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The geographical distribution of fossil fuels unused when limiting global warming to 2 °C

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Policy makers have generally agreed that the average global temperature rise caused by greenhouse gas emissions should not exceed 2 °C above the average global temperature of pre-industrial times[1]. It has been estimated that to have at least a 50 per cent chance of keeping warming below 2 °C throughout the twenty-first century, the cumulative carbon emissions between 2011 and 2050 need to be limited to around 1,100 gigatonnes of carbon dioxide (Gt CO_2)[2,3]. However, the greenhouse gas emissions contained in present estimates of global fossil fuel reserves are around three times higher than this[2,4], and so the unabated use of all current fossil fuel reserves is incompatible with a warming limit of 2 °C. Here we use a single integrated assessment model that contains estimates of the quantities, locations and nature of the world's oil, gas and coal reserves and resources, and which is shown to be consistent with a wide variety of modelling approaches with different assumptions[5], to explore the implications of this emissions limit for fossil fuel production in different regions. Our results suggest that, globally, a third of oil reserves, half of gas reserves and over 80 per cent of current coal reserves should remain unused from 2010 to 2050 in order to meet the target of 2 °C. We show that development of resources in the Arctic and any increase in unconventional oil production are incommensurate with efforts to limit average global warming to 2 °C. Our results show that policy makers' instincts to exploit rapidly and completely their territorial fossil fuels are, in aggregate, inconsistent with their commitments to this temperature limit. Implementation of this policy commitment would also render unnecessary continued substantial expenditure on fossil fuel exploration, because any new discoveries could not lead to increased aggregate production.

Recent climate studies have demonstrated that average global temperature rises are closely related to cumulative emissions of greenhouse gases emitted over a given timeframe[2,6,7]. This has resulted in the concept of the remaining global 'carbon budget' associated with the probability of successfully keeping the global temperature rise below a certain level[4,8,9]. The Intergovernmental Panel on Climate Change (IPCC)[3] recently suggested that to have a better-than-even chance of avoiding more than a 2 °C temperature rise, the carbon budget between 2011 and 2050 is around 870–1,240 Gt CO_2.

Such a carbon budget will have profound implications for the future utilization of oil, gas and coal. However, to understand the quantities that are required, and are not required, under different scenarios, we first

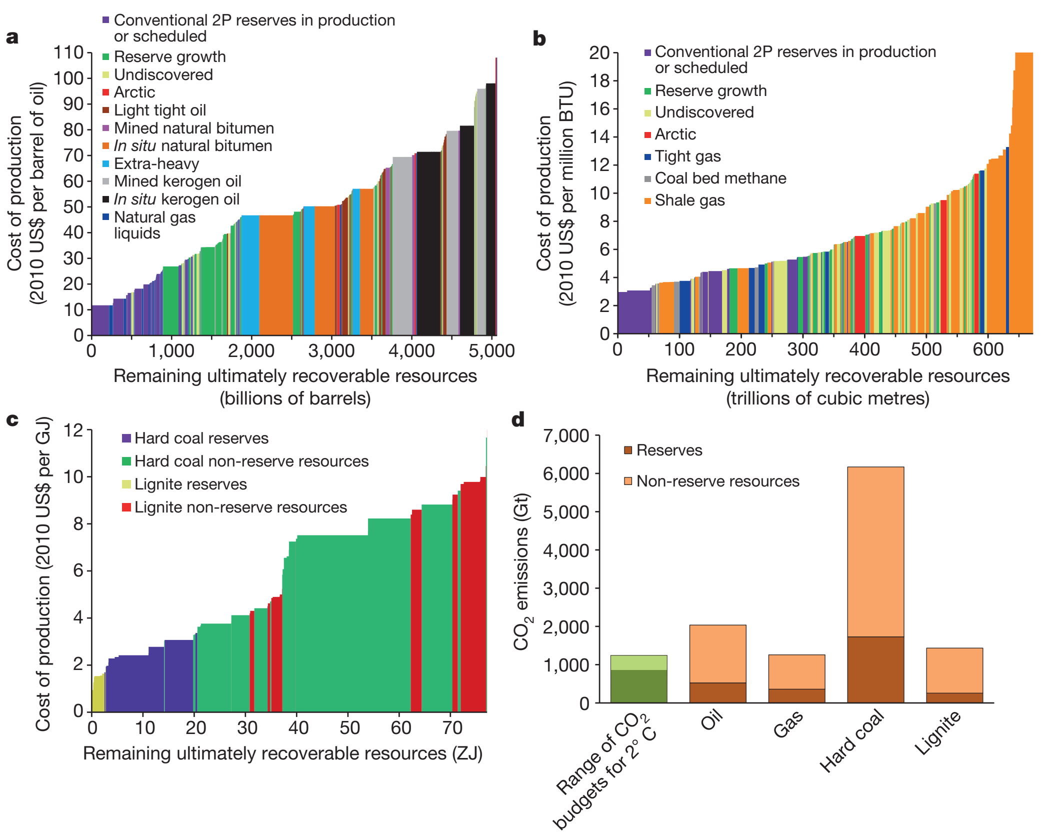

Figure 1 | Supply cost curves for oil, gas and coal and the combustion CO_2 emissions for these resources. a–c, Supply cost curves for oil (**a**), gas (**b**) and coal (**c**). **d**, The combustion CO_2 emissions for these resources. Within these resource estimates, 1,294 billion barrels of oil, 192 trillion cubic metres of gas, 728 Gt of hard coal, and 276 Gt of lignite are classified as reserves globally. These reserves would result in 2,900 Gt of CO_2 if combusted unabated. The range of carbon budgets between 2011 and 2050 that are approximately commensurate with limiting the temperature rise to 2 °C (870–1,240 Gt of CO_2) is also shown. 2P, 'proved plus probable' reserves; BTU, British thermal units (one BTU is equal to 1,055 J). One zettajoule (ZJ) is equal to one sextillion (10^{21}) joules. Annual global primary energy production is approximately 0.5 ZJ.

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need to establish the quantities and location of those currently estimated to exist. A variety of metrics with disparate nomenclature are relied upon to report the availability of fossil fuels[10,11], but the two most common are 'resources' and 'reserves'. In this work 'resources' are taken to be the remaining ultimately recoverable resources (RURR)—the quantity of oil, gas or coal remaining that is recoverable over all time with both current and future technology, irrespective of current economic conditions. 'Reserves' are a subset of resources that are defined to be recoverable under current economic conditions and have a specific probability of being produced[11]. Our best estimates of the reserves and resources are presented in Fig. 1 and, at the regional level, in Extended Data Table 1.

