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Demand vs supply-side approaches to mitigation: What final energy demand assumptions are made to meet 1.5 and 2 °C targets?

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ABSTRACT

Today's climate policies will shape the future trajectory of emissions. Consumption is the main driver behind recent increases in global greenhouse gas emissions, outpacing savings through improved technologies, and therefore its representation in the evidence base will impact on the success of policy interventions. The IPCC's Special Report on Global Warming of 1.5 °C (SR1.5) summarises global evidence on pathways for meeting below-2 °C targets, underpinned by a suite of scenarios from integrated assessment models (IAMs). We explore how final energy demand is framed within these, with the aim to making demand-related assumptions more transparent, and evaluating their significance, feasibility, and use or underutilisation as a mitigation lever. We investigate how the integrated assessment models compensate for higher and lower levels of final energy demand across scenarios, and how this varies when mitigating for 2 °C and 1.5 °C temperature targets through an analysis of (1) final energy demand projections, (2) energy-economy relationships and (3) differences between energy system decarbonisation and carbon dioxide removal in the highest and lowest energy demand pathways. We look across the full suite of mitigation pathways and assess the consequences of achieving different global carbon budgets. We find that energy demand in 2100 in the highest energy demand scenarios is approximately three to four times higher than the lowest demand pathways, but we do not find strong evidence that 1.5 °C-consistent pathways cluster on the lower end of demand levels, particularly when they allow for overshoot. The majority of demand reductions happen pre-2040, which assumes absolute decoupling from economic growth in the near-term; thereafter final energy demand levels generally grow to 2100. Lower energy demand pathways moderately result in lower renewable energy supply and lower energy system investment, but do not necessarily reduce reliance on carbon dioxide removal. In this sense, there is more scope for IAMs to implement energy demand reduction as a longer-term mitigation lever and to reduce reliance on negative emissions technologies. We demonstrate the need for integrated assessments to play closer attention to how final energy demand interacts with, relates to, and can potentially offset supply-side characteristics, alongside a more diverse evidence base.

1. Introduction

Consumption is arguably the strongest accelerator of climate change, and has effectively cancelled out any gains from low carbon technologies (Wiedmann et al., 2020). If rising demand for energy is not addressed (across more affluent populations), technological solutions have the increased pressure of counteracting rising demand (Haberl et al., 2020). Global mitigation scenarios tend to focus on technology and price solutions related to energy supply (Grubler et al., 2018, Gambhir et al., 2019, Kriegler et al., 2015, van Sluisveld et al., 2018), yet much less has been done to frame 1.5 and 2 °C pathways from a demand perspective across the Intergovernmental Panel on Climate Change (IPCC) mitigation assessments.

Most recently, chapter 2 of the IPCC Special Report on 1.5 °C (SR1.5) provides an assessment of the mitigation pathways consistent with limiting average global warming to 1.5 °C to 2 °C above pre-industrial levels. "[Integrated assessment models] lie at the basis of the assessment of mitigation pathways in this chapter, as much of the quantitative

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global scenario literature is derived with such models" (Rogelj et al., 2018b). This dominance means they play a leading role in the climate-science policy interface (van Beek et al., 2020, Keppo et al., 2021). While the report itself states the results are meant to be interpreted in a 'what if' context, some have questioned the extent to which such reports inevitably shape, potentially limiting, effective policy solutions (Beck and Krueger, 2016, Edenhofer and Kowarsch, 2015, Anderson, 2015, Hulme, 2016). While scenarios published in IPCC assessment reports are not designed to provide a comprehensive sample of the real world futures that might occur, it is important to reflect on how they frame the mitigation options available (and what they leave out), the sensitivity of the outcomes to the model inputs, and their societal and political feasibility, given their prominence (van Beek et al., 2020, Rosenbloom, 2017). We provide the first broad analysis of final energy demand (FED) in the mitigation pathways of the IPCC SR1.5 to increase transparency around demand-related assumptions.

Integrated assessment models (IAMs) are simplified representations of some of the complex interactions between human and natural subsystems used to evaluate the implications of climate policy decisions (Schwanitz, 2013). IAMs are intended to elaborate on developments to the energy system, land use and greenhouse gas emissions from a series of quantified socio-economic pathway narratives (Riahi et al., 2017). Modules representing the economy and energy system are linked to land and climate systems. Natural systems tend to be represented by physical laws, whereas human systems (e.g. energy supply and demand corresponding to levels of production and consumption) are governed by harder-to-measure preferences and behaviours that are constantly subject to change. They are informed by economic relationships, in which energy demand is optimised based on technology costs or energy prices, and historical relationships. These are implicitly uncertain and have been criticised for not being applicable to the wide variety of cultures and political contexts across the world (McCollum et al., 2017, Mercure et al., 2016, Gambhir et al., 2019).

The modelling process used to generate scenarios for SR1.5 starts with a list of common input assumptions describing a range of socio-economic drivers, including quantified estimates of economic growth, final energy demand (FED), population and technology developments, with narratives around political landscapes and lifestyles. Well-known examples are Shared Socio-economic Pathways (SSPs), providing the underlying logic for the quantifiable estimates (Riahi et al., 2017, O'Neill et al., 2017). Only very recently has energy demand reduction been linked to the activity level and intensity provided by end-use services such as thermal comfort, mobility, food and industry using IAMs (van Vuuren et al., 2018b, Grubler et al., 2018). This helps determine what lifestyle measures could actively reduce energy demand. Model outcomes on costs to the economy, emissions levels, energy system make up and land use changes are calculated through predefined equations, with arguably limited representation of feedbacks considered (Mercure et al., 2018), for example, how warming impacts on employment, consumption, and economic losses (Woodard et al., 2019).

SR1.5 analyses 222 scenarios from 25 IAMs that are 1.5 and 2 °C "consistent" in some way and which have varying socio-economic assumptions. Remaining carbon budgets consistent with these temperature targets depend on assumptions made about the acceptable probability of achieving a budget and whether and how much temporary temperature overshoot occurs (Rogelj et al., 2016). While all 1.5 and 2 °C-consistent pathways analysed in the SR1.5 rely on some level of carbon capture (afforestation and/ or technology), temperature overshoot in some pathways resulting from delayed mitigation is offset with greater use of carbon dioxide removal (CDR) technologies (Gasser et al., 2015). However, temporarily exceeding temperature targets compensated for by a sustained period of negative emissions later in this century comes with additional risks (Fuss et al., 2018). Some argue that relying on large-scale emissions capture will also impede earlier decarbonisation efforts (Minx et al., 2018, Gregory et al., 2018, Fuss et al., 2016, Fuss et al., 2018); technical potentials remain very uncertain (Anderson and Peters, 2016, Smith et al., 2016, Larkin et al., 2017); currently Nationally Determined Contributions (NDCs) are limited in their details to deploy CDR technologies, albeit emissions removals are within their scope; and policy instruments to mobilise them are fairly speculative (Honegger and Reiner, 2018, Gregory et al., 2018).

Mitigation scenarios within 1.5 and 2 °C pathways are characterised by major transformations in energy supply (Grubler et al., 2018), such as a complete phase out of fossil fuels, widespread increases in renewable energy, and improved energy efficiencies, alongside more often rapid increases in CDR (Rogelj et al., 2018a, Gambhir et al., 2017). While the development and deployment of low carbon energy technologies has prevented past emissions, technology improvements have in effect only moderated emissions from rising demand instead of contributing to absolute emissions reductions (Lamb et al., 2014, Csereklyei and Stern, 2015, Wiedmann et al., 2020). This is evident from past data which fails to show a decoupling of energy consumption from economic growth at a global scale (Hickel and Kallis, 2019), suggesting the need to combine technology improvements with sufficiency measures (Alcott, 2010).

