inconsistent with the Paris Agreement's ambition of limiting global warming to well below 2°C and pursuing to limit it to 1.5°C[25]. Our COVID-19 shock-and recovery demand-side scenarios do not alter this picture, in the absence of additional stringent climate policies. 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 the activity and structural changes in buildings, transport and industry (grey shaded area in Figure 2d). Even with very strong reductions in global GDP, carbon budgets consistent with Paris Agreement goals will still be depleted fast (Figure 2f-g). At most, it delays their depletion by 3 to 5 years (for 1.5°C and 2°C, respectively) compared to a scenario without the pandemic. This emphasises the continued importance of stringent and sustained climate policies alongside or as part of the economic recovery.

The strongest CO2 reductions are found in the *Global North.* Projected growth in energy and emission trends dominate the relatively small COVID-19 demand change effect in the *Global South* (Supplementary Note 5.1 for more detail, region definitions in Supplementary Note 1).

Energy transition challenges under alternative recoveries

Across a diverse set of indicators, a lower energy demand *green push* recovery is found to have the lowest climate mitigation challenge (Figure 3, more regional detail in Supplementary Figures 19-26, and the online Scenario Explorer tool under Data Availability). Here we discuss the relative differences between scenarios staying below a 1.5°C target, investigating the effects of missing opportunities to maintain parts of the energy reductions observed during the pandemic. A demand-side recovery from the pandemic which locks in high energy demand practices means system-wide post-recovery decarbonization rate has to be up to 3% faster over the period 2025-2040 (*self-reliance*). The largest variation in decarbonization rates across scenarios is from transportation energy demand (4% for *smart use* to 8% for *self-reliance* with increased private vehicle use). Demand-side decarbonization rates for industry (3 to 5%) and residential and commercial buildings (2 to 5%) are slightly less dependent on the overall recovery (Figure 3 *Decarbonizing Buildings, Industry, Transport*).

Pathways that aim to stabilize global temperatures around 1.5°C require considerable energy investments. Even if differences in the required pace of decarbonisation are small, maintaining lower energy demand as in *green push* reduces energy investments until 2030 considerably. Letting energy demand *restore* to pre-pandemic structures instead means about 9% higher investments (Figure 3 *Energy Investments*) or 1.8 trillion US dollars globally. The additional energy investments required for a *self-reliance* recovery that still meets the 1.5°C targets amount to 3.5 trillion (18%). The potential missed opportunity for reducing energy investment needs is largest in the Global North (up to 21% for *self-reliance*). Similarly, the simulated aggregate carbon pricing until 2030 to meet the 1.5°C target is significantly higher for *self-reliance* (15%) and *restore* (19%) compared to *green push* (Figure 3 *Carbon Costs*). Thus, if the post-COVID-19 recovery fails to embed low-carbon activity and structural change, economic incentives to decarbonise the system must be markedly stronger, particularly in the *Global North* due to the larger impact of COVID-19 on activity, energy and emissions compared to the *Global South* (Supplementary Note 5.1).

Increased near-term transport energy demand forces transport electrification to be faster to meet the 1.5°C climate target. Electricity in transport in 2030 accounts for 9.5 EJ/yr in the *green push* scenario (11% of transport final energy). In the *self-reliance* scenario it is higher at 12 EJ/yr (12% of transport final energy). These noteworthy differences in the relative speed of electrification in Figure 3 (*Electrification Transport*) show the greater electrification challenge for transport if passenger mobility recovers from the COVID-19 shock mostly in the form of private vehicle use, increasing transport electricity from 1.7 EJ/yr in 2019. Failing to push for a green recovery that includes modal shift risks increasing the electrification challenge in the order of 13 trillion EV-kilometers extra per year by 2030 or about an extra 8 times the 2019 global electricity demand from EVs[26].

A low-carbon energy transition requires strong decarbonisation of the energy supply as well. Higher global energy demand means faster renewables growth to reduce emissions. Consequently, the share of electricity coming from wind and solar installations in 2030 could be more than 5% higher in *self-reliance* than in *green push,* requiring a 10% faster upscaling of non-biomass renewable energy generation (Figure 3 *Electricity Generation*). Regardless of the recovery pathway, the transitional challenge is large. Wind and solar electricity shares for 2030 range between 49% and 54% in our 1.5°C scenarios, up from 8% in 2019.