Figure 1 also compares the above carbon budget with the CO_2 emissions that would result from the combustion of our estimate of remaining fossil fuel resources (nearly 11,000 Gt CO_2). With the combustion emissions of the remaining reserves alone totalling nearly 2,900 Gt CO_2, the disparity between what resources and reserves exist and what can be emitted while avoiding a temperature rise greater than the agreed 2 °C limit is therefore stark.

Although previous research[12] has examined the implications that emissions mitigation might have on the rents collected by fossil fuel resource owners, more pertinent to policy and industry are the quantities of fossil fuel that are not used before 2050 in scenarios that limit the average global surface temperature rise to 2 °C. Such geographically disaggregated estimates of 'unburnable' reserves and resources are provided here using the linear optimization, integrated assessment model TIAM-UCL[13].

To provide context to the issue of unburnable fossil fuels and our results, it is useful to examine scenarios provided by other models that quantify separately the volumes of oil, gas and coal produced globally under a range of future emissions trajectories[5]. Cumulative production between 2010 and 2050 from these are presented in Fig. 2. Since they have very different future greenhouse gas emissions profiles, we have converted them to approximate temperature rise trajectories. These have been calculated using the climate model MAGICC[14], which generates a probability distribution over temperature rise trajectories for a given emissions profile. We use the 60th percentile temperature trajectory (to correspond with assumptions within TIAM-UCL) and then group the scenarios by the final temperature rise in 2100: below 2 °C, between 2 °C and 3 °C, or exceeding 3 °C.

In this work we have constructed three core scenarios that are constrained to limit the average surface temperature rise in all time periods to 2 °C, to 3 °C, and to 5 °C. Cumulative production of each fossil fuel between 2010 and 2050 in each of these scenarios can be identified within each of the three temperature groupings in Fig. 2.

The global reserves of oil, gas and coal included in Fig. 1 total approximately 7.4 ZJ, 7.1 ZJ and 20 ZJ, respectively. With narrow inter-quartile ranges, relative to the level of reserves available, Fig. 2 shows good agreement on the levels of fossil fuels produced within the temperature groups, despite the range of modelling methodologies and assumptions included.

Since assumptions in modelling the energy system are subject to wide bands of uncertainty[15], we further constructed a number of sensitivity scenarios using TIAM-UCL that remain within a 2 °C temperature rise. These span a broad range of assumptions on production costs, the availability of bio-energy, oil and gas, demand projections, and technology availability (one with no negative emissions technologies, and one with no carbon capture and storage (CCS)) (Extended Data Table 2). The availability of CCS has the largest effect on cumulative production levels (Extended Data Fig. 1); however, there is little variability in the total production of fossil fuels if the world is to have a good chance of staying within the agreed 2 °C limit.

Global production of oil, gas and coal over time in our main 2 °C scenario is given in Fig. 3. This separates production by category, that is, by the individual kinds of oil and gas that make up the global resource base, and compares total production with the projections from the 2 °C scenarios in Fig. 2. The results generated using TIAM-UCL are a product

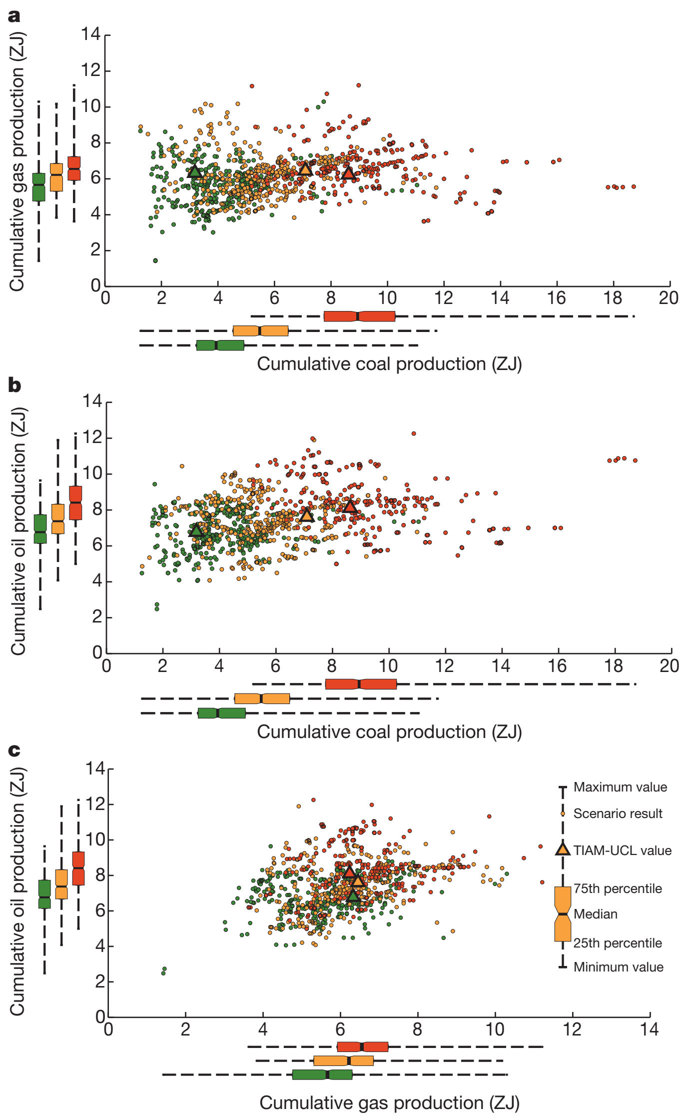

Figure 2 | Cumulative production between 2010 and 2050 from a range of long-term energy scenarios. Panels refer to coal and gas (**a**), coal and oil (**b**), and gas and oil (**c**). Scenarios[5] are coloured according to their approximate resultant 2100 temperature rise above pre-industrial levels. 379 individual scenarios result in a temperature rise of less than 2 °C (green), 366 of between 2 °C and 3 °C (orange), and 284 of more than 3 °C (red). Triangles are the values from the 2 °C (with CCS), 3 °C and 5 °C TIAM-UCL scenarios. Ranges and symbols are as shown in the key in **c**.

of the economically-optimal solution, and other regional distributions of unburnable reserves are possible while still remaining within the 2 °C limit (even though these would have a lower social welfare). A future multi-model analysis could therefore usefully build on and extend the work that is presented here, but results at the aggregate level can be seen to lie within range of the ensemble of models and scenarios that also give no more than a 2 °C temperature rise.