While IAMs originate from different modelling domains, Keppo et al. (2021) suggest they have been converging. Relying on similar model types has implications for policy outcomes. Kriegler et al. (2015) found a distinct fingerprint of model structure emerged across their diagnostic analysis of the outputs of 11 global IAMs (21 are used in the SR1.5). The 11 IAMs surveyed responded relatively similarly to a carbon price in two distinct ways, with one set of models being more reliant on reducing the carbon intensity of energy supply and the other relying more on energy intensity improvements. The former set saw greater transformations in the energy system and higher emissions abatement. Whilst the different models provided a range of results, the distinct model structures implies IAMs are likely to be biased towards limited courses of action, but the authors do note the preliminary nature of this research. Beck and Krueger (2016) discuss the need improve understanding of the epistemic, ethical and political dimensions of modelling choices, demonstrating from the existing literature that the dominant market failure framing often assumed in IAMs side-lines non-market-based policy approaches and continues demand for studies that determine optical carbon prices or emissions caps. In other words, this domination reinforces specific outcomes, unless they are thoroughly reflected on. This reflexivity is somewhat lacking, but gaining traction.

Reframing emissions pathways around energy demand can challenge the prevalent techno-economic response to climate change to inform more ambitious demand reduction climate policies. This is not to underplay the role of CDR or other technologies, but to overcome issues around timing, lock-in and political (im)mobility. van Vuuren et al. (2018a) and Grubler et al. (2018) are the only SR1.5 pathways that focus on low energy demand. van Vuuren et al. (2018a) implement lifestyle change and more rapid electrification of energy demand to the IAM IMAGE, however these changes are complemented with a uniform carbon tax and lower levels of BECCS as they are not in themselves sufficient to meet the Paris Agreement. Grubler et al. (2018) project the lowest energy-demand scenario in the MESSAGE-ix/GLOBIOM IAM, achieved through improvements in energy efficiency e.g. retrofitting programmes and improved building standards, and changing forms of energy service provision including, digitalisation, sharing and dematerialisation. Both studies are framed in terms of reducing or eliminating reliance on negative emissions technologies. Our analysis explores how the full suite of IAMs reported by the IPCC SR1.5 respond to different FED assumptions. This helps us understand what variables are traded-off with high levels of energy demand, and vice versa, how model variables respond when lower demand levels are assumed. We analyse only final demand levels assumed in the IPCC SR1.5, however, we argue in the discussion the need for more diverse quantitative and qualitative approaches to contribute to the evidence base, including higher demand reduction scenarios, like those recently published in Millward-Hopkins et al. (2020).

2. Methods

We analyse FED across a range of emissions scenarios from the IPCC SR1.5 that achieve end of century warming of 2 °C or lower, aligned with the Paris Agreement. 217 scenarios are selected from the IAMC 1.5 °C Scenario Explorer (Huppmann et al., 2018a, Huppmann et al., 2018b, Huppmann et al., 2018c) using the same temperature categories defined in SR1.5, shown in Table 1. In SR1.5 222 scenarios were analysed across these categories, however five of them do not include assumptions for final demand within the database and are therefore excluded here, e.g. C-ROADS model.

The analysis is split into five parts, as described in Table 2, demonstrating (1) how FED is characterised across scenarios; (2) the relationship between economic growth and FED; (3) differences between the highest and lowest FED pathways; (4) decarbonisation characteristics consistent with growth in FED using simple correlations; and (5) impacts on achieving carbon budgets. Assumptions around FED are constrained to the pre-determined range included in the scenario explorer tool. Most model variables are projected at five or ten year intervals. When calculating cumulative emissions we have linearly interpolated between years. When correlating FED with temperature, (negative) emissions and CDR trajectories we model an *absolute* change in the level of variables from 2020 to 2100, however, for correlations with energy supply we model the *percentage* growth in variables between 2020 and 2100, not the absolute level of change. Where we indicate a change in the share of energy we calculate a percentage growth in the share of that energy source relative to the total. CDR growth rates were very high due to the sudden and sharp introduction of these technologies, whereas it was more intuitive to look at the percentage (share) increase/decrease in renewable/ fossil fuel energy sources.

In section 3.1 we apply a k-means clustering technique to the final energy timeseries across all the models to identify common shapes in the FED pathways. K-means clustering is an unsupervised approach that optimises the location of a pre-defined number of cluster centres to minimise the distance of all datapoints from the cluster average. Here we use dynamic time warping to compare timeseries, as this accounts for small temporal shifts in otherwise similar timeseries, which with a

Table 1
Categorisation of emissions pathways.

Temp. goal	Temp. category	Pathway selection criteria	No. of scenarios
1.5 °C	Below 1.5 °C	Pathways limiting peak warming to below 1.5 °C during the entire 21st century with 50–66% likelihood	7
	1.5 °C with low overshoot	Pathways limiting median warming to below 1.5 °C in 2100 and with a 50–67% probability of temporarily overshooting that level earlier, generally implying less than 0.1 °C higher peak warming than Below-1.5 °C pathways	43
	1.5 °C with high overshoot	Pathways limiting median warming to below 1.5 °C in 2100 and with a greater than 67% probability of temporarily overshooting that level earlier, generally implying 0.1–0.4 °C higher peak warming than Below-1.5 °C pathways	35
2 °C	Lower 2 °C	Pathways limiting peak warming to below 2 °C during the entire 21st century with greater than 66% likelihood	74
	Higher 2 °C	Pathways assessed to keep peak warming to below 2 °C during the entire 21st century with 50–66% likelihood	58
Total	2 °C or lower	All of the above	217

Table 2
Analysis summary.

Key research questions	Detailed research questions	Analysis
Section 3.1. How is energy demand projected in SR1.5?	What levels of FED are projected across the mitigation scenarios?	Time series of absolute and per capita FED shows variations in FED trajectories by temperature category. Distributions of FED projections in 2100 and cumulatively from 2020 to 2100 shows the range of FED assumptions across models and scenarios.
	How does the rate of change of FED differ?	Shape-based cluster analysis identifies distinct patterns of FED trajectories. Percentage change in FED in 2100 relative to 2020, and at 20 year intervals (2020–2040, 2040–2060, 2060–2080, 2080–2100) indicates time-dependency.
	What sectors drive changes in FED?	Correlation of changes in FED and FED for industry, transport and residential and commercial to identify sectoral drivers. Distribution of cumulative sectoral FED from 2020 to 2100 compared across temperature categories.
Section 3.2. To what extent is energy demand decoupled from economic growth?	What happens to GDP across the scenarios?	Percentage change in GDP in 2100 relative to 2020 and the distribution of GDP in 2100 summarise economic growth assumptions.
	What levels of decoupling are projected?	Comparison of past and projected rates of change in FED compared to GDP to show variation in decoupling projections across median and high and low FED scenarios.
Section 3.3. How do the lowest and highest FED pathway decarbonisation characteristics differ in 2 °C or lower pathways?	What energy sources and levels of CDR are present in the lowest and highest energy demand scenarios?	Comparison of decarbonisation characteristics (including energy system and emissions changes) in 2020, 2050 and 2100 for the lowest and highest energy demand pathways for 1.5 and 2 °C, compared to median scenarios.
Section 3.4. Do levels of FED drive systemic changes in energy system decarbonisation and CDR across scenarios?	What energy sources are being used to meet FED?	Correlation of changes in FED with growth in electrification and the share of fossil fuels, non-biomass renewables, biomass and nuclear in the energy mix.
	Are levels of CDR deployed dependent on growth in FED?	Correlation of changes in FED with changes in absolute levels of sequestered carbon from biomass, fossil energy and land use change; the year of net negative emissions; and cumulative sequestered biomass-based carbon from 2020 to 2100.