Alongside rapid renewables deployment, rapid fossil fuel phase out is another energy transition challenge. Lower energy demand in the near term is associated with faster phase-out of coal-fired power generation . This comes with potential near-term social challenges, though these are regionally heterogeneous due to different coal plant characteristics (Figure 3 *Coal Phase-out*). None of the presented scenarios with ambitious climate mitigation strategies towards 1.5°C see a recovery of coal use for energy after the steep reduction during the 2020 pandemic[27].

Medium-term green recovery yields climate mitigation benefits

Most scenarios that aim to limit global warming to 1.5°C show global net-zero CO2 emissions around 2050[28]. This requires fast and continued emission reductions through the decarbonization of energy systems. The pre-pandemic global emission level of about 42 GtCO2/yr[29], which was still trending upwards, would leave less than 10 years before closing the door on limiting temperature increase to 1.5°C [25,30].

Our study confirms that the direct effect of the COVID-19 pandemic lockdowns on global emissions is negligible in the context of this challenge. The effects of the persistence of activity changes alone (14-45 GtCO2 less by 2030 compared to scenarios pre-COVID-19) are not nearly sufficient to meet emissions reduction targets, which require more fundamental structural 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. Additionally, we calculate that if the energy demand recovery pathways were combined with an equal carbon price trajectory consistent with the 1.5°C target, a *green push* recovery could avoid another 24 GtCO2, compared to *restore*.

Because of the urgent need for strong CO2 emission reductions, seizing opportunities for maintaining energy demand changes (*green push*) can increase the probability of staying below 1.5°C, reducing the cost of similar emissions abatement. Conversely, a recovery pathway with higher energy demand means further efforts are needed by 2030 to achieve an additional 2.5 EJ/yr electricity for transport, an additional 5% electricity generation share from wind and solar, and invest an additional 3.5 trillion USD. These additional efforts are on top of already highly ambitious decarbonisation needs. We also find these comparative differences between scenarios to be robust for different climate mitigation goals (Supplementary Figure 25 for comparison with the wider scenario literature).

Insights for an energy demand recovery

It is important to understand to what extent different behavioral and structural changes drive emissions or enable emissions reductions. We have shown the implications of four alternative internally-consistent pathways of energy demand recovery from the COVID-19 shock, and have quantified first-order effects of demand-side changes in each pathway.

The full sectoral contributions to CO2 emissions savings from demand-side changes include both direct end-use emissions and indirect effects on emissions in manufacturing, supply chains, and production. For industry, these upstream effects of energy-demand reduction are a much larger portion of the change than for transport CO2 change, which is mostly related to direct energy end-use (Supplemental Note 5.3). Even after accounting for upstream effects, the CO2 emissions savings that could persist related to the pandemic are predominantly transport related. Full transport CO2 reductions by 2025 in *green push* without additional climate policies would amount to about 9% of the emission reductions in a *restore* 1.5°C consistent pathway. Looking at relative emission changes in sectors when switching from *restore* to *green push* further illustrates the relative importance of the transport sector. Between the two scenarios, increased emissions related to residential and commercial buildings are about an order of magnitude less than transport-related reductions. Emissions reductions in the transport sector are also about 4 times larger than in the industry sector. This relative difference in emissions saving increases to 8 times when additionally applying a stringent 1.5C consistent climate constraint, illustrating that the persistence of transportation changes is key to the differences in mitigation challenges we report in our results, especially in the *Global North* where higher shares of the workforce have the resources to change commuting habits.

There is no magic bullet for reaching Paris Climate Agreement goals. However, guiding post-pandemic recovery in energy demand-related activities towards less energy-intensive activities is an important part of the arsenal. Supporting working from home and teleconferencing to reduce flying and commuting can have strongly beneficial outcomes for emissions, especially if combined with the rationalization and reduction of office space, other workspace, reduced administration (e.g. public), entertainment, shopping spaces and intensities (*green push*). With online, delivery-based, less material intensive alternatives becoming popular during the pandemic, reducing the carbon intensity of such services is important too, albeit not a dominant factor currently. In addition, enabling the shift to more active transport and more public transport under mitigated health and safety risks is important. Industrial supply chain rationalization and moderation of freight distances can help further decrease emissions. For more sectoral detail and intersectoral comparison of the magnitudes of change in terms of activity and energy intensity, see Supplementary Notes 2-5.