In the TIAM-UCL scenarios, production of reserves and non-reserve resources occurs contemporaneously. It is therefore important to recognize that it would be inappropriate simply to compare the cumulative production figures in Fig. 2 with the reserve estimates from Fig. 1 and declare any reserves not used as 'unburnable'. Although there may be sufficient reserves to cover cumulative production between 2010 and 2050, it does not follow that only reserves should be developed and all other resources should remain unused. For oil and gas, resources that are not currently reserves may turn out to be cheaper to produce than some reserves, while new resources will also be developed to maintain

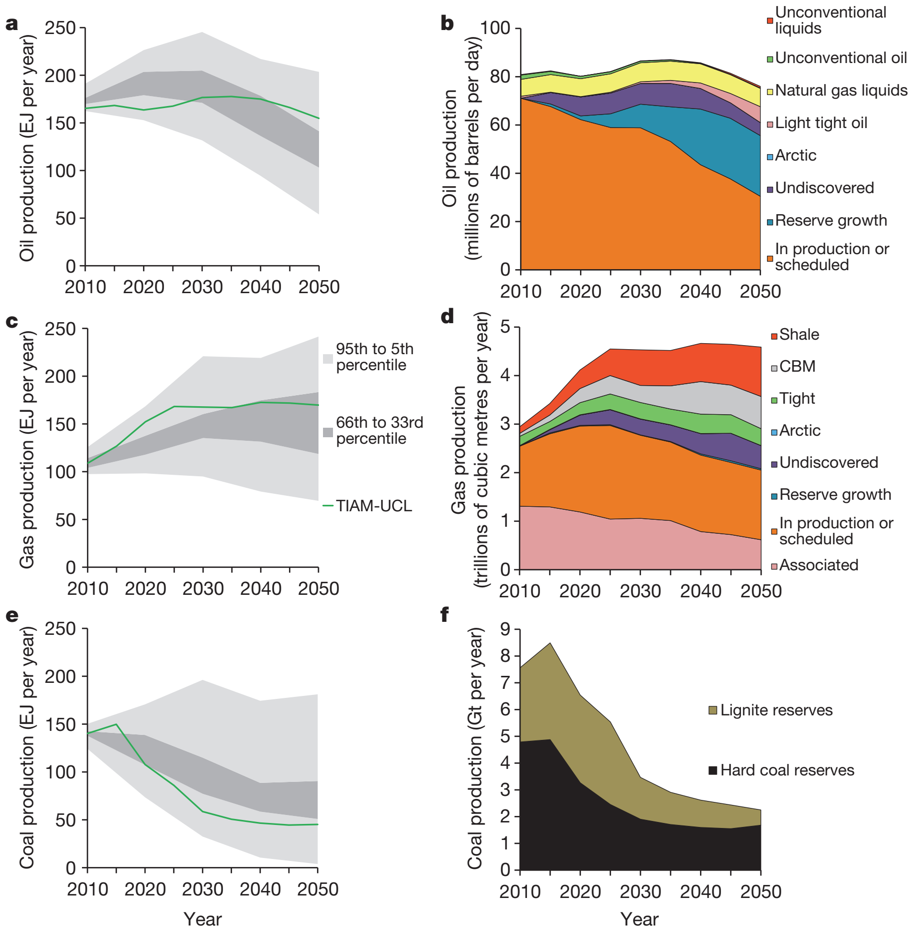

Figure 3 | Oil, gas and coal production in the TIAM-UCL 2 °C scenario (with CCS) and comparison with all other 2 °C scenarios in the Intergovernmental Panel on Climate Change Fifth Assessment Report (AR5) database[5]. **a**, **c** and **e** compare total production by oil, gas and coal with the AR5 database; **b**, **d** and **f** provide a disaggregated view of production for the TIAM-UCL 2 °C scenario separated by category. Associated gas is gas produced alongside crude oil from oil fields. One exajoule (EJ) is equal to one quintillion (10^{18}) joules.

the flow rates demanded by end-use sectors. However, if resources that are currently non-reserves are produced, a greater proportion of reserves must not be produced to stay within the carbon budget.

The reserves of oil, gas and coal that should be classified as unburnable within each region, and the percentage of current reserves that remain unused, are set out in Table 1. Since total production is most sensitive to assumptions on CCS, and since it has been suggested that the deployment of CCS will permit wider exploitation of the fossil fuel resource base[16], Table 1 includes the unburnable reserves from two alternative 2 °C scenarios. One scenario permits the widespread deployment of CCS from 2025 onwards, and the other assumes that CCS is unavailable in any time period.

Globally, when CCS is permitted, over 430 billion barrels of oil and 95 trillion cubic metres of gas currently classified as reserves should remain unburned by 2050. The Middle East, although using over 60% of its oil reserves, carries over half of the unburnable oil globally, leaving over 260 billions of barrels in the ground. Canada has the lowest utilization of its oil reserves (25%), as its natural bitumen[17] deposits remain largely undeveloped (see below) while the United States has the highest, given the proximity of supply and demand centres. The Middle East also holds half of unburnable global gas reserves, with Former Soviet Union countries accounting for another third, meaning that they can use only half their current reserves.

Coal reserves are by far the least-used fossil fuel, with a global total of 82% remaining unburned before 2050. The United States and the Former Soviet Union countries each use less than 10% of their current reserves, meaning that they should leave over 200 billion tonnes (Gt) coal (both hard and lignite) reserves unburned. Coal reserve utilization

Table 1 | Regional distribution of reserves unburnable before 2050 for the 2 °C scenarios with and without CCS

	2 °C with CCS						2 °C without CCS					
	Oil		Gas		Coal		Oil		Gas		Coal	
Country or region	Billions of barrels	%	Trillions of cubic metres	%	Gt	%	Billions of barrels	%	Trillions of cubic metres	%	Gt	%
Africa	23	21%	4.4	33%	28	85%	28	26%	4.4	34%	30	90%
Canada	39	74%	0.3	24%	5.0	75%	40	75%	0.3	24%	5.4	82%
China and India	9	25%	2.9	63%	180	66%	9	25%	2.5	53%	207	77%
FSU	27	18%	31	50%	203	94%	28	19%	36	59%	209	97%
CSA	58	39%	4.8	53%	8	51%	63	42%	5.0	56%	11	73%
Europe	5.0	20%	0.6	11%	65	78%	5.3	21%	0.3	6%	74	89%
Middle East	263	38%	46	61%	3.4	99%	264	38%	47	61%	3.4	99%
OECD Pacific	2.1	37%	2.2	56%	83	93%	2.7	46%	2.0	51%	85	95%
ODA	2.0	9%	2.2	24%	10	34%	2.8	12%	2.1	22%	17	60%
United States of America	2.8	6%	0.3	4%	235	92%	4.6	9%	0.5	6%	245	95%
Global	431	33%	95	49%	819	82%	449	35%	100	52%	887	88%

FSU, the former Soviet Union countries; CSA, Central and South America; ODA, Other developing Asian countries; OECD, the Organisation for Economic Co-operation and Development. A barrel of oil is 0.159 m^3; %, Reserves unburnable before 2050 as a percentage of current reserves.

is twenty-five percentage points higher in China and India, but still they should also leave nearly 200 Gt of their current coal reserves unburned.