(*continued on next page*)

Table 2 (*continued*)

Key research questions	Detailed research questions	Analysis
	What are the implications of FED on energy investment costs?	Correlation of changes in FED with percentage change in investment in energy supply and electricity supply from 2020 to 2100.
Section 3.5. What are the implications of energy demand for achieving temperature-related carbon budgets?	What is the relationship between energy demand and temperature overshoot and cumulative emissions?	Correlation of percentage change in FED with level and year of peak temperature and cumulative CO_2 emissions from 2020 to 2100.

simple point-by-point comparison would appear to be very different. We first standardise the data so every timeseries has a mean of 0 and variance of 1 in order to cluster according to the shape of the final energy pathway, and not the absolute values. We ran the algorithm five times with different random seeds and used the outcome that best minimised the distance to the cluster centres. The analysis was performed using the TimeSeriesKMeans function of the tslearn Python package. We tested the use of 3–5 cluster and present results using 4 clusters as this provided the most distinct set of pathways.

For the correlations in section 3.1, 3.4 and 3.5 we have generated the Pearson's correlation coefficient (r) to indicate the strength of the relationship between two variables, and a two-tailed p-value to determine the statistical significance. However, we note that many IAMs share similar structures (Kriegler et al., 2015), and the same models are used for multiple scenarios, therefore the assumptions that all points are independent of each other does not necessarily hold and can reduce the statistical significance. We use it as an indicative measure to explore possible correlations of different IAM variables. Not all models include all variables, as shown in Table 2.SM.6 in Forster et al. (2018), and therefore some variables will have more or less datapoints than others. The number of scenarios that include the variable of interest are given in figures and captions.

3. Results

Each research question is taken in turn. Sub-sections first provide a brief summary of chapter 2 of the SR1.5 report (Rogelj et al., 2018b) in relation to the research question, providing context, followed by our analysis. A summary of the main findings is provided in the conclusions.

3.1. How is final energy demand (FED) projected in SR1.5?

FED is driven by demand for mobility (transport), residential and commercial buildings and manufacturing (industry), which are reliant on assumptions about socio-economic futures depicted in the SSPs. SR1.5 says that "[1.5 °C-consistent pathways] tend to cluster on the lower end for energy … demand. They still encompass, however, a wide range of developments from decreasing to increasing demand levels relative to today" (pg. 110). A new Low Energy Demand (LED) scenario from Grubler et al. (2018) is included in SR1.5 reflecting a strong demand-side focus. Energy demand reductions are quoted as "key and common features in 1.5 °C pathways" (pg. 136), however, our results below do not fully support this.

What levels of FED are projected across the mitigation scenarios? Levels of FED in 2020 across the models are between 344 and 478 EJ, with the majority of mitigation scenarios projecting levels of between 360 and 840 EJ by 2100 (for cumulative results see section 1.2 of the Supporting information, SI). Levels of FED in the mitigation scenarios are reduced compared to equivalent high emissions scenarios from the same IAM (section 1.1, SI). Less than 5% of mitigations scenarios project a reduction in energy demand from 2020 levels, with the SR1.5 LED pathway reducing FED to 235EJ in 2100 (245EJ in 2050). For context, this is 40% higher than Millward-Hopkins et al. (2020) estimate for the global energy required for universal decent living standards, which requires a much more equitable distribution of energy consumption. Trends are similar from a per capita perspective (section 1.3, SI).

Fig. 1a shows FED trajectories by temperature category, with the medians for each category highlighted in bold. The median of below 1.5 °C scenarios has the lowest FED, and the order from lowest to highest corresponds to the end-point target, except for the median for 1.5 °C with overshoot, which consistently rises. We do not find that 1.5 °C-consistent pathways tend to cluster on the lower end for energy when looking at 2100 FED levels (colour coded blue and green in Fig. 1b), yet it is more evident from a cumulative perspective (section 1.2, SI). Pathways classed as 1.5 °C-consistent can be found across the spectrum of low and high FED levels in 2100, however, 1.5 °C scenarios with low or no overshoot represent the lowest cumulative energy demands in the dataset, and 1.5 °C with high overshoot and 2 °C scenarios represent the highest cumulative energy demand levels.

How does the rate of change of FED differ? Fig. 1c clusters FED pathways by the shape of trajectory. It shows four distinct clusters of final energy demand trajectories from 2020 to 2100 with the centre of each cluster shown in bold. These have been normalised which ignores the level of demand and instead focuses on the pattern of FED trajectories. 5% of FED pathways are in cluster four which rises and then falls beyond the mid-century, 7% of pathways are in cluster three which falls sharply to 2040 then rises to levels lower than 2020, nearly a third of pathways are in cluster two which shows early reductions up to 2030, but then rises above 2020 levels, and the majority (57%) are in cluster one which shows constant increases in FED. Therefore scenarios which project lower (cluster 4) or similar (cluster 3) energy demand levels in 2100 relative to present are a clear minority. We analyse decarbonisation differences in low, median and high demand scenarios which highlight differences within and between clusters in section 3.3.

Fig. 1d shows the percentage change in FED in 2100 from 2020 by temperature category. Results within the interquartile range (25th–75th percentiles) indicate an inclination towards lower levels of demand growth for lower temperature categories without high overshoot. However, the full range of demand levels across temperature categories are similar, ranging from reductions of 45% to more than double current day levels. Below 1.5 °C (with no overshoot) is the only temperature category whose median scenario projects a reduction in demand levels (of 7%) by 2100, yet this category is comprised of only 7 out of 217 scenarios, and three of the scenarios project an increase in FED by 2100. Growth in median FED for 1.5 °C with low overshoot and lower 2 °C scenarios is around 25%, compared to 50% in higher overshoot scenarios.

Almost all FED reductions are anticipated in the short term (pre-2040) with more sustained growth thereafter, as highlighted by the cluster analysis where only the smallest cluster ($n = 10$) shows any reductions in FED post-2040 (Fig. 1c) (changes at 20 year intervals are given in section 1.4 of the SI). For example, scenarios aiming for below 1.5 °C without any overshoot achieve a mean change of −29% by 2040 (−48 to +20% 5–95th percentile range), followed by 10 to 20% of growth every 20 years to 2100. This is consistent with the fact that five of the seven scenarios are in clusters two and three, which show this early decrease. Similar growth rates are observed after 2040 across virtually all temperature categories. Demand reduction can be inferred as a short-term measure to allow the energy system to decarbonise and removal technologies to be deployed, but not necessarily a long term measure to be sustained.