This study has systematically explored the consequences of persistent energy demand shifts for energy transition challenges, acknowledging large economic uncertainty. The insights from this study provide the background against which proposed recovery packages can be evaluated. Investigating potential additional path dependency of either intensifying or weakening structural changes related to shifts in lifestyles beyond 2025 could usefully expand on this work.

References

1. van Ballegooijen, H., Goossens, L., Bruin, R. H., Michels, R. & Krol, M. Concerns, quality of life, access to care and productivity of the general population during the first 8 weeks of the coronavirus lockdown in Belgium and the Netherlands. *BMC Health Serv. Res.* **21**, 1–8 (2021).
2. Fernandes, N. Economic Effects of Coronavirus Outbreak (COVID-19) on the World Economy. *SSRN Electron. J.* (2020). doi:10.2139/ssrn.3557504
3. Nicola, M. *et al.* The socio-economic implications of the coronavirus pandemic (COVID-19): A review. *International Journal of Surgery* **78**, 185–193 (2020).
4. Forster, P. M. *et al.* Current and future global climate impacts resulting from COVID-19. *Nat. Clim. Chang.* 1–7 (2020). doi:10.1038/s41558-020-0883-0
5. Jiang, P., Fan, Y. Van & Klemeš, J. J. Impacts of COVID-19 on energy demand and consumption: Challenges, lessons and emerging opportunities. *Appl. Energy* **285**, 116441 (2021).
6. Le Quéré, C. *et al.* Temporary reduction in daily global CO2 emissions during the COVID-19 forced confinement. *Nat. Clim. Chang.* 1–7 (2020). doi:10.1038/s41558-020-0797-x
7. Liu, Z. *et al.* Near-real-time monitoring of global CO2 emissions reveals the effects of the COVID-19 pandemic. *Nat. Commun.* **11**, 5172 (2020).
8. Friedlingstein, P. *et al.* Global Carbon Budget 2020. *Earth Syst. Sci. Data* **12**, 3269–3340 (2020).
9. Sharmina, M. *et al.* Decarbonising the critical sectors of aviation, shipping, road freight and industry to limit warming to 1.5–2°C. *Clim. Policy* 1–20 (2020). doi:10.1080/14693062.2020.1831430

10. Andrijevic, M., Schleussner, C.-F., Gidden, M. J., McCollum, D. L. & Rogelj, J. COVID-19 recovery funds dwarf clean energy investment needs. *Science (80-.).* **370**, 298 LP – 300 (2020).

11. Pianta, S., Brutschin, E., van Ruijven, B. & Bosetti, V. Faster or slower decarbonization? Policymaker and stakeholder expectations on the effect of the COVID-19 pandemic on the global energy transition. *Energy Res. Soc. Sci.* **76**, 102025 (2021).

12. Hepburn, C., O'Callaghan, B., Stern, N., Stiglitz, J. & Zenghelis, D. Will COVID-19 fiscal recovery packages accelerate or retard progress on climate change? *Oxford Rev. Econ. Policy* **36**, S359–S381 (2020).

13. Creutzig, F. *et al.* Towards demand-side solutions for mitigating climate change. *Nature Climate Change* **8**, 268–271 (2018).

14. Creutzig, F. *et al.* Beyond Technology: Demand-Side Solutions for Climate Change Mitigation. *Annu. Rev. Environ. Resour.* **41**, 173–198 (2016).

15. Dafnomilis, I., Elzen, M. Den, Hans, F. & Kuramochi, T. Exploring the impact of the COVID-19 pandemic on global emission projections Assessment of green versus non-green recovery. (2020).

16. Malliet, P., Reynès, F., Landa, G., Hamdi-Cherif, M. & Saussay, A. Assessing Short-Term and Long-Term Economic and Environmental Effects of the COVID-19 Crisis in France. *Environ. Resour. Econ.* **76**, 867–883 (2020).