The utilization of current reserves is lower in nearly all regions for all of the fossil fuels when CCS is not available, although there is a slight increase in gas production in some regions to offset some of the larger drop in coal production. Nevertheless, Table 1 demonstrates that the reserves of coal that can be burned are only six percentage points higher when CCS is allowed, with the utilization of gas and oil increasing by an even smaller fraction (around two percentage points). Because of the expense of CCS, its relatively late date of introduction (2025), and the assumed maximum rate at which it can be built, CCS has a relatively modest effect on the overall levels of fossil fuel that can be produced before 2050 in a 2 °C scenario.

As shown in Fig. 3, there is substantial production of many of the non-reserve resource categories of oil and gas. Extended Data Table 3 sets out the regional unburnable resources of all coal, gas and oil in the scenario that allows CCS by comparing cumulative production of all fossil fuel resources with the resource estimates in Fig. 1.

The RURR of both types of coal and unconventional oil vastly exceed cumulative production between 2010 and 2050, with the overwhelming majority remaining unburned. Resources of conventional oil are used to the greatest extent, with just under 350 billion barrels of non-reserve resources produced over the model timeframe. The Middle East again holds the largest share of the unburnable resources of conventional oil, but there is a much wider geographical distribution of these unburnable resources than was the case for oil reserves.

Regarding the production of unconventional oil, open-pit mining of natural bitumen in Canada soon drops to negligible levels after 2020 in all scenarios because it is considerably less economic than other methods of production. Production by *in situ* technologies continues in the 2 °C scenario that allows CCS, but this is accompanied by a rapid and total decarbonization of the auxiliary energy inputs required (Extended Data Fig. 2). Although such a decarbonization would be extremely challenging in reality, cumulative production of Canadian bitumen between 2010 and 2050 is still only 7.5 billion barrels. 85% of its 48 billion of barrels of bitumen reserves thus remain unburnable if the 2 °C limit is not to be exceeded. When CCS is not available, all bitumen production ceases by 2040. In both cases, the RURR of Canadian bitumen dwarfs cumulative production, so that around 99% of our estimate of its resources (640 billion barrels), remains unburnable. Similar results are seen for extra-heavy oil in Venezuela. Cumulative production is 3 billion barrels, meaning that almost 95% of its extra-heavy reserves and 99% of the RURR are unburnable, even when CCS is available.

The utilization of unconventional gas resources is considerably higher than unconventional oil. Under the 2 °C scenario, gas plays an important part in displacing coal from the electrical and industrial sectors and so there is over 50 trillion cubic metres unconventional gas production globally, over half of which occurs in North America. Nevertheless, there is a low level of utilization of the large potential unconventional gas resources held by China and India, Africa and the Middle East, and so over 80% of unconventional gas resources (247 trillion cubic metres) are unburnable before 2050. Production of these unconventional gas resources is, however, only possible if the levels of coal reserves identified in Table 1 are not developed: that is, it is not possible for unconventional gas to be additional to current levels of coal production.

Finally, we estimate there to be 100 billion barrels of oil (including natural gas liquids) and 35 trillion cubic metres of gas in fields within the Arctic Circle that are not being produced as of 2010. However, none is produced in any region in either of the 2 °C scenarios before 2050. These results indicate to us that all Arctic resources should be classified as unburnable.

To conclude, these results demonstrate that a stark transformation in our understanding of fossil fuel availability is necessary. Although there have previously been fears over the scarcity of fossil fuels[18], in a climate-constrained world this is no longer a relevant concern: large portions of the reserve base and an even greater proportion of the resource base should not be produced if the temperature rise is to remain below 2 °C.

Online Content Methods, along with any additional Extended Data display items and Source Data, are available in the online version of the paper; references unique to these sections appear only in the online paper.

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METHODS

Fossil fuel definitions. A 'McKelvey' box[19] is often used to provide an overview of the relationship between different resource and reserve estimates[20]. The best estimates of current oil and gas reserves in Extended Data Table 1 were of the 'proved plus probable' or '2P' quantities. Since 2P reserve estimates are rare for coal and none are in the public domain, the best estimates shown for coal were of the 'proved' or '1P' reserves. Broadly speaking, 1P estimates are more conservative, often corresponding to an estimate with a 90% probability of being exceeded, while 2P estimates are the median estimate of the reserves for a given field or region[11].

Oil and gas can be further separated into 'conventional' and 'unconventional' reserves and resources. Again, there is no single definition of these terms, but here we define oil with density greater than water (often standardized as '10° API') to be unconventional and all other quantities as conventional. We therefore categorize the 'light tight oil' extracted from impermeable shale formations using hydraulic fracturing as conventional oil.

For gas, tight gas (gas trapped in relatively impermeable hard rock, limestone or sandstone), coal-bed methane (gas trapped in coal seams that is adsorbed in the solid matrix of the coal), and shale gas (gas trapped in fine-grained shale) are considered as the three 'unconventional gases'; all other quantities are considered to be conventional.

Coal is distinguished by its energy density following the definitions used by the Federal Institute for Geosciences and Natural Resources (BGR)[21]. Hard coal has an energy density greater than 16.5 MJ kg^{-1}; any quantities with energy density less than this are classified as lignite.

Derivation of reserve and resource estimates. The estimated oil and gas reserves and resources shown in Extended Data Table 1 were derived in the following manner[22]. We first identified the individual elements or categories of oil and gas that make up the global resource base. For oil these are: current conventional 2P reserves in fields that are in production or are scheduled to be developed, reserve growth, undiscovered oil, Arctic oil, light tight oil, natural gas liquids, natural bitumen, extra-heavy oil, and kerogen oil. The latter three of these are the unconventional oil categories.

Reserve growth is defined to be 'the commonly observed increase in recoverable resources in previously discovered fields through time'[23]. Quantities in this category here include any contributions from reserves in fields that have been discovered but are not scheduled to be developed ('fallow fields'), the new implementation of advanced production technologies such as enhanced oil recovery, changes in geological understanding, and changes in regional definitions.

There are eight categories of conventional and unconventional gas: current conventional 2P reserves that are in fields in production or are scheduled to be developed, reserve growth, undiscovered gas, Arctic gas, associated gas, tight gas, coal-bed methane, and shale gas. As noted above, the latter three of these are collectively referred to as unconventional gas.

We then selected the most robust data sources that provide estimates of the resource potential of each individual category within each country; these sources are set out in Extended Data Table 4. Taken together, differences between these sources provide a spread of discrete quantitative resource estimates for each category within each country. We also differentiated between the quantities of conventional oil that are natural gas liquids, and the quantities of natural gas that are associated with oil fields; these distinctions are important for modelling purposes but are rarely made in the literature.