What sectors drive changes in FED? Changing levels of energy demand are more strongly correlated with demand for energy in industry/ manufacturing ($r = 0.9$, $p < 0.01$) and buildings ($r = 0.84$, $p < 0.01$) than transport ($r = 0.34$, $p < 0.01$), as shown in Fig. 1e-g. Lower growth rates of FED are met by similarly lower rates of energy demand

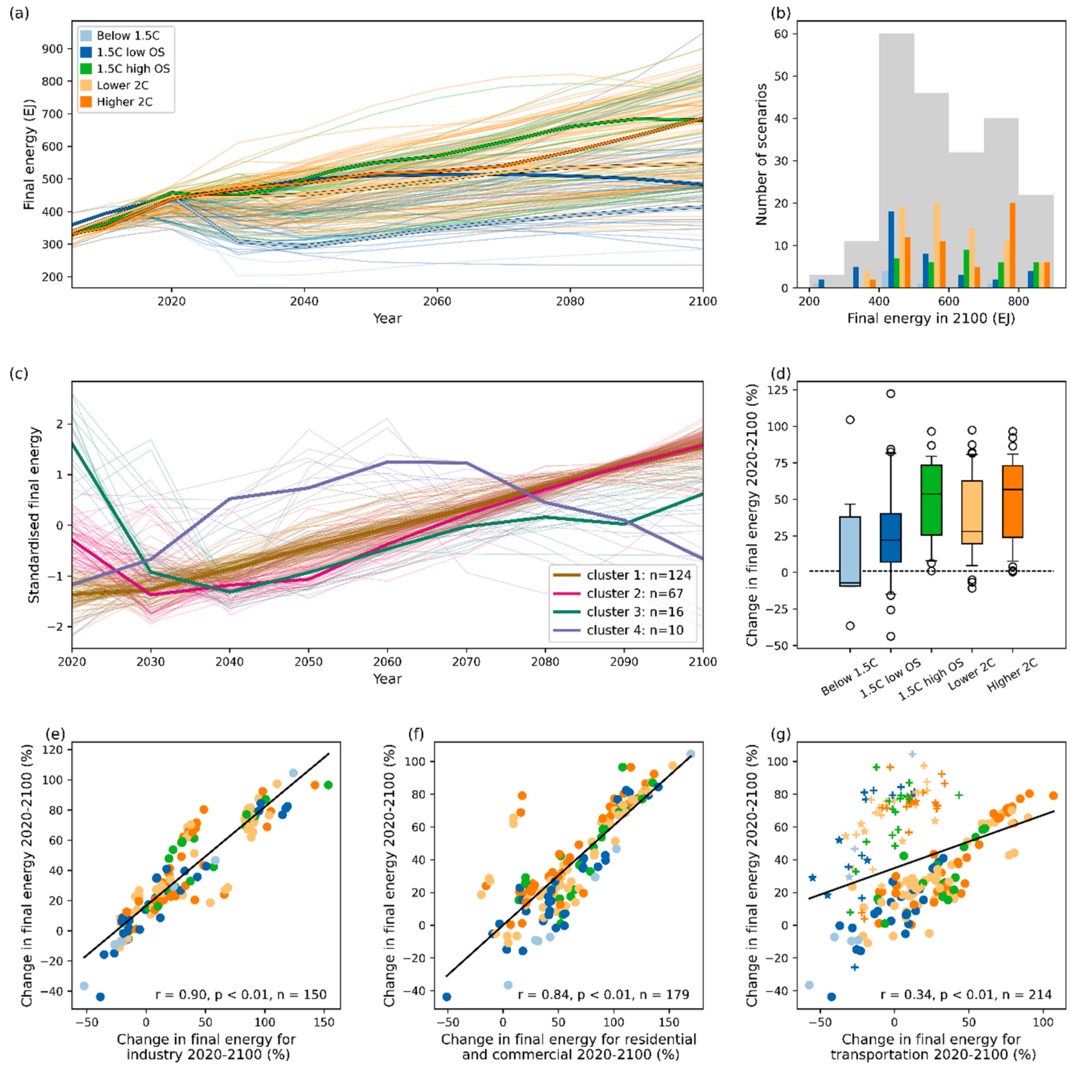

Fig. 1. Final energy demand (FED) characteristics. (a) projected FED levels from 2010 to 2100 for all scenarios (thin lines) and the scenario with the median FED in 2100 for each temperature category (thick lines); (b) distribution of FED levels in 2100 for all scenarios (grey) and broken down by temperature category (colours); (c) shaped-based cluster analysis of FED trajectories; (d) boxplots of % change in FED from 2020 to 2100 (box boundaries represent the 25th and 75th percentiles, the line inside the box is the median, whiskers show the 5th and 95th percentiles and the circles show outliers); (e-g) scatterplots of % change in FED and % change in FED for (e) industry, (f) residential and commercial buildings, and (g) transport sectors for 2020 to 2100. n = number of scenarios. In (g) the data points from the REMIND and WITCH IAMs are shown as crosses and stars respectively. The black line shows the linear least-squares regression fit to all the data. 'r' and 'p' values shown represent the Pearson correlation coefficient and significance value respectively. The colour legend in panel (a) applies to all subpanels except (c).

for industrial and residential and commercial uses. While the relationship with energy demand for transport is considerably weaker, Fig. 1g shows a cluster of scenarios towards the top left, represented by crosses and stars. These points relate to two distinct IAMs: REMIND (crosses) and WITCH (stars), where the positive correlation is much steeper in these two models. High growth in overall energy demand is found alongside lower rates of energy demand for transport. In relation to transport, both models implicitly consider energy efficiency improvements, higher shares of useful energy e.g. lightweight vehicles endogenously and reduced energy service demand, with REMIND being one of few IAMs to reduce energy demand for international transport (Table 2. SM.6, Forster et al. (2018)). Although not unique to these models, there are clearly some underlying differences in how they model energy demand for transport.

Cumulative FED for transportation from 2020 to 2100 tends to be on the lower end of scenarios for 1.5 °C targets with no or low overshoot (section 1.5, SI), which is less apparent for the other two FED sectors, which broadly consume more energy by 2100. The carbon intensity of industry and buildings is projected to be lower than transport in the SR1.5 (section 2.4.3), implying decarbonisation in transport across some IAMs is more dependent on demand reductions through structural changes including avoiding travel or shifting modes of transport, than mitigation strategies that reduce the carbon intensity of energy supply. However, not all IAMs feature structural change (section 2.4.3.3 SR1.5).

3.2. To what extent is energy demand decoupled from economic growth?

SR1.5 states that "[b]aseline projections for energy-related GHG emissions are sensitive to economic growth assumptions" (pg. 109), which is determined by underlying SSPs relating to human development and technological progress. High rates of decoupling of energy demand from economic growth are anticipated – "[a]lthough GDP increases by a factor of 3.4 from 2010 to 2050, the total energy consumption of end-use sectors grows by only about 30% and 20% in 1.5 °C overshoot and 2 °C-consistent pathways, respectively" (pg. 137), through full exploitation of supply-side decarbonisation.