17. Keramidas, K. *et al. Global Energy and Climate Outlook 2020 : A New Normal Beyond Covid-19*. (JRC Science for Policy Report, 2021). doi:10.2760/608429

18. Bertram, C. *et al.* COVID-19-induced low power demand and market forces starkly reduce CO2 emissions. *Nat. Clim. Chang.* **11**, 193–196 (2021).

19. Lahcen, B. *et al.* Green Recovery Policies for the COVID-19 Crisis: Modelling the

Impact on the Economy and Greenhouse Gas Emissions. *Environ. Resour. Econ.* **76**, 731–750 (2020).

20. Huppmann, D. *et al.* The MESSAGEix Integrated Assessment Model and the ix modeling platform (ixmp): An open framework for integrated and cross-cutting analysis of energy, climate, the environment, and sustainable development. *Environ. Model. Softw.* **112**, 143–156 (2019).

21. International Energy Agency (IEA). *Energy Efficiency 2020*. (2020).

22. Madurai Elavarasan, R. *et al.* COVID-19: Impact analysis and recommendations for power sector operation. *Appl. Energy* **279**, 115739 (2020).

23. Hook, A., Court, V., Sovacool, B. K. & Sorrell, S. A systematic review of the energy and climate impacts of teleworking. *Environ. Res. Lett.* **15**, (2020).

24. Grubler, A. *et al.* A low energy demand scenario for meeting the 1.5 °c target and sustainable development goals without negative emission technologies. *Nat. Energy* **3**, 515–527 (2018).

25. Rogelj, J., Forster, P. M., Kriegler, E., Smith, C. J. & Séférian, R. Estimating and tracking the remaining carbon budget for stringent climate targets. *Nature* **571**, 335–342 (2019).

26. International Energy Agency (IEA). *Global EV Outlook 2020. Global EV Outlook 2020* (2020). doi:10.1787/d394399e-en

27. *Global Energy Review 2020. The impacts of the Covid-19 crisis on global energy demand and CO2 emissions*. (2020). doi:10.1787/a60abbf2-en

28. IPCC. *Special Report on Global Warming of 1.5C. Global Warming of 1.5 °C: An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening*

the global response to the threat of climate change (2018).

29. Friedlingstein, P. *et al.* Global Carbon Budget 2020. *Earth Syst. Sci. Data* **12**, 3269–3340 (2020).

30. Mengis, N. & Matthews, H. D. Non-CO2 forcing changes will likely decrease the remaining carbon budget for 1.5 °C. *npj Clim. Atmos. Sci.* **3**, 1–7 (2020).

31. Huppmann, D. *et al.* IAMC 1.5°C Scenario Explorer and Data hosted by IIASA. (2019). doi:10.5281/ZENODO.3363345

32. Krey, V. *et al.* MESSAGEix-GLOBIOM Documentation-2020 release. (2020).

33. Huppmann, D. *et al.* The MESSAGEix Integrated Assessment Model and the ix modeling platform (ixmp): An open framework for integrated and cross-cutting analysis of energy, climate, the environment, and sustainable development. *Environ. Model. Softw.* **112**, 143–156 (2019).

34. Messner, S. & Schrattenholzer, L. MESSAGE-MACRO: Linking an energy supply model with a macroeconomic module and solving it iteratively. *Energy* **25**, 267–282 (2000).

35. Fricko, O. *et al.* The marker quantification of the Shared Socioeconomic Pathway 2: A middle-of-the-road scenario for the 21st century. *Glob. Environ. Chang.* **42**, 251–267 (2017).

36. Riahi, K. *et al.* The Shared Socioeconomic Pathways and their energy, land use, and greenhouse gas emissions implications: An overview. *Glob. Environ. Chang.* **42**, 153–168 (2017).

37. Rogelj, J. *et al.* Energy system transformations for limiting end-of-century warming to below 1.5 °C. *Nature Climate Change* **5**, 519–527 (2015).

38. McCollum, D. L. *et al.* Energy investment needs for fulfilling the Paris Agreement and

achieving the Sustainable Development Goals. *Nat. Energy* **3**, 589–599 (2018).

39. Riahi, K. *et al.* Chapter 17: Energy pathways for sustainable development. (2012).

40. The World in 2050 (TWI2050). *Innovations for Sustainability. Pathways to an efficient and post-pandemic future. Report prepared by The World in 2050 initiative.* (2020). doi:10.22022/TNT/07-2020.16533

41. O'Neill, B. C. *et al.* The roads ahead: Narratives for shared socioeconomic pathways describing world futures in the 21st century. *Glob. Environ. Chang.* **42**, 169–180 (2017).