For unconventional oil, we first generated a range of estimates for the in-place resources of natural bitumen, extra-heavy oil, and kerogen oil, and a range of potential recovery factors for different extraction technologies. We separately characterized the natural bitumen and kerogen oil resources that are extractable using mining technologies and those resources that are extractable using *in situ* technologies because the resource potential, costs, and energy requirements of these technologies are very different.

Continuous distributions were next constructed across these data ranges. Since there is no empirical basis for the choice of a suitable shape or form for such distributions, we used both the triangular and the beta distributions, chosen because they can be skewed both positively and negatively, and because they allow identical distributions to be used across all of the ranges derived. With equal weighting for each distribution, we combined these into a single individual resource distribution for each category within each country.

We then estimated the production costs of each of the oil and gas resource categories. Taking account of the resource uncertainty, these were used to develop supply cost curves for each category of oil and gas within each country.

We finally used a Monte Carlo selection process to combine these country-level supply cost curves. Regional supply cost curves were thus formed from aggregated supply cost curves for individual countries, and similarly supply cost curves formed for multiple categories of oil or gas within one or more countries. Data in Fig. 1 are the median values from these aggregate distributions with Extended Data Table 4 giving high (95th percentile), median, and low (5th percentile) estimates for each category at the global level.

In most industry databases of oil and gas reserves (for example, the database produced by the consultancy IHS CERA[24,25]), some of the quantities classified as reserves lie in fields that were discovered over ten years ago, yet these fields have not been developed and there are no plans at present to do so. These are sometimes referred to as 'fallow fields'. For gas these quantities can also be called 'stranded gas', and they can be quite substantial; for example ref. 24 suggests that 50% gas reserves outside of North America are in stranded fields. Strictly, oil and gas in such fields should not be classified as reserves (for example, ref. 11 states that reserve quantities must have a 'reasonable timetable for development'). However, in this work, to ensure that the reserve estimates provided in Table 1 are not substantially different from the global totals provided by these industry databases, we follow their convention of classifying these quantities as reserves.

There are fewer independent estimates of reserves for coal and so we simply relied upon the estimates provided by the BGR[21] for the reserve figures in Extended Data Table 1. The RURR of coal are more problematic to characterize, however. The 'resource' estimates provided by the BGR are not estimates of the quantities that can actually be extracted but are the in-place quantities; large portions of these are unlikely ever to be technically recoverable.

We therefore used the proved, probable and possible reserve estimates for hard coal and lignite provided by the World Energy Council[26] for a selection of countries. The sum of these three figures gives an estimate of the 'tonnage within the estimated additional amount in place that geological and engineering information indicates with reasonable certainty might be recovered in the future' (the definition provided by the World Energy Council). Since the sum of these three figures takes account of technical recoverability, we consider that, while imperfect, they provide a better estimate of the ultimately recoverable resources of coal than either the (narrower) proved reserve or the (broader) in-place resource estimates.

There are a number of countries that are estimated by the BGR to hold large quantities of coal in place but for which no probable and possible reserve estimates are provided by the World Energy Council. The ratio of the World Energy Council resource estimate to the BGR in-place estimate in countries that have estimates provided by both sources can vary substantially, but the average ratio is 16% for hard coal and 31% for lignite. We therefore assumed this ratio to generate resource estimates for all countries for which only BGR in-place estimates are provided. The proved reserve estimates of coal are so large themselves that the resource estimates are less important than is the case for oil and gas resource estimates.

There are few other sources providing a comprehensive overview of fossil fuel availability. Further, these often do not provide their sources or the methods used to generate estimates, do not define fully what categories or elements are included or excluded, and do not indicate sufficient conversion factors that would allow a like-with-like comparison. Some exceptions, however, are the IEA[27,28], the IIASA Global Energy Assessment (GEA)[29], and the BGR[21]. Their estimates are shown together with our aggregated reserve and resource estimates in Extended Data Table 5.

A number of factors contribute to the large variation between these estimates. A key reason is that the definitions of 'reserves' and 'resources' differ among sources, and so it is problematic to seek to compare them directly. For example, as noted above, the BGR, whose estimates are followed closely by the other sources, gives the total coal in place rather than an estimate of the resources that can be recovered, as in our study. Other reasons for the differences seen include: (1) the exclusion or inclusion of certain categories of fossil fuels such as light tight oil, aquifer gas, and methane hydrates; (2) whether proved (1P) or proved plus probable (2P) reserves are reported, and the methods used to generate the 1P reserve estimates; (3) the potential inflation of reserve estimates for political reasons, and whether they should consequently be increased or reduced[30]; (4) the inclusion of stranded gas volumes in gas reserve estimates; (5) differences in the functional form used to estimate volumes of reserve growth (if reserve growth is included at all); (6) the difficulty in estimating current recovery factors (the ratio of recoverable resources to total resources in place), and how these may increase in the future; (7) differences between the methods used to estimate undiscovered oil and gas volumes; (8) the scarcity of reports providing reliable estimates of the potential resources of Arctic oil and gas, light tight oil, tight gas and coal bed methane, and the frequent consequent reliance upon expert judgement; (9) variation in what unconventional oil production technologies, which vary considerably in their recovery factors, will be used in the future; and (10) the chosen cut-off 'yield' (the volume of synthetic oil produced from a given weight of shale rock) for kerogen oil.

The estimates considered in our model are the result of careful and explicit consideration of all these issues, with our choices justified in the light of available knowledge. It can be seen in Extended Data Table 5, however, that our median figures are generally lower than the estimates provided by the other sources shown there. Therefore, although we consider our median resource estimates to be more robust than the figures used by these other sources, if in fact these other estimates were found to be closer to being correct, then the unburnable resources given in Extended Data Table 3 would also be larger. For example, if total gas resources are actually at the GEA high estimate, then the percentage that should be classified as unburnable before 2050 under the 2 °C scenario would increase to 99% rather than our estimate of 75%.

The cut-off date after which quantities that have not been produced should be considered 'unburnable' is also an important assumption. While there are no specific timeframes attached to the definition of reserves, quantities are usually required to be developed within, for example, a 'reasonable timeframe'[11]. It is doubtful whether any reserves not produced by 2050 would fulfil this criterion. We therefore take cumulative production of reserves between 2010 and 2050 as the reserve 'utilization', and classify any quantities not used within this time as those that should be 'unburnable' if a certain temperature rise is not to be exceeded. Similarly, if none, or only a minor proportion, of a certain non-reserve resource is produced before 2050, then any current interest in developing it would be questionable. We thus also rely on 2050 as the cut-off date for classifying resources that should be considered as unburnable.