What happens to GDP across the scenarios? The median GDP across scenarios is projected to increase 5-fold (i.e. 400%) by 2100, with

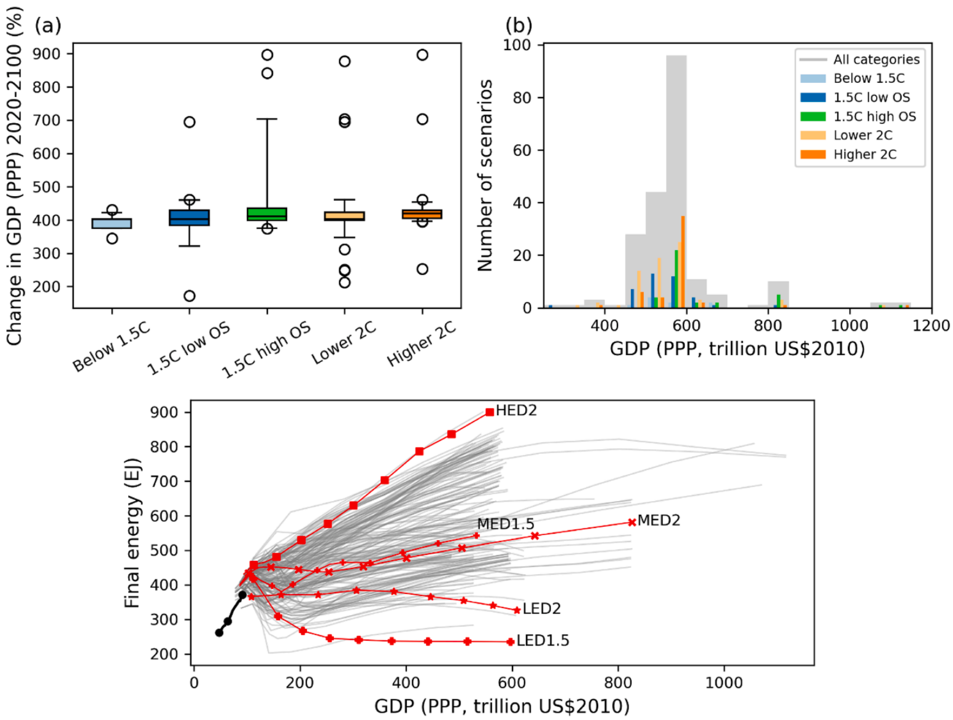

Fig. 2. Economic-based characteristics. (a) boxplot of % change in GDP (PPP) from 2020 to 2100 by temperature category (see Fig. 1 caption for boxplot description), (b) distribution of GDP (PPP, $US trillion 2010) in 2100 for all scenarios (grey) and broken down by temperature category (colours), and (c) observed (1990–2015) and projected (2020–2100) relationship between levels of FED and GDP for all scenarios with GDP projections (grey) and for the lowest (LED), highest (HED) and median (MED) final energy demand pathways corresponding to 1.5 and 2 °C. 202 scenarios have FED and GDP projections.

little difference in the 5th to 95th percentile range (Fig. 2a). GDP is measured as purchasing power parity (PPP) which is indicative of a country's standard of living (i.e. reflects costs of equivalent baskets of goods across countries). The distribution of GDP in 2100 across temperature categories exhibits little variation (Fig. 2b), with the majority of scenarios anticipating GDP in the region of $600 trillion in 2100, equivalent to just over 2% annual growth. However, GDP measures do not account for opportunities for (low carbon) growth compared to investment needs and the costs to the economy resulting from climate damages, which are likely to be strong determining factors going forward.

What levels of decoupling are projected? Fig. 2c compares observed (black) and projected levels of energy demand and economic growth (grey) for the mitigation scenarios, similar to Semieniuk et al. (2021) who devote a paper to analysing the trends summarised here. Bold red lines represent projections for the lowest, highest and median 2100 FED levels for scenarios achieving 1.5 and 2C targets. Observed energy and economic data (pre-2015) from the International Energy Agency (IEA) and World Bank respectively are not necessarily those used by IAMs and therefore observed and projected lines do not always connect. There is a gradual structural break in the energy-economy relationship towards lower levels of projected FED. Observed energy-economy relationships are reversed in the low energy demand scenarios towards sustained absolute decoupling. Median scenarios project relative decoupling compared the highest energy demand pathway that achieves much lower rates of relative decoupling. The 1.5 °C pathways show an immediate and sharp drop compared to 2 °C pathways, although this is accompanied by growth thereafter in the median scenarios. GDP is anticipated to grow 300–400% (four to five fold) by 2100 in the majority of scenarios, with the overall median scenarios growing just over 2% per year. The highest final energy demand pathway corresponding to 1.5 °C change does not have a GDP projection. Levels of FED increase less at 32% in the overall median scenario (23–73% interquartile range), growing at an annual rate of about 0.4% (0.3–0.7% interquartile range), yet reducing in the short-term (pre-2030). Without absolute decoupling, technology levels will have to compensate for increased consumption from growing economies.

3.3. How do the lowest and highest FED pathway decarbonisation characteristics differ in 2 °C or lower pathways?

Although the focus of most IAM scenarios is not on demand, SR1.5 does include for the first time a low energy demand scenario that is intended to "[facilitate] the rapid phase-out of fossil fuels and process emissions that exclude BECCS and CCS use" (pg. 122), with limited CDR from AFOLU including afforestation and reforestation. This is achieved by electrifying and dramatically reducing demand for transportation and manufacturing, resulting in negligible residual non-electric fuel (Grubler et al., 2018).

What energy sources and levels of CDR are present in the lowest and highest energy demand scenarios? We explore how the most extreme FED pathways achieve the same temperature end-goal, including median scenarios as a benchmark. Table 3 identifies the lowest, highest and median FED pathways corresponding to 1.5 and 2 °C

Table 3
Identification of the lowest and highest FED pathways for 1.5 °C and 2 °C. Cluster identifies which shape-based trajectory from Fig. 1c each scenario is grouped.

Pathway	FED	Temperature	Model	Scenario	Cluster
LED1.5	Low energy demand	1.5 °C	MESSAGEix-GLOBIOM 1.0	LowEnergyDemand	3
LED2		2 °C	AIM/CGE 2.0	SSP1-26	4
MED1.5	Median energy demand	1.5 °C	AIM/CGE 2.1	EMF33_WB2C_cost100	2
MED2		2 °C	POLES CD-LINKS	CD-LINKS_NPi2020_1000	1
HED1.5	High energy demand	1.5 °C	MERGE-ETL 6.0	DAC15_50	1
HED2		2 °C	REMIND 1.7	CEMICS-2.0-CDR20	1

Table 4
Decarbonisation characteristics in 2020, 2050 and 2100 of the lowest, highest and median FED pathways for 1.5 °C and 2 °C.

	Low energy demand pathways (LED)						Median energy demand pathways (MED)					
	1.5C			2C			1.5C			2C		
	2020	2050	2100	2020	2050	2100	2020	2050	2100	2020	2050	2100
Final Energy, EJ	418	245	235	366	385	326	432	442	542	434	437	581
Final Electricity*, EJ	85 (20%)	132 (54%)	128 (54%)	84 (23%)	169 (44%)	222 (68%)	85 (20%)	185 (42%)	311 (57%)	82 (19%)	149 (34%)	303 (52%)
Primary Energy, EJ	551	289	309	513	501	447	603	628	839	595	584	883
Fossil fuels w/ CCS*, EJ	–	–	–	–	58 (12%)	98 (22%)	–	163 (26%)	277 (33%)			
Fossil fuels w/o CCS*, EJ	454 (82%)	55 (19%)	2 (1%)	436 (85%)	222 (44%)	67 (15%)	522 (87%)	172 (27%)	87 (10%)			
Non-Biomass Renewables*, EJ	37 (7%)	164 (57%)	218 (71%)	21 (4%)	134 (27%)	181 (40%)	18 (3%)	140 (22%)	214 (26%)	27 (5%)	96 (16%)	201 (23%)
Biomass*, EJ	50 (9%)	45 (16%)	75 (24%)	42 (8%)	63 (13%)	78 (17%)	48 (8%)	134 (21%)	228 (27%)	60 (10%)	149 (26%)	316 (36%)
Nuclear*, EJ	11 (2%)	25 (9%)	15 (5%)	13 (3%)	24 (5%)	24 (5%)	14 (2%)	19 (3%)	34 (4%)	11 (2%)	40 (7%)	62 (7%)
BECCS, $MtCO_2$				–	416	3,028	–	2,831	7,770	–	3,294	22,299
Fossil-CCS, $MtCO_2$				–	4,138	6,192	–	163	277	3	2,562	8,915
Land use carbon Sequestration, $MtCO_2$	613	2,415	4,784	1,648	3,963	3,462						
Energy supply investment	1,169	1,054	960				1,523	2,799	3,955	1,879	2,958	6,853
Electricity supply investment*	611 (52%)	865 (82%)	855 (89%)				821 (54%)	2,062 (74%)	3,337 (84%)			
CO_2 emissions, $MtCO_2$	39,564	2,736	3,524	37,181	13,679	18	43,736	8,028	347	38,552	11,418	12,974
Year of negative CO_2 emissions	2060		2060	2070								
Cumulative CO_2 emissions, $MtCO_2$		473,517	391,419		771,950	988,478		645,287	611,020		822,476	660,773
Cumulative BECCs, $MtCO_2$					2,472	112,691		22,890	334,860		20,398	672,764