42. Riahi, K. *et al.* The Shared Socioeconomic Pathways and their energy, land use, and greenhouse gas emissions implications: An overview. *Glob. Environ. Chang.* **42**, 153–168 (2017).

43. Apple. Apple LLC Mobility Trends Reports.

44. COVID-19 Community Mobility Reports.

45. Andrijevic, M., Schleussner, C.-F., Gidden, M. J., McCollum, D. L. & Rogelj, J. COVID-19 recovery funds dwarf clean energy investment needs. *Science (80-.).* **370**, 298–300 (2020).

46. Altig, D. *et al.* Economic uncertainty before and during the COVID-19 pandemic. *J. Public Econ.* **191**, 104274 (2020).

47. The World Bank. *Global Economic Prospects, January 2020 : Slow Growth, Policy Challenges*. (2020). doi:10.1596/978-1-4648-1469-3

48. The World Bank. *Global Outlook: Pandemic, Recession: The Global Economy in Crisis*. (2020). doi:10.1596/978-1-4648-1553-9_ch1

49. Estrada, F., Tol, R. S. J. & Gay-García, C. The persistence of shocks in GDP and the estimation of the potential economic costs of climate change. *Environ. Model. Softw.* **69**, 155–165 (2015).

50. Google. Google LLC Community Mobility Reports.

51. Parkinson, J. Coronavirus: Traffic ‘reaching early 1970s levels’. *BBC News* (2020).

52. GEP. Impact of COVID-19 on the Medical Supply Chain. *Supply Chain Blog* (2020).

53. AFRY. *Global disruption: the impact of COVID-19 on the bioindustry sector*. (2020).

54. PWC. Preparing the chemicals industry for ‘the day after’ the COVID-19 pandemic. *News on COVID-19* (2020).

55. Huuhka, S. Vacant residential buildings as potential reserves: a geographical and statistical study. *Build. Res. Inf.* **44**, 816–839 (2016).

56. Statista. Vacancy rates of office space in selected cities worldwide in 2018 and 2021. *Statista* (2021).

57. O’Brien, W. *et al.* An international review of occupant-related aspects of building energy codes and standards. *Build. Environ.* **179**, 106906 (2020).

58. O’Brien, W. & Yazdani Aliabadi, F. Does telecommuting save energy? A critical review of quantitative studies and their research methods. *Energy and Buildings* **225**, (2020).

59. Hale, T. *et al.* Oxford COVID-19 Government Response Tracker. (2020).

60. International Labour Organization (ILO). *Working from Home: Estimating the worldwide potential. International Labour Organization Policy Brief* (2020).

61. Rogelj, J. *et al.* A new scenario logic for the Paris Agreement long-term temperature goal. *Nature* **573**, 357–363 (2019).

62. Huppmann, D., Rogelj, J., Kriegler, E., Krey, V. & Riahi, K. A new scenario resource for integrated 1.5 °C research. *Nat. Clim. Chang.* **8**, 1027–1030 (2018).

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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.

Competing interests

The authors declare no competing interests.

Figure Captions

Figure 1: Scenario design along the axis of COVID-related impacts. Note that y-axis denotes disturbance compared to pre-pandemic ‘normality’, and not an increase in demand. Bar charts show relative changes in energy-related activity between 2019 and 2025 in passenger mobility, freight transport, buildings (residential and non-residential), and industrial sectors for the four

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. Indicators are passenger-kilometer (p.km), tonne-kilometer (t.km), meter squared-degree days (m^2.DD), and material production in million tonnes (Mt).