Description and key assumptions in TIAM-UCL. The TIMES Integrated Assessment Model in University College London ('TIAM-UCL') is a technology-rich, bottom-up, whole-system model that maximizes social welfare under a number of imposed constraints. It models all primary energy sources (oil, gas, coal, nuclear, biomass, and renewables) from resource production through to their conversion, infrastructure requirements, and finally to sectoral end-use. An extended explanation of input assumptions, approaches and data sources can be found in ref. 13. The base year of TIAM-UCL is 2005, the model is run in full to 2100, and thereafter the climate module is run to 2200. Results are presented here only between 2010 and 2050 (and are reported in five-year increments). All scenarios in this paper are run with the assumption of perfect foresight.

Resources and costs of all primary energy production are specified separately within 16 regions covering the world, and separately within the regions that contain members of the Organisation of Petroleum Exporting Countries (OPEC); the names of these are presented in Extended Data Table 6. For clarity in the main text, we have aggregated some of these regions into ten more-encompassing groups.

The climate module of TIAM-UCL is calibrated to the MAGICC model[14]. This module can be used to project the effects of greenhouse gas emissions on: atmospheric concentrations of greenhouse gas, radiative forcing, and average global temperature rises. It can also be used to constrain the model to certain bounds on these variables. In this work, the climate module is used to restrict the temperature rise to certain levels (as explained below). For the calibration to MAGICC, values from the probability distributions of climate parameters in MAGICC were selected so that there is a 60% chance that the temperature rise will remain below any level reported. Any constraints imposed using the TIAM-UCL climate module thus also correspond to this probability.

The emissions profiles[5] used in Fig. 2 were converted to temperature rises using MAGICC. To ensure consistency with TIAM-UCL, we use the 60th percentile temperature trajectory from MAGICC and then group by the final temperature rise in 2100; there is therefore also a 60% chance that the temperature rise will be below the level indicated.

For each of the scenarios run in this paper using TIAM-UCL, a 'base case' is first formed that incorporates no greenhouse gas abatement policies. This base case uses the standard version of the model that relies upon minimizing the discounted system cost. This is used to generate base prices for each commodity in the model. TIAM-UCL is then re-run using the elastic-demand version with the greenhouse gas abatement policies introduced. This version of the model maximizes social welfare (the sum of consumer and producer surplus) and allows the energy-service demands to respond to changes in the endogenously determined prices resulting from these new constraints.

Fossil fuel modelling in TIAM-UCL. Oil and gas are both modelled in a similar manner in TIAM-UCL. The nine categories of conventional and unconventional oil and eight categories of conventional and unconventional gas identified above are all modelled separately. Coal production in TIAM-UCL is modelled more collectively, with only two categories, reserves and resources, for hard coal and lignite.

Natural bitumen and kerogen oil resources can be produced using either mining or *in situ* means, the technologies for which have different costs, efficiencies, and energy inputs. Although natural gas is predominantly used at present for the energy inputs to these unconventional resources, the model is free to choose any source of heat, electricity and hydrogen to allow greater flexibility. The costs of the auxiliary energy inputs required to extract and upgrade the native unconventional oils are determined endogenously by the model.

Each of the coal, gas and oil categories are modelled separately within the regions listed in Extended Data Table 6, with each resource category within each region split into three cost steps. As discussed above, the supply cost curves given in Fig. 1 comprise the data input to TIAM-UCL.

After processing, oil is next refined into products (gasoline, diesel, naphtha and so on), whereas processed gas and coal can be used directly. Fuel switching to and from all of the fossil fuels is possible. Trade of hard coal, crude oil, refined products, natural gas, both in pipelines and as liquefied natural gas, is allowed. Lignite cannot be traded between the regions.

Refined oil products can also be produced directly using Fischer–Tropsch processes with possible feedstocks of coal, gas, or biomass; these technologies can also be employed either with or without carbon capture and storage. Regional coal, oil and gas prices are generated endogenously within the model. These incorporate the marginal cost of production, scarcity rents, rents arising from other imposed constraints, and transportation costs.

A new key aspect of TIAM-UCL is the imposition of asymmetric constraints on the rate of production of oil and gas given a certain resource availability; these are intended to represent 'depletion rate constraints'. In TIAM-UCL, these constraints are modelled through introducing maximum annual production growth and maximum 'decline rate' restrictions. These are imposed on each cost step of each category of both oil and gas in each region, and ensure that the production follows a more realistic profile over time.

Data for these constraints are available at the field level from the bottom-up economic and geological oil field production model ('BUEGO')[31]. BUEGO contains a data-rich representation of 7,000 producing 'undiscovered' and discovered but undeveloped oil fields. These data include each field's 2P reserves, potential production capacity increases, water depth, capital and operating costs, and natural decline rate (the rate at which production would decline in the absence of any additional capital investment).

We used production-weighted averages (as of 2010) of the individual fields within each region to give average regional natural decline rates, which were imposed as maximum decline constraints in TIAM-UCL in the form of equal maximum annual percentage reductions. Although data on gas natural decline rates are much more sparse, some are available at a regional level[32], which can be compared with similar results for oil natural decline rates[25]. This comparison suggests that gas natural decline rates are on average 1% per year greater than for oil, with similar distributions for location (onshore/offshore) and size. The constraints placed on the maximum annual reductions in natural gas production were thus assumed to be 1% higher than those derived for oil.

As identified in the main text, to understand the quantities of reserves of oil and gas that are unburnable, production of reserve sources only should be compared with reserve estimates, while cumulative production of all sources should be compared with the resource estimates. For coal, the reserves are so much greater than cumulative production under any scenario that this distinction is not as important.

The base year of TIAM-UCL is 2005, but the base year of this study is 2010. Since reserves have grown, and oil and gas have been discovered in the intervening five years, some quantities that were classified as reserve growth and undiscovered oil and gas in 2005 should be classified as reserves in 2010. Within each region, the cumulative production figures to which the reserve estimates in Extended Data Table 1 are compared therefore contain production from the conventional 2P reserves in the 'fields in production or scheduled to be developed' category, as well as some portions of production from the 'reserve growth' and 'undiscovered' categories. In addition, since, for example, reserves of natural bitumen are included in the reserves figures of Canada and unconventional gas reserves are included in the reserves figures of the United States, production of some of the unconventional categories are also included in these cumulative production figures. To ensure consistency within each region, the maximum production potentials over the modelling period from the categories included in the cumulative production figures are equal to the reserve estimates given in Extended Data Table 1.

Overview of scenarios implemented. A brief overview of the main assumptions within the four scenarios run as part of this work is provided in Extended Data Table 7. For the emissions mitigation scenarios (those that limit the temperature rise to 3 °C and 2 °C), we assume that there are only relatively modest efforts to limit emissions in early periods as explained. The assumptions within the 2 °C sensitivity scenarios used to construct Extended Data Fig. 1 are provided in Extended Data Table 2.