	High energy demand pathways (HED)					
	1.5C			**2C**		
	2020	**2050**	**2100**	**2020**	**2050**	**2100**
Final Energy, EJ	426	544	948	458	577	900
Final Electricity*, EJ	112 (26%)	342 (63%)	591 (62%)	94 (21%)	256 (44%)	596 (66%)
Primary Energy, EJ	538	666	1,180	610	714	1,304
Fossil fuels w/ CCS*, EJ	–	32 (5%)	167 (14%)	–	33 (5%)	64 (5%)
Fossil fuels w/o CCS*, EJ	425 (79%)	114 (17%)	99 (8%)	511 (84%)	289 (40%)	35 (3%)
Non-Biomass Renewables*, EJ	35 (7%)	304 (46%)	546 (46%)	28 (5%)	291 (41%)	960 (74%)
Biomass*, EJ	67 (12%)	188 (28%)	300 (25%)	62 (10%)	80 (11%)	218 (17%)
Nuclear*, EJ	12 (2%)	28 (4%)	68 (6%)	9 (1%)	20 (3%)	26 (2%)
BECCS, $MtCO_2$	–	7,923	14,414	–	2,135	8,307
Fossil-CCS, $MtCO_2$	–	2,398	10,197	–	2,361	3,304
Land use carbon Sequestration, $MtCO_2$				–	2,706	2,408
Energy supply investment				1,775	4,010	10,557
Electricity supply investment*				1,247 (70%)	3,356 (84%)	9,462 (90%)
CO_2 emissions, $MtCO_2$	39,452	8,268	42,664	45,912	14,978	16,974
Year of negative CO_2 emissions	2070	2070				
Cumulative CO_2 emissions, $MtCO_2$		722,547	54,504		869,457	600,581
Cumulative BECCs, $MtCO_2$		65,294	665,034		16,448	375,263

Note: Not all models and pathways cover all variables and therefore some cells have been left blank (see Forster et al. (2018) for detailed model descriptions).
*Percentages are given in brackets (electricity as a share of final energy, energy sources as a share of primary energy and electricity investment as a share of energy investment).

of warming, and Table 4 summarises their decarbonisation characteristics in 2020, 2050 and 2100. FED in 2100 in the high energy demand (HED) scenarios are approximately three to four times higher than the lowest in the respective temperature categories. LED1.5 is the lowest energy pathway and LED2 has the 4th lowest FED across all scenarios. The HED pathways have the two highest demand levels. Therefore, temperature is not the deciding factor in energy demand levels at these extremes. The highest energy demand pathways follow a very similar FED trajectory, while meeting a different temperature target, identified from the cluster analysis in Fig. 1c, whereas the lowest FED pathways are distinct in shape and end-point (i.e. they fall into different shape-based clusters). This section explores similarities and differences across their decarbonisation characteristics.

The share of fossil fuels with and without CCS is much higher in LED2 compared to LED1.5 and the share of renewables much lower. A reduction in FED levels is delayed in LED2 which relies on CDR, compared to LED1.5 where we see an immediate and sustained reduction in FED. The only CDR in LED1.5 is from land use change (reforestation and afforestation), compared to >9GtCO_2 being captured from biomass and fossil fuels in 2100 in LED2, amounting to 113 GtCO_2 cumulative BECCS by 2100. The two HED pathways have a similar FED trajectory. HED1.5 has a higher share of fossil fuels and lower share of renewables compared to HED2, yet is more reliant on CDR. Much more carbon is cumulatively sequestered in the HED pathways, with HED1.5 sequestering 665 GtCO_2 by 2100 (cumulatively). Emissions levels in 2100 are higher in the LED pathways. LED2 does not achieve net negative emissions, despite sequestering carbon, unlike LED1.5 which achieves net zero in 2060, but relies much less on CDR to meet targets. Both HED scenarios achieve net negative emissions in 2070, with HED1.5 capturing 2.5 times the amount in 2100. These factors affect the cumulative CO_2 emissions. LED1.5 has considerably lower cumulative CO_2 in 2050 than the other scenarios, but LED2 has the highest cumulative emissions in 2100 (less CDR and no net negative emissions). HED1.5 has the lowest cumulative emissions in 2100 due to much greater CDR levels. This comparison shows that FED levels are not dependent on the temperature target, and that even when trajectories of FED appear very similar, decarbonisation pathways compensate for high and low FED levels in very different ways. A low FED pathway is not necessarily a fossil-free one.

3.4. *Do levels of FED drive systemic changes in energy system decarbonisation and CDR across scenarios?*

SR1.5 describes how the energy system needs to decarbonise, electrify and remove carbon further and faster to achieve lower temperature targets, with higher supply-side investments, but say that "[m]uch hinges on the reductions in energy demand growth embodied in the 1.5 °C pathways, which require investing in energy efficiency" (pg. 154). They suggest that lower levels of energy demand allow for greater flexibility in how to structure energy supply, less reliance on CDR technologies (a feature prominent in almost all pathways), and lower investments, yet acknowledge the degree of demand-side investments is very uncertain and not well represented in IAMs.

What energy sources are being used to meet FED? Electrification is strongly linked to growth in FED ($r = 0.88$, $p < 0.01$]) (section 2.1, SI). The higher the demand for energy the greater the rate of electrification, alongside higher deployment of renewable energy. We find a strong correlation between the change in FED and non-biomass renewable energy in absolute terms ($r = 0.73$, $p < 0.01$) (section 2.2, SI), but a weaker correlation when looking at the changing share of renewables ($r = 0.44$, $p < 0.01$) (Table 5). When FED doubles, levels of renewable energy supply can increase more than 30 fold from 2020 levels. However, there were no statistically significant correlations with any other energy source in absolute terms.

Table 5 shows the correlation between change in FED and growth in shares of energy sources. While statistically significant, the correlations are weak, indicating the energy demand does not appear to exert a strong influence on energy supply characteristics. Higher levels of FED across all temperature categories are (weakly) accompanied with lower fossil-based energy shares (−0.34, $p < 0.01$), compensated for by higher shares of renewables ($r = 0.44$, $p < 0.01$). This relationship is strongest in the 1.5 °C high OS category. Growth in energy demand is negatively correlated with shares of biomass ($r = -0.49$) and nuclear ($r = -0.28$) energy, indicating potential generation capacity constraints explored more in section 2.3 of the supporting information. Despite lower shares at higher levels of FED, absolute levels of biomass and nuclear increase in the energy mix. In virtually all scenarios absolute levels of fossil fuels reduce, compared to increases in renewables, biomass and nuclear energy, however, as mentioned, the only significant correlation in absolute generation is with non-biomass renewable energy ($r = 0.73$, $p < 0.01$). This corresponds with the considerable variation in energy shares when comparing FED pathways in section 3.3 (Table 4). LED pathways are not necessarily fossil-free ones.

