Electronic Supplementary Material (ESI) for Energy & Environmental Science.

# ELECTRONIC SUPPLEMENTARY MATERIAL

## to the article:

# Likelihood of climate change pathways under uncertainty on fossil fuel resource availability

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## 1. GCAM baseline scenario

The baseline scenario from the standard GCAM 3.2 release version runs for the period 2005-2100 and is characterised by a climate response at the lower bound of the range for the sample of scenarios considered in the IPCC-AR5 baseline model review (reaching a radiative forcing of 7.1 $W/m^2$ and a temperature change of 3.8°C by 2100).[1,2] With the purpose of allowing comparability between the results of the present study and the IPCC-AR5 review results, the exogenous socioeconomic inputs of the GCAM 3.2 baseline were slightly modified in order to produce a climate response in the middle of the range of the IPCC-AR5 baseline model review to reach 7.5 $w/m^2$ and 4°C by 2100. Specifically, the applied baseline scenario is characterised by a global population that grows steadily for the next 60 years, peaking at almost 10 billion people in 2070 and then beginning to slowly decline. Global gross domestic product (market exchange rate GDP) increases almost 10 times from 2005 to 2100 (+2.4% average annual growth). Applying this socioeconomic scenario with the default energy resources of the model (see Supplementary Table 1) results in a significant expansion of the global energy system over the century. Primary energy consumption (direct equivalent) increases from 450 EJ per year in 2005 to more than 1,425 EJ per year in 2100, the energy system continuing to be dominated by fossil fuels at the end of the century. Therefore, global energy and industrial $CO_2$ emissions continue to increase, exceeding 92 $GtCO_2$/year in 2100. Total anthropogenic $CO_2$ emissions are dominated by energy system emissions throughout the century.

**Supplementary Table 1:** Energy resources available from 2005 in the standard GCAM 3.2 release version

| *EJ* | RURR |
|---|---|
| Conventional oil | 14,960 |
| Unconventional oil | 93,635 |
| Natural Gas | 243,398 |
| Coal | 263,833 |
| Uranium | 1,707,594 |

## 2. Shape of the supply-cost curves

A review of the literature revealed that there is uncertainty about the shape of supply-cost curves.[3–8]

Three main patterns were identified:

1. **Exponential**: extraction costs increase steadily with cumulative extraction of the first grades. We approximate this behaviour by an exponential curve:

$$\%MaxCost = a \cdot e^{b \cdot (\%MaxRURR)} \qquad (1)$$

The parameter *a* makes it possible to calibrate past production and costs, while *b* represents the growth rate to reach the maximum cost at RURR.

*%MaxCost* refers to the extraction cost in relation to the maximum cost.

*%MaxRURR* refers to the amount of cumulative resource in relation to the total remaining resource (the RURR).

2. **Inverse**: it is possible that large amounts of resources might be available at an extraction cost that is fairly constant and cheap (relative to higher grades). This is, for example, the case of conventional crude oil in the Middle-East, where large resources have been and are still extracted at costs in the range of $5-15 per barrel.[9] We approximate this behaviour by an inverse curve:

$$\%MaxCost = \frac{a}{URR - \%MaxRURR} \qquad (2)$$

Again, the parameter *a* adjusts the expression for past production and costs.