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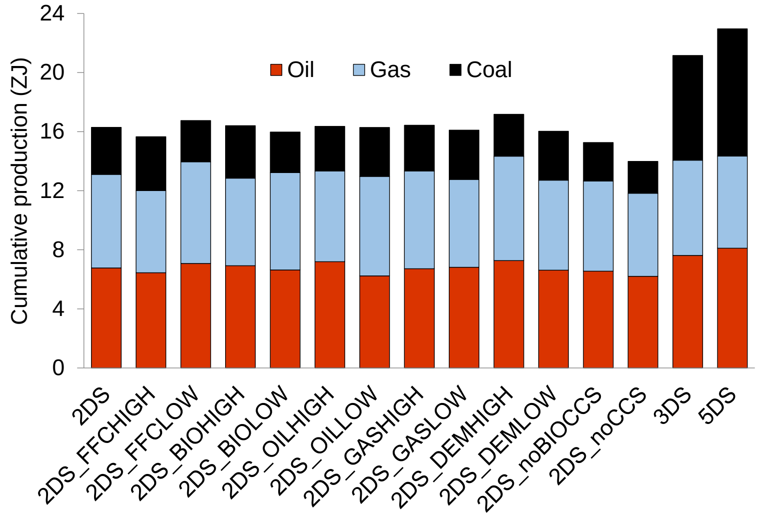
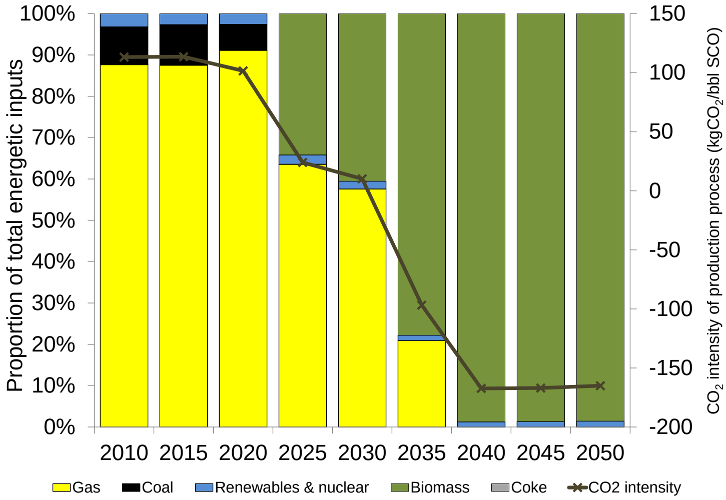


Extended Data Figure 1 | Cumulative fossil fuel production under a range of sensitivity scenarios run using TIAM-UCL. Scenario names and characteristics are given in Extended Data Table 2.



Extended Data Figure 2 | The auxiliary energy inputs for natural bitumen production in Canada by *in situ* technologies in the 2 °C scenario and the CO_2 intensity of these. bbl SCO, a barrel of synthetic crude oil, the oil that results after upgrading the natural bitumen.

Extended Data Table 1 | Best estimates of remaining reserves and remaining ultimately recoverable resources from 2010

	Oil (Gb)			Gas (Tcm)			Hard coal (Gt)		Lignite (Gt)	
Country or region	Res	Con RURR	Uncon RURR	Res	Con RURR	Uncon RURR	Res	RURR	Res	RURR
Africa	111	280	70	13	45	35	31	45	2	5
Canada	53	60	640	1	5	25	4	35	2	40
China and India	38	90	110	5	10	40	255	1,080	16	120
FSU	152	370	360	61	95	30	123	580	94	490
CSA	148	360	450	9	30	55	10	25	5	10
Europe	25	110	30	6	25	20	17	70	66	160
Middle East	689	1,050	10	76	105	20	2	10	2	5
OECD Pacific	6	30	130	4	10	20	45	120	44	200
ODA	23	75	5	9	25	15	15	40	14	155
United States	50	190	650	8	25	40	226	560	31	335
Global	1,294	2,615	2,455	192	375	300	728	2,565	276	1,520

'Con' and 'Uncon' stand for conventional and unconventional sources, respectively. Coal is specified in billions of tonnes (Gt), gas in trillions of cubic metres (Tcm) and oil in billions of barrels (Gb). Res, reserves.

Extended Data Table 2 | Labels and description of the sensitivity scenarios modelled in this project

Sensitivity Name	Description
2DS_FFCHIGH	Production costs of all fossil fuel technologies are 50% larger in 2015 and 100% larger in 2020 than in 2DS, with equal annual percentage changes between these dates and remaining at this level for the model horizon
2DS_FFCLOW	Production costs of all fossil fuel technologies are 33% lower in 2015 and 50% lower in 2020 than in 2DS, with equal annual percentage changes between these dates and remaining at this level for the model horizon
2DS_BIOHIGH	The maximum annual production of solid biomass and bio-crops in 2050 is assumed to be 350 EJ. This is close to the highest level of production of bio-energy in any of the scenarios from the AR5 scenario database[5] and is around three times the equivalent figure in 2DS (119 EJ).
2DS_BIOLOW	The maximum annual production of solid biomass and bio-crop in 2050 is assumed to be 38 EJ. This is similar to the figure given in the central scenario from [33] and is around a third of the equivalent figure in 2DS (119 EJ).
2DS_OILHIGH	Uses the high values of each category of oil in each region from the aggregate resource distributions described in the methods section (Extended Data Table 4)
2DS_OILLOW	Uses the low values of each category of oil in each region (Extended Data Table 4)
2DS_GASHIGH	Uses the high values of each category of gas in each region (Extended Data Table 4)
2DS_GASLOW	Uses the low values of each category of gas in each region (Extended Data Table 4)
2DS_DEMHIGH	The major drivers of energy service demands in TIAM-UCL are growth in GDP, population, and GDP/capita. Future regional growth in GDP and population are therefore modified to the values given in Shared Socioeconomic Pathway (SSP) number 5[34] the SSP with the highest GDP and GDP/capita growth by 2050 (a 240% increase in the global average; cf. a 120% increase in 2DS). All other energy service demands (not relying on GDP or population) are also modified commensurately.
2DS_DEMLOW	Future regional growth in GDP and population are modified to the values given in Shared Socioeconomic Pathway (SSP) number 3:[34] the SSP with the lowest GDP and GDP/capita growth by 2050 (a 50% increase in the global average).
2DS_NOBIOCCS	No negative emissions technologies are permitted i.e. carbon capture and storage (CCS) cannot be applied to any electrical or industrial process that uses biomass or bio-energy as feedstock in any period.
2DS_NOCCS	CCS is not permitted to be applied to any electrical or industrial process in any period.

Data for bio-energy sensitivities from refs 5 and 33, and for demand sensitivities from ref. 34.