Table 5

Correlations between changes in FED and decarbonisation characteristics from 2020 to 2100 by temperature category. Decarbonisation characteristics include the share of energy sources, negative emissions (start year and volume captured), energy investment ($), cumulative emissions (Gt) and temperature (peak and year of peak). The number of scenarios is included in square brackets. Statistical significance (p) is indicated by the formatting: normal: 10%, bold: 5% and bold + italic: 1%.

	Share of fossil fuels (%)	Share of non-biomass renewables (%)	Share of biomass (%)	Share of nuclear (%)	Year net neg.	Cumulative BECCS ($GtCO_2$)	Biomass - CCS ($GtCO_2$)	Fossil - CCS ($GtCO_2$)
Below 1.5 °C	– [7]	– [7]	**−0.78 [7]**	**−0.85 [7]**	– [7]	– [7]	– [7]	0.82 [5]
1.5 °C low OS	**−0.32 [43]**	***0.41 [43]***	***−0.48 [43]***	***−0.4 [43]***	– [42]	– [42]	– [42]	– [32]
1.5 °C high OS	***−0.59 [35]***	***0.69 [35]***	***−0.45 [35]***	−0.3 [35]	– [35]	– [35]	– [35]	*−0.65 [24]*
Lower 2 °C	***−0.46 [74]***	***0.43 [74]***	***−0.51 [74]***	**−0.23 [74]**	– [55]	0.24 [61]	0.22 [61]	– [54]
Higher 2 °C	***−0.47 [57]***	***0.45 [57]***	***−0.34 [57]***	– [57]	– [40]	– [50]	– [50]	– [44]
All	***−0.34 [216]***	***0.43 [217]***	***−0.49 [217]***	***−0.28 [217]***	– [179]	– [195]	0.12 [195]	−0.13 [159]

	Land use sequestration ($GtCO_2$)	**Energy supply investment ($US)**	**Electricity supply investment ($US)**	**Peak temp (°C)**	**Year of peak temp.**	**Cumulative CO_2 emissions ($GtCO_2$)**
Below 1.5 °C	– [3]	– [3]	***1.0 [2]***	– [7]	**0.87 [7]**	– [7]
1.5 °C low OS	– [21]	***0.64 [24]***	**0.62 [16]**	0.27 [43]	– [43]	***−0.47 [43]***
1.5 °C high OS	– [16]	***0.54 [26]***	**0.45 [20]**	***0.6 [35]***	0.31 [35]	– [35]
Lower 2 °C	0.4 [30]	***0.87 [48]***	***0.5 [43]***	***0.39 [74]***	***−0.33 [74]***	**−0.27 [74]**
Higher 2 °C	0.62 [12]	***0.82 [33]***	***0.85 [33]***	– [57]	***−0.44 [57]***	−0.26 [57]
All	0.25 [82]	***0.68 [134]***	***0.56 [114]***	***0.35 [216]***	– [216]	– [216]

Note: when correlating FED and temperature, (negative) emissions and CDR trajectories we model a level change in the variables from 2020 to 2100, however, for correlations with energy supply and investment we model the percentage change in variables between 2020 and 2100 (see Methods).

The above trends are relatively representative across all temperature targets, except Below 1.5 °C. In this category lower levels of energy demand are more reliant on biomass and nuclear, but we cannot draw any conclusions from this due to the small sample size of 7.

Are levels of CDR deployed dependent on growth in FED? The type and level of sequestered carbon varies considerably within the highest and lowest demand pathways, and this changes little when looking across all mitigation scenarios (or within temperature categories): no significant correlations were found between changing levels of FED and the year of net negative emissions or the cumulative carbon sequestered (see Table 5). In the 82 scenarios that report carbon sequestration from land use, we find, with increasing strength, that higher levels of FED are combined with higher land use sequestration, however, there is little evidence to suggest that BECCS is used to offset higher growth in FED.

What are the implications of energy demand on energy investment costs? Regardless of levels of FED, investment in energy efficiency and renewable capacity needs to rise, and investment in unabated fossil fuels must stop. We find in those scenarios that consider investment (134 out of 217) that higher growth in FED is anticipated to increase energy supply investment (Table 5) ($r = 0.68$, $p < 0.01$), partly through electrification ($r = 0.56$). Hence, reductions in FED are likely to reduce energy system investments due to less supply to decarbonise, but it is unclear to what extent demand-side investments would offset reductions in supply-side investment. We find more variation in the relationship between investment costs and changes in FED in 1.5 °C pathways than 2 °C ones, which could reflect the halting of fossil fuel investments. Supply-side investment costs however are not weighted against the cost of inaction and rising costs of adaptation, nor an understanding of the necessary redistribution of subsidies from high to low carbon energy sources. While SR1.5 states "energy-related investments increase by about 12% (range of 3% to 24%) in 1.5 °C pathways relative to 2 °C pathways" (pg. 96), our relationship is stronger in the 2 °C scenarios ($r = 0.82$ and 0.85 respectively in Lower and Higher 2 °C).

3.5. What are the implications of energy demand for achieving temperature-related carbon budgets?

The low energy demand (LED) pathway in SR1.5 meets 1.5 °C with low overshoot (<0.1 °C) through "deeper emissions reductions in 2030 to limit the cumulative amount of CO_2 until net zero global CO_2 emissions (carbon neutrality)" (pg. 115), compared to higher CDR deployment rates which feature largely in high fossil fuel and high overshoot pathways.

What is the relationship between energy demand and temperature overshoot and cumulative emissions? We correlated the change in FED from 2020 to 2100 with temperature and emissions variables (peak temperature, year of peak temperature and cumulative CO_2 emissions) to see whether FED impacts on achieving carbon budgets. We find only a weak correlation with peak temperatures in Table 5 ($r = 0.35$). Besides weakly reducing peak temperature, low FED pathways in general do not tend to have much of an influence on cumulative carbon emissions. 1.5 °C high OS has the strongest correlation between FED and peak temperature. Higher FED correlates with temperature overshoot, implying lower levels of FED would reduce this overshoot. Higher growth in FED does not correlate with cumulative emissions up to 2100, implying other abatement efforts are mitigating the higher growth in demand. The analysis in section 3.4 however indicates that this is not necessarily through the use of BECCS, but more likely through greater deployment of renewable energy technologies.

4. Discussion and conclusions

We explored how final energy demand (FED) is framed across integrated assessment models (IAMs) in the IPCC's SR1.5, with the aim to making demand-related assumptions more transparent, and to evaluate their significance, feasibility, and use as a mitigation lever. We investigate how the IAMs compensate for higher and lower levels of final energy demand across scenarios, and how this varies when mitigating for 2 °C and 1.5 °C temperature targets. Interpretation of these results is important when making policy decisions on decarbonisation. Our conclusions are summarised in Table 6.

Table 6
Results summary.