Figure 2: Final energy and emissions pathways under alternative COVID-19 recovery scenarios and their combination with economic uncertainty. Final energy use for the buildings (a), transport (b), industry (c) sectors. Total annual CO2 emissions, including National Determined Contributions (NDCs) and National Policies from CD-LINKS scenarios (d), from ref.[31]. Sectoral final energy in 2025 compared with five global integrated assessment model pathways simulating national policies. A: AIM/CGE 2.1, I: IMAGE 3.0.1, P: POLES CD-LINKS, R: REMIND-MAgPIE 1.7-3.0, W: WITCH-GLOBIOM 4.4, for scenario CD-LINKS_NPi. National policies are harmonized to the 2020 values in *Baseline-no-COVID* using a constant offset (e). Cumulative CO2 emissions starting from 2019, with global CO2 budgets visualized as reported in SR15 (f). Global GDP (market exchange rates) indexed to 2019 levels for our scenarios (bold), the pre-pandemic prediction (dashed line) and uncertainty range (g). Grey shading shows the sensitivity range considering GDP uncertainty (a-g), see Supplementary Note 6 for more detail.

Figure 3: 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* - green). 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.

Extended Data Figure 1: 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.

Extended Data Figure 2: 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.

Extended Data Figure 3: 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.

Extended Data Figure 4: 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.

Extended Data Figure 5: 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.

Extended Data Figure 6: 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.

Tables

Table 1: Sectoral elements of four scenario narratives. These elements represent potential avenues of reaching characteristic levels of persistence of sectoral changes in 2025, compared to 2019 levels. Indicated values are global aggregations of the estimation for the two macro-region Global North and Global South, 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 levels of private and public space usage in terms of size, intensity, and location.	Industrial activity, production levels, and supply chain structures return to pre-pandemic levels, thus coupled with the reduction in economic activity.
Self-reliance	Concerns about health risks remain for a longer time. Shift to private transport is combined with pre-pandemic teleworking levels, leading to a strongly muted overall increase in public transit (+3%) while car and 2-wheeler usage surges (+24%). Air travel is high (+11%). Freight activity nearly fully recovers, but to lower levels than counterfactual projections given by the persistence of the economic shock.	Health risk considerations and persistent social distancing behavior mean total utilization rate (m^2.degree-days) increases (+11% globally, +12% in residential, +9% in non-residential buildings). Both home usage (office, school, online services and e-retail), and shares of under-occupied but temperature-controlled non-residential space increase, and lead to duplication of certain personal space.	Growth in private space (living, working, travel) and new business solutions (online, thus delivery and packaging), a legacy of duplication of industrial sourcing (glocalization). The largest effect is demand for steel (+5-10%) due to machinery demand, chemical and paper (+2-3%) due to new uses. The combined effect with an economic recession results in a global +10% activity compared to 2019, which is 4% higher than it would be without a pandemic.
Smart use	Teleworking levels during the pandemic partially persist, leading to muted growth in the use of both light-duty vehicles (+3%) and public transport (+6%), compared to pre-pandemic structures. Surge in online retailing increases overall road freight activity. Aviation does not recover to pre-pandemic levels due to reduced international tourism (-4%).	Transformed space use for work, leisure, administration, and services becomes the norm, increasing the intensity of home space use (+9% utilization rate, i.e. m^2.degree-days), with moderate (+2%) increase of non-residential space, mainly driven by population increase, as space use intensity is unchanged.	Return to pre-pandemic production structures and levels, with minor material reduction and intensity improvement (e.g. as a legacy of cost pressures, staff shortage, automatization, etc.). Overall, the change is insignificant and only -1% lower than it would be without a pandemic, yet +7% in 2019, with large regional differences.
Green push	The large reduction in commuting trips and long-distance travel is highly persistent (-17% aviation). Especially in urban areas, private car use remains low (-7%). Transport needs are instead fulfilled by rail (+31%) and road public transport (+23%) in part enabled by lower actual and perceived health risks compared to other scenarios.	Utilization rate of buildings (+7% globally). Strong increase in the use of thermally-conditioned homes (+11%) due to relocation of work, services (schooling, retail, administration), and intensification of domestic activities (cooking, entertainment). Some offsetting effect by reduction and optimal use of non-residential space (-8%) and efficiency gains (-5%) due to user behavior and non-residential space optimization.	Increased efficiency in industries (as a legacy of the pandemic, where industries worked under labor and raw material shortage pressure). Rebalancing between local production and imports. Lower mobility and change in modal splits and building activity (global steel demand -5%, aluminum -3% compared to non-pandemic situation). Also impacts on building utilization moderates the increase of aluminum and cement. Increase in online shopping (packaging), stay at home (more hygiene) lead to changes in paper and chemical demand, and an overall increase in material production (+2%).