Extended Data Table 3 | Regional distribution of resources unburnable before 2050 in absolute terms and as a percentage of current resources under the 2 °C scenario that allows CCS

	Conven oil		Unconven oil		Conven Gas		Unconven Gas		Hard Coal		Lignite	
Country or region	Gb	%	Gb	%	Tcm	%	Tcm	%	Gt	%	Gt	%
Africa	141	50%	70	100%	28	61%	35	100%	42	94%	2.8	56%
Canada	43	72%	633	99%	3.6	73%	18	71%	34	98%	39	97%
China and India	54	60%	110	100%	8.0	80%	35	88%	1,003	93%	106	88%
FSU	201	54%	360	100%	63	67%	27	89%	576	99%	480	98%
CSA	198	55%	447	99%	23	76%	51	92%	21	85%	6.3	63%
Europe	64	58%	30	100%	18	72%	16	78%	69	99%	142	89%
Middle East	554	53%	10	100%	72	68%	20	100%	10	100%	5.0	99%
OECD Pacific	23	77%	130	100%	9.0	90%	15	74%	116	97%	198	99%
ODA	38	51%	5.0	100%	14	55%	12	78%	34	84%	142	92%
United States	99	52%	650	100%	19	75%	20	50%	556	99%	317	95%
Global	1,417	54%	2,445	100%	257	69%	247	82%	2,462	96%	1,438	95%

'Conven' and 'Unconven' stand for conventional and unconventional resources, respectively.

Extended Data Table 4 | Principal data sources used to derive reserve and resource estimates and estimates at the global level for each category of production

Category	Data sources used to provide country-level estimates of resources	Aggregated high estimate	Aggregated median estimate	Aggregated low estimate
Oil		(in Gb)	(in Gb)	(in Gb)
Current conventional 2P reserves in fields in production or scheduled to be developed	[21,31,35,36]	950	820	620
Reserve growth	[37,38]	1,200	850	610
Undiscovered oil	Fact sheets since USGS World Petroleum Assessment [39] and [35,40,41]	580	300	180
Arctic oil	[42,43]	80	65	40
Light tight oil	[10]	470	300	150
Natural gas liquids (NGL)	[26] Ancillary data associated with [39]	380	280	170
Natural bitumen	Oil in place estimates [17,26]	Mined RURR 130	Mined RURR 100	Mined RURR 70
	Extraction technologies [44–46]	*In situ* RURR 1290	*In situ* RURR 840	*In situ* RURR 520
Extra-heavy oil	Oil in place estimates [47,48] Extraction technologies [47] and refs for bitumen	750	440	230
Kerogen oil	Oil in place estimates [49,50]	Mined RURR 740	Mined RURR 485	Mined RURR 270
	Extraction technologies [51]	*In situ* RURR 1,080	*In situ* RURR 590	*In situ* RURR 190
Total		7,650	5,070	3,050
Gas		(in tcm)	(in tcm)	(in tcm)
Current conventional 2P reserves in fields in production or scheduled to be developed	[35,52]	140	130	110
Reserve growth	[24,37,38]	125	90	60
Undiscovered gas	Fact sheets since USGS World Petroleum Assessment [39] and [35,41]	180	120	80
Arctic gas	[42,43]	40	35	25
Tight gas	[20]	60	60	60
Coal-bed methane	[20]	45	40	20
Shale gas	[20]	310	200	120
Associated gas	[36,37,44]	Included in the above		
Total		900	675	475

High and low values are the aggregated 95th and 5th percentile estimates, respectively. 'tcm', trillions of cubic metres. Data are from references 10, 17, 20, 21, 31, 35, 36, 37, 38, 39, 40, 41, 42, 43, 44, 45, 46, 47, 48, 49, 50 and 51.

Extended Data Table 5 | Global aggregated oil, gas and coal reserve and resource estimates from a selection of data sources

	Oil (Gb)		Gas (Tcm)		Coal (Gt)	
Organisation	Reserves	Resources	Reserves	Resources	Reserves	Resources
BGR	1,600	4,750	195	825	1,000	23,500
IEA	1,700	5,950	190	810	1,000	21,000
GEA	1,500 - 2,300	4,200 - 6,000	670 - 2,000	2,000 - 12,500	850 - 1,000	14,000 - 20,000
This study's median figures	1,300	5,070	190	675	1,000	4,085

BGR, Federal Institute for Geosciences and Natural Resources[21]; IEA, International Energy Agency[27,28]; GEA, Global Energy Assessment[29].

Extended Data Table 6 | Regions included in TIAM-UCL and their aggregation to the regions given in the main text

Region	Aggregated region in main text
Non-OPEC Africa	Africa
OPEC Africa	Africa
Australia	OECD Pacific
Canada	Canada
Non-OPEC Central and South America	Central and South America (CSA)
OPEC Central and South America	Central and South America (CSA)
China	China and India
Eastern Europe	Europe
Former Soviet Union	Former Soviet Union (FSU)
India	China and India
Japan	OECD Pacific
Non-OPEC Middle	Middle East
OPEC Middle East	Middle East
Mexico	Central and South America (CSA)
Other Developing Asia	Other Developing Asia (ODA)
South Korea	OECD Pacific
United Kingdom	Europe
United States	United States
Western Europe	Europe

Extended Data Table 7 | Labels and description of the four core scenarios modelled in this project

Scenario Name	Description
5DS	The model is constrained to keep the average global surface temperature rise to less than 5ºC in all years to 2200. No other emissions constraints are imposed, and since allowed emissions under this scenario are so high (i.e. the constraint is very lax), no real emissions mitigation is required. These constraints result in 2050 GHG emissions of 71 Gt CO_2-eq (up from around 48 Gt CO_2-eq in 2010).
3DS	From 2005 to 2010, the model is fixed to the solution given in the 5ºC temperature i.e. we assume that no emissions reductions are required. From 2010-2015, it is assumed that the model must be on track to achieve the emissions reduction pledges set out in the Copenhagen Accord[1], but no other emissions reductions are required. From 2015 onwards the model must meet the Copenhagen Accord emissions reductions in 2020, and emissions must be such as to keep the average global surface temperature rise below 3ºC in all years to 2200. These constraints result in 2050 GHG emissions of 54 Gt CO_2-eq
2DS	The constraints between 2005 and 2015 in this scenario are identical to the 3DS. From 2015 onwards the model must meet the Copenhagen Accord emissions reductions in 2020, and emissions must be such as to keep the average global surface temperature rise below 2ºC in all years to 2200. These constraints result in 2050 GHG emissions of 21 Gt CO_2-eq
2DS-noCCS	Emissions reduction requirements are identical to 2DS. Carbon capture and storage (CCS) is not permitted to be applied to any electricity or industrial process in any period.

GHG, greenhouse gas measured in tonnes of CO_2 equivalent (CO_2-eq). Data from ref. 1.