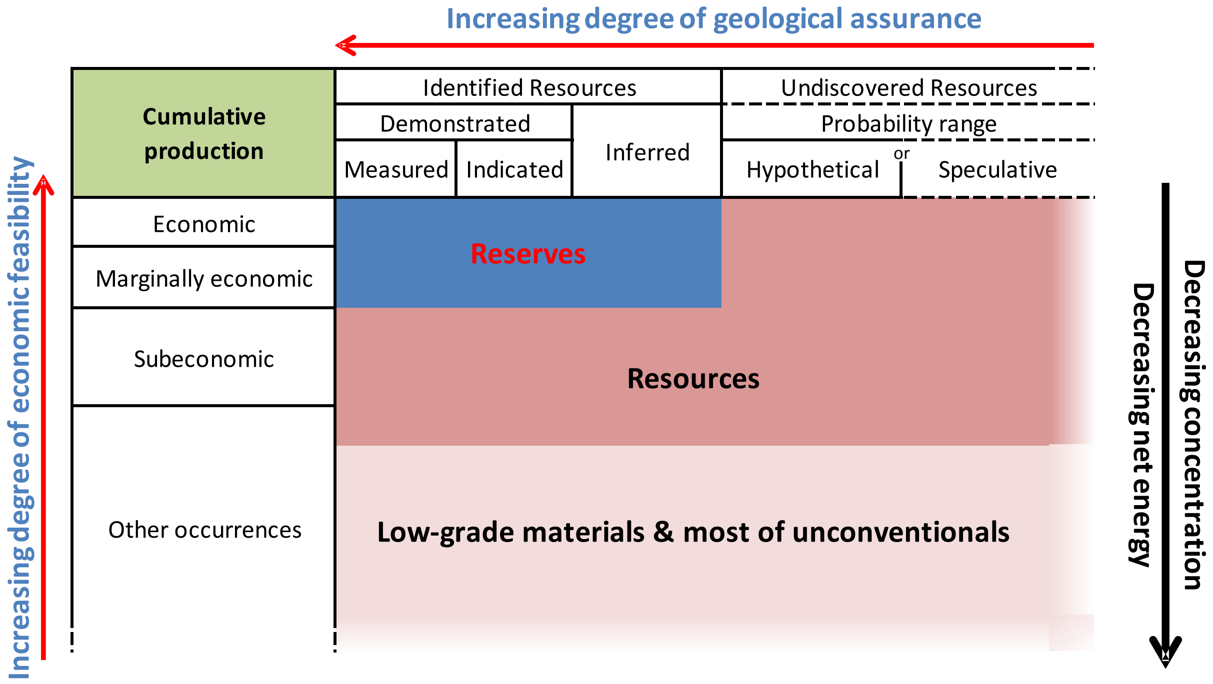
3. **Logistic**: on the other hand, it is possible that the amount of resources that are cheap (relative to the costs of higher grades) would be relatively small in relation to large quantities of significantly more expensive resources. We approximate this behaviour by an adapted logistic function.