Methods

MESSAGEix-GLOBIOM

We use the MESSAGEix-GLOBIOM Integrated Assessment Model (IAM)[32] 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.

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[33]. MESSAGEix-GLOBIOM includes a linkage to 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[34].

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.[32]).

MESSAGEix-GLOBIOM has been widely used for the analysis of GHG emission pathways under a range of climate and socio-economic futures[35,36], as well as in the assessment of climate mitigation strategies including specific assessments of energy investment needs[37,38]. It has been one of the models informing global emission pathway analyses such as the reports of Intergovernmental Panel on Climate Change (IPCC)[28], Global Energy Assessment (GEA)[39], and the World in 2050[40]. 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, crucially allows for a better focus on the short-term dynamics that is important for COVID-19 shock-and-recovery scenarios.

The socio-economic assumptions of MESSAGEix-GLOBIOM are based on the Shared Socioeconomic Pathways (SSPs)[36,41], a set of internally consistent narratives, and assumptions for main socio-economic drivers widely adopted and updated by the Integrated Assessment Modelling community[42]. SSP2 is adopted as the starting point for this analysis[35], because it is designed to extend historical trends.

The impact of COVID-19 on the economy is modelled based on external GDP estimates for 2020, and sees a four-year recovery to ‘reference’ growth rate values of SSP2 in the main scenarios. Energy demand reductions are a result 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 rates* and *autonomous energy efficiency improvements (AEEI)*, which guarantee that the desired trend of GDP and energy demand in MACRO align with the exogenously defined values over time. The alternative energy demand pathways thus come with slightly different *AEEI* values. Further details on the calibration process can be found in refs[32,34].

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[43,44]. It has changed the activity, structure, and intensity (ASI) components of our mobility, how we use residential and public buildings and workspaces, and the production of goods and materials. The changes that we have taken into account are direct, or first-order impacts induced by the COVID-19 pandemic itself and the containment measures, such as local and national lockdowns, distancing requirements, higher hygiene standards, as well as restricted international trade and travel[4,6]. We also included second-order (indirect) effects of inter-sectoral changes. The energy demand shock before macro-economic calibration was assessed using a bottom-up approach mostly independent from the economic downturn. We did this by assessing changes in activity and structure in three demand sectors: transport, buildings, and industry.First we collected data on observed demand shocks during the COVID-19 crisis in each of the sectors (data until December 2020, collection cut-off date: March 2021). We mapped the 2020 data onto 2019 observations using a year-on-year method. Where no full-year data were available, we estimated 2020 values on a cluster of impact assessments taking into account the peak impacts. Then, we combined assessments of individual sub-sectoral activity reductions and aggregated them to calculate a total effect on global energy demand, extrapolated onto the spatial resolution of the MESSAGEix-GLOBIOM Integrated Assessment Model (IAM)[20]. A detailed description of the estimation of the 2020 energy demand shocks can be found in Supplementary Notes 2, 3, and 4 for the three demand sectors, respectively.

COVID-19 scenario framework

The recovery narratives in this study explore two principal uncertainties through a branching point design (Figure 1) exploring potentially persistent changes related to the demand-side shock during the pandemic. The medium-term trends (2021-2025) use 2019 as a base year to compare changes to the pre-pandemic levels. Detailed narratives and quantitative assumptions for the transport, industry and buildings sectors are described below and in Supplementary Notes 2, 3, and 4. These scenarios are considered baseline scenarios that do not include explicit climate policy assumptions. Our modeling approach does not include the dynamic modeling of specific policy interventions, such as the effects of the large-scale fiscal stimulus packages announced by many countries (see e.g. ref.[45]). Rather, the alternative scenarios assume different levels of persistence of COVID-19 related impacts, that are plausibly linked with narratives of demand-related changes, such as lifestyle changes (teleworking, entertainment and travel routines) or business models (online health consultations) that could be induced or pertained through various packages of policies and that can have benefits for climate mitigation. These pathways are combined with carbon budgets to create combined COVID-19-recovery and climate mitigation scenarios (see Mitigation analysis section of Methods).