Key research questions	Summary of results
How is energy demand projected in SR1.5?	Less than 5% of mitigations scenarios project a reduction in energy demand from current levels and over 80% have consistently rising trajectories, particularly post 2030. 1.5 °C-consistent pathways with no or low overshoot tend to cluster on the lower end of cumulative FED. Demand-reduction is generally a short-term measure that is not sustained. Post-2040 FED growth rates increase at similar levels across all temperature targets (~10–20% every 20 years).
To what extent is energy demand decoupled from economic growth?	Economic growth is anticipated to grow four to five-fold from 2020 to 2100, equivalent to just over 2% per year, with little variation, compared to median energy demand growing by just over a third in the same time period (23–73% interquartile range), at a much lower rate of 0.4%. Tightly coupled historic relationships are broken to achieve absolute decoupling in the short term (pre-2030) and relative decoupling thereafter.
How do the lowest and highest FED pathway decarbonisation characteristics differ?	FED in 2100 in the high energy demand (HED) scenarios are three to four times higher than the lowest, but temperature target is not the deciding factor. Despite similar levels of FED, the lowest and highest FED pathways have contrasting routes to decarbonisation, which need to be carefully compared when designing climate policies.
Do levels of FED drive systemic changes in energy system decarbonisation and CDR across scenarios?	Low FED does not appear to exert a strong influence on energy sources, except to reduce energy supply investment. Electrification and higher shares of renewable energy sources seem to (weakly) compensate for higher growth in FED, but there is little evidence to suggest that low FED is used to reduce reliance on BECCS.
What are the implications of energy demand for achieving temperature-related carbon budgets?	We found moderate evidence to suggest that higher levels of FED resulted in overshoot in 1.5 °C scenarios, however, there is little evidence to suggest that lowering FED is used as a lever to meet carbon budgets.

We do not find strong evidence to suggest that FED is used as a mitigation lever to meet 1.5 °C compared to 2 °C targets in many scenarios, although without overshoot 1.5 °C pathways tend to cluster around lower FEDs. Even when trajectories of FED appear very similar, decarbonisation pathways compensate for high and low FED levels in very different ways. Lower energy demand pathways generally result in lower renewable energy supply levels and lower energy system investment, but do not necessarily reduce reliance on CDR. FED increases in the overwhelming majority of scenarios but is only weakly compensated for by non-biomass renewable energy shares. The main difference between temperature categories is in reductions pre-2030. Reaching 1.5 or 2 °C is mainly determined by what is done in the next 20 years (from policy decisions that need to be made today). Post-2030 all IAMs project sustained growth in FED. 2050 levels of energy demand are between 40% to more than four times higher than those calculated by Millward-Hopkins et al. (2020) to provide a universal decent living standard. While FED is the primary lever used to reduce reliance on CDR in the SR1.5 low energy demand (LED) scenario by Grubler et al., energy demand reduction is not broadly implemented to reduce reliance on negative emissions technologies. We therefore conclude that there is more scope for IAMs to meet cumulative carbon budgets while reducing reliance on often criticised levels of NETs through more detailed energy demand reductions.

Energy demand and economic growth are strongly correlated historically, yet our analysis shows that IAMs assume structural changes of absolute decoupling of energy demand from economic growth in today's decade (2020–2030s), and relative coupling at considerably higher rates than historically thereafter. The feasibility of such assumptions have been questioned and evidenced (e.g. Semieniuk et al. (2021), Wiedmann et al. (2020), Haberl et al. (2020) and Keyßer and Lenzen (2021)). However, as explained in Hickel and Kallis (2019), IAMs assume that economic growth can be sustained due to gains in energy efficiency. IAMs do not account for how reduced material throughput and associated drops in production and consumption impact GDP, and therefore they do not find conclusive evidence that the economy can grow while reducing FED. If in reality decoupling of energy and the economy cannot be achieved (i.e. if energy efficiency is not coupled with a cap on high consumption lifestyles), the outcomes could be worse for the climate, and IAMs will have downplayed the significant role of economic growth in driving climate change. Without a more comprehensive understanding of the relationship between economic growth and energy demand, most IAMs risk overestimating the potential savings from reductions in final energy demand.

While we found that lower growth rates of FED result (weakly) in lower peak temperatures, variability in FED more strongly determined the share of renewables in the energy mix, but not the timings and rates of negative emissions. In scenarios with higher FED, models compensate by increasing the share of renewables in the energy mix, raising the need for energy system investment. We found little evidence to suggest that reducing energy demand was broadly being used as a lever to reduce reliance on negative emissions. According to IAMs, reducing energy demand is instead a means to reduce the need for and investment in renewables. Yet CDRs are surrounded by much more political and physical uncertainty.

The results have implications for a new range of low energy demand scenarios. While there have been strong assertions that IAMs are ill-equipped to fully take advantage of demand reductions due to their techno-economic response to mitigation e.g. (Larkin et al., 2017), in their current structure lowering pre-defined energy demand levels could maintain a higher degree of fossil fuels while still relying on uncertain and expensive negative emissions technologies to stay within temperature goals. These assumptions do not consider the high adaptation costs if CDR fails to perform at suggested levels, or the need to redirect subsidies from fossil fuels to low carbon developments (Monasterolo and Raberto, 2019, Chepeliev and van der Mensbrugghe, 2020).

IAMs are not fully taking advantage of demand reduction policy options, with some exceptions in transport. There is more potential for IAMs to model structural changes (avoidance and shifting activities) to reduce energy demand, than predominantly rely on carbon intensity reductions through e.g. fuel switching, as captured more in bottom-up sectoral models. To overcome such criticisms raised in this paper, thought needs to be given to how useful IAMs can be to informing low energy demand reduction policies, and whether, as Gambhir et al. (2019) investigate for BECCS, there is a need to scrap IAMs and use different techniques, improve the existing models with better real-world process representations, or supplement IAMs with other models and approaches. Several papers highlight the need for diverse approaches to investigating and framing climate solutions (for example (Rosenbloom, 2017, Longhurst and Chilvers, 2019, Stirling, 2011), which Saujot et al. (2020) demonstrate is necessary due to the societal, political, geographical and modelling complexity of lifestyle changes. Certainly, we hope to have at least demonstrated the need for assessments to play closer attention to how final energy demand interacts with and relates to supply-side and economic characteristics and how these could be used to reduce the risks associated with reliance on CDR technologies.

Previous research has shown that a demand-oriented perspective provides additional policy levers to reduce GHG emissions and therefore IAMs would benefit from a supply chain perspective showing where emissions become embodied in alternative, and more disaggregated end uses (Creutzig et al., 2018, Creutzig et al., 2016, Barrett and Scott, 2012, Schanes et al., 2016). Focusing on demand reduction also raises questions about the distribution of final energy and who gets to use how much and for what. Further effort is needed to examine what levels of final demand mean for meeting basic human needs within a 1.5 °C pathway i.e. at scale (Pirgmaier and Steinberger, 2019, Millward-Hopkins et al., 2020). Understanding how end use services meet human needs (e.g. access to healthy food, clean water, mobility, healthcare and education) can further shape policies that not only encourage lower carbon lifestyles (and not only lower carbon production processes), but are more equitable (Brand-Correa and Steinberger, 2017, Brand-Correa et al., 2020). While this analysis was done before the global COVID-19 pandemic, this context also raises questions about the road to recovery. The impact of the pandemic on emissions levels is likely to be modest, yet the pathway of recovery could change the course of emissions pathways depending on the scope and scale of green stimulus packages. There are real opportunities to align recovery with low carbon solutions.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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