$$\%MaxRURR = \frac{RURR}{1 + a \cdot e^{-b \cdot (\%MaxCost)}} \tag{3}$$

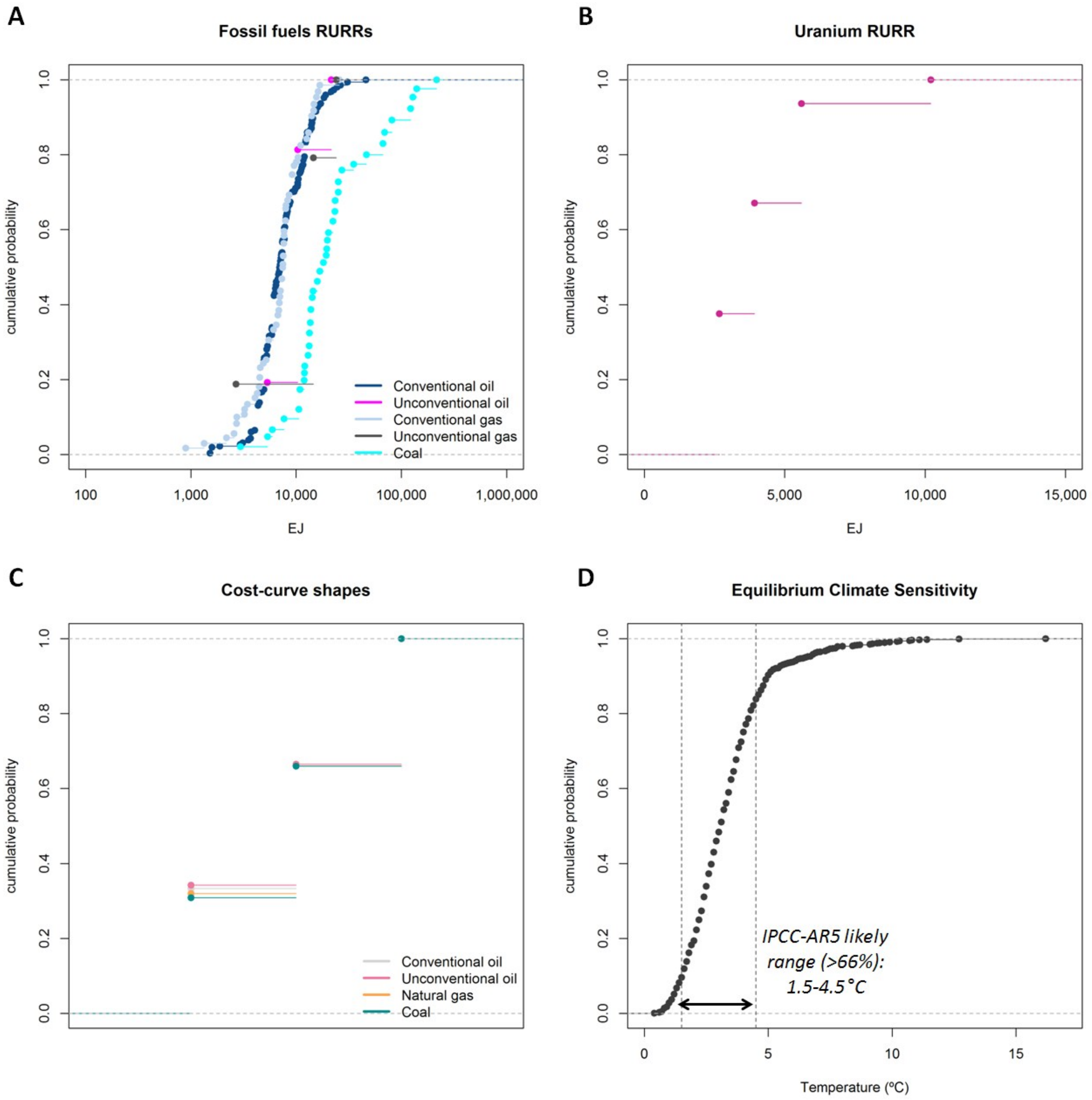
$$\%MaxCost = \frac{1}{12} \cdot \ln\left(\frac{a \cdot b}{\frac{RURR}{\%MaxRURR} - 1}\right) + \frac{1}{2} \tag{4}$$

The three identified shapes are represented in Figure 3 as RURR and extraction cost percentage relative to maximum values.