GDP pathways, coupling, and sensitivities

Along with transformations in energy service demand, the COVID-19 pandemic has come with a major financial and economic crisis in 2020. 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 and after has been a challenge for economists, including the major financial institutes and central banks[46]. Consequently, initial, very uncertain estimates have been updated over time (e.g. refs. [47,48]). 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[49], 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, while allowing for macroeconomic feedbacks to energy demand shocks using the MESSAGE-MACRO iteration for each baseline calibration. We refrain from explicit exogenous coupling of GDP trajectories and energy scenarios because the nature of this crisis and its recovery is too uncertain to warrant such an approach. The main recovery scenarios discussed in the main text thus follow the same GDP recovery trajectory, with supplemental 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[43,50,51]. 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 the 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 in 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 levels 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 the detailed description of the quantitative analysis and assumptions in Supplementary Note 2). We used the MESSAGEix-GLOBIOM SSP2 scenario as a 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 the energy demand and climate impact of the industry sector, we have evaluated how the changes in 2020 in the activity, structure, and intensity (ASI) components of material production persist, 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[52,53], 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[54]. 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 as 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 a 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. [24] as the starting point for two global regions, Global North and Global South. We estimated the utilization factor of total space in the residential and the non-residential sectors in the base year (2019), expressed in floorspace.degree-days (m^2.DD). This estimate is based on vacancy rates due to second homes, relocation, lack of tenants in the residential sector (e.g. ref. [55]), and lack of tenants, closed, but not yet sold business space[56]as well as occupancy and thermo-regulation rates (space and time) in homes, offices, and retail (using refs. [57,58]), in addition to assessing the additional energy demand for heating/cooling for longer occupancy[57,58]. 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.DD) is 2% increase compared to 2019, because the decrease in the utilization of non-residential floorspace is compensated by an increase in-home use. Region and country-specific stringency of pandemic measures critically transforms 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[59].

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 behavioral, infrastructural, and business model changes. The key drivers influencing behavior and lifestyle change are the 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 with 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 the extension of distancing measures due to the persistence of higher health concerns and related distancing preference due to a fear of extended or 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[23]. The emergence of secondary homes increases the average floor space per person. And the increased time spent at home increases energy demand for cooking, crafting, ICT usage and entertainment.

In the *smart use* scenario, the building sector is characterized by a persistence of the transformation of building space for work, leisure, administration, and services experimented during 2020. As the intensity of used floorspace remains unchanged, the energy intensity of total floorspace increases (+6% compared to 2019) due to a higher use of residential buildings (+9%), which is not compensated by a similar reduction in commercial and public buildings (0%) because of increased idle floorspace. In spite of the limited teleworking potential in much of the Global South[60], a similar change can be seen (+8% intensity), due to population increase and already high multi-purpose use of buildings. In the *green push* scenario, the increase of activity and energy demand per floorspace (+10,5%; +5% respectively) in homes as a result of the increased teleworking and other activities at home (cooking, crafting, entertainment) is moderated by space reductions and efficiency gains in non-residential buildings (-10,5%; -0.5%). 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 a 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. [61] 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 of the COVID-19 related assumptions. This scenario set-up allows us to combine climate mitigation targets with different post-pandemic recovery pathways and to compare thee differences of these latter under different perspectives. In addition, the scenario *restore* and *green push* have been run with the same carbon price that is consistent with 1.5C target (equivalent to the mitigation scenario Restore with 550 Gton CO2 budget). This allows studying the effect on emissions of different energy demand trajectory given the exact same carbon cost assumptions, in supplement of the above-mentioned setup that explores the economic differences while maintaining the same carbon emission goals.

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.

The results presented in this article explore only a small portion of the model outputs from our scenario analysis. A web tool hosted by IIASA provides access to a database of these and more variables of interest, defined for each scenario on the detail of MESSAGE regions, with a few example workspaces available within the ENGAGE Scenario Explorer at https://data.ene.iiasa.ac.at/engage/#/workspaces/60.

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.

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. [31,62] at https://data.ene.iiasa.ac.at/iamc-1.5c-explorer/.

Code availability

Model code has been published open source at https://github.com/iiasa/message_ix, with online documentation available at https://docs.messageix.org/en/stable/ and in ref.[32]. The code and data used to generate the figures in the main text is made available at 10.5281/zenodo.5081155.