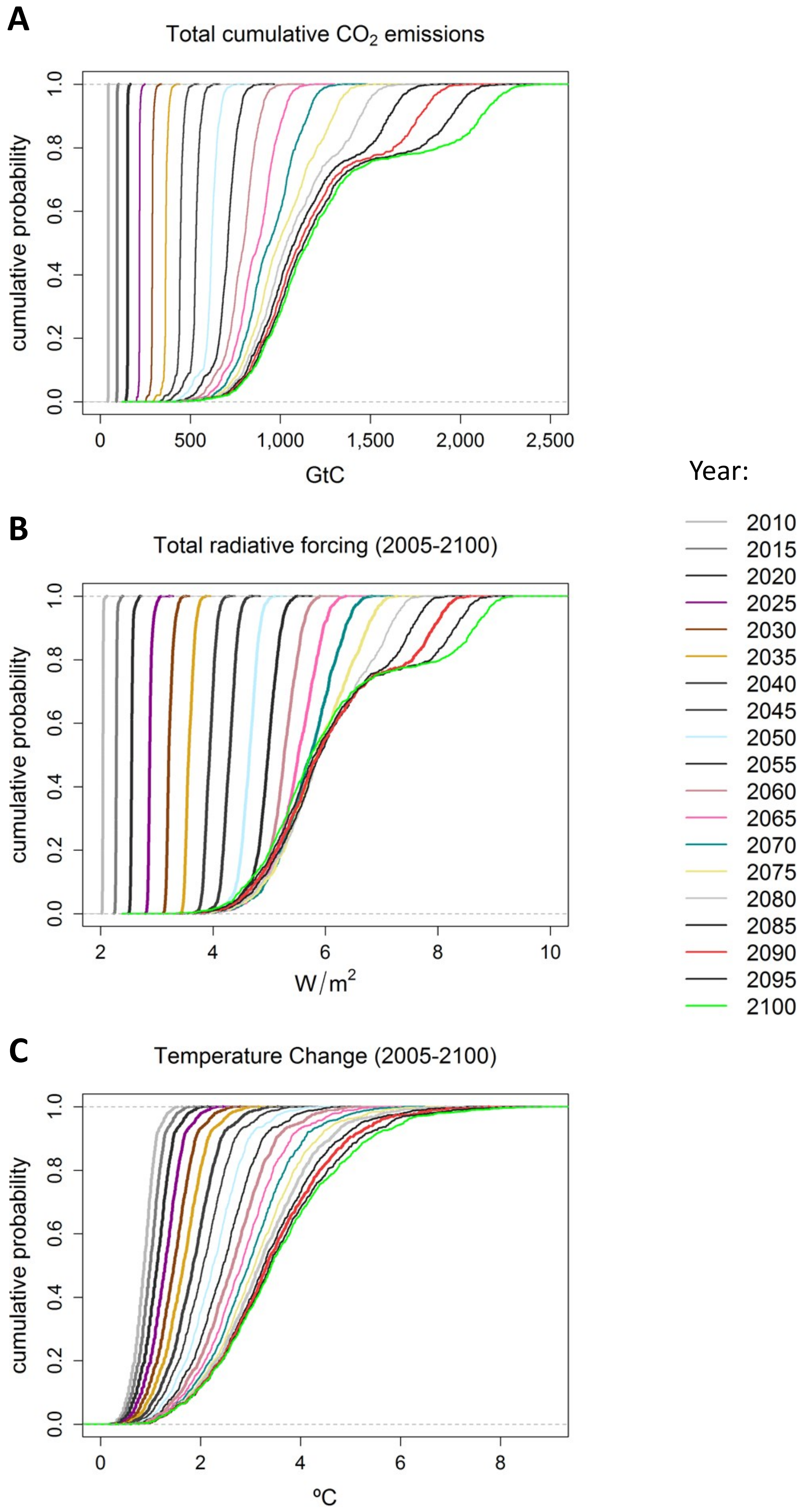
## 4. Supplementary figures



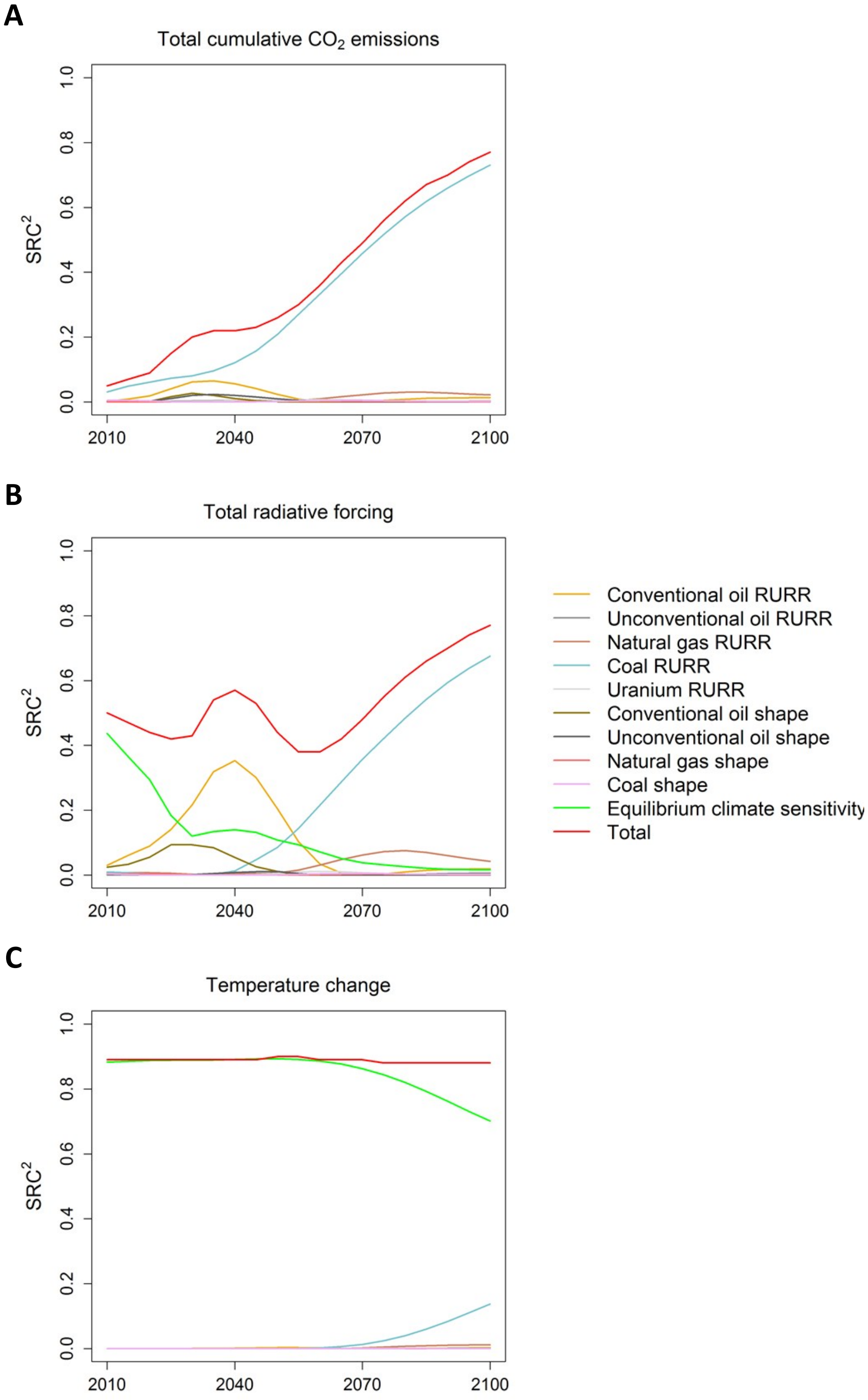
**Supplementary Figure 1: Classification of reserves and resources from USGS/USBM (McKelvey Box).**[10] Reserves are depicted in blue, resources in dark red and "low-grade materials & most of unconventionals" in light red. Adapted from refs.[10–12]



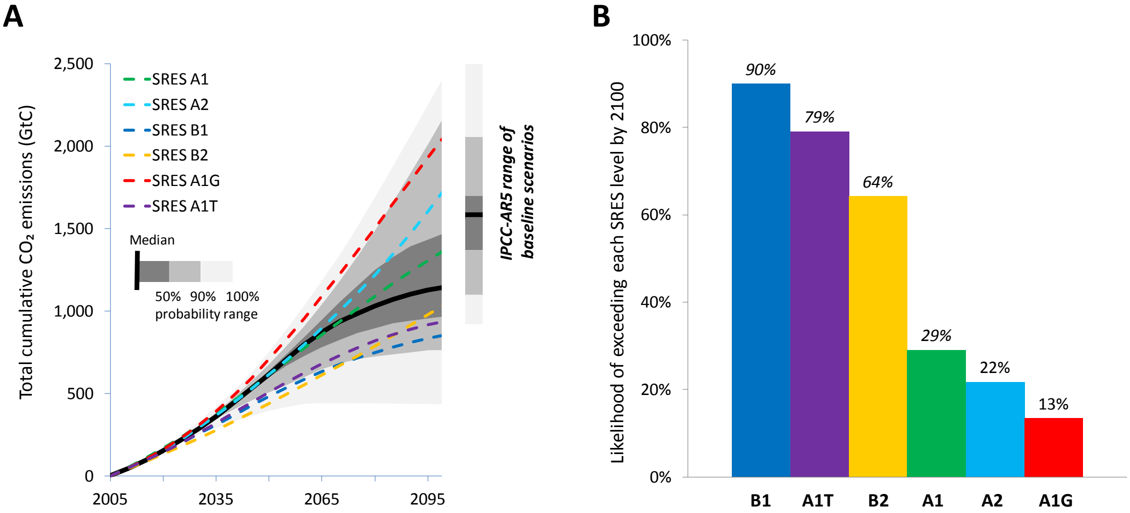
**Supplementary Figure 2: Empirical cumulative distribution functions (ECDFs) of the inputs.** **A**, for oil (conventional and unconventional), gas (conventional and unconventional) and coal RURRs (log scale); **B**, for uranium RURR. The ECDFs for non-renewable resources are available as Electronic Supplementary Information. **C**, shapes of the supply-cost curve. For the fossil fuels, the probability assigned to each shape (inverse, exponential and logistic) is 1/3. The shape for uranium is fixed to inverse. There is only one shape for natural gas since GCAM model aggregates conventional and unconventional gas in a single supply-cost curve; **D**, for equilibrium climate sensitivity.



**Supplementary Figure 3**: **Empirical cumulative distribution function per 5-year period (2010-2100) of the outputs: a,** Total cumulative $CO_2$ emissions; **b,** Total radiative forcing and **c,** Temperature change.



**Supplementary Figure 4: Evolution of the Squared Standardized Regression Coefficients (SRC$^2$) over time for the three outputs. a,** Total cumulative $CO_2$ emissions; **b,** Total radiative forcing and **c,** Temperature change. SRC$^2$ (adimensional) approximates the contribution of the inputs to the output variance. The interpretation of each figure is as follows: the Total (red curve) represents the coefficient of determination of the total multivariate regression. The rest of curves represent the fraction of output variance (cumulative $CO_2$ emissions, total radiative forcing and temperature change) explained by the different inputs (namely, conventional oil RURR, unconventional oil RURR, natural gas RURR, etc.).



**Supplementary Figure 5: Comparison of the results from the sensitivity analysis with the IPCC-AR5 review of baseline scenarios[1] and the SRES marker scenarios[13]. A,** Total cumulative CO$_2$ emission pathways 2005-2100; **B,** Likelihood of exceeding the 2100 level of each SRES scenario.

## 5. Supplementary tables

**Supplementary Table 2: Global oil, gas and coal resource estimates from our study compared with a selection of data sources (EJ)**

| EJ | | **Conv. Oil** | **Unconv. Oil** | **Conv. Gas** | **Unconv. Gas** | **Coal** |
|---|---|---|---|---|---|---|
| Resources + reserves | *GEA (Rogner et al., 2012[11]) & IPCC-AR5* | 9,070 - 13,760 | 15,030 - 20,400 | 12,200 - 16,000 | 60,300 - 189,000 | 308,300[b] - 456,000[b] |
| | *BGR (2013)[14]* | 13,782 | 13,193 | 19,023 | 20,232 | 496,975[b] |
| Remaining recoverable resources | *IEA (WEO 2014)[15]* | 15,508 | 18,826 | 17,363 | 12,743 | 504,000[b] |
| RURR | *Mohr et al (2015)[16] [Low; BG; High]* | *(8,134; 8,527; 15,053)* | *(5,297; 10,351; 15,997)* | *(8,038; 10,051; 16,470)* | *(2,689; 14,559; 18,099)* | *(7,757; 15,694; 25,524)* |
| | *This study[a] [Mean ± SD]* | 8,511 ± 5,333 | 11,977 ± 5,199 | 7,952 ± 4,278 | 14,159 ± 6,604 | 35,047 ± 45,060 |

[a] RURR estimates for conventional oil, conventional gas and coal are derived from Dale (2012)[17]'s dataset, and for unconventional oil and unconventional gas from Mohr et al (2015)[16]. See section 3.1.1.1 for details.

[b] Coal resources that refer to the amount in-place.

**Supplementary Table 3: Numeric values of the climate outcomes shown in Figure 2 (total cumulative $CO_2$ emissions (2005-2100), total radiative forcing and temperature change) by 2100 in comparison with the IPCC-AR5 review of baseline scenarios[1]**

| | **Total cumulative $CO_2$ emissions** | **2100 Total radiative forcing** | **2100 Temperature change** |
|---|---|---|---|
| | *GtC* | *$W/m^2$* | *°C* |
| This study | | | |
| **Median value** | 1,147.1 | 5.6 | 3.4 |
| **Median range (50%)** | 969.2 - 1,474.7 | 5 - 6.8 | 2.6 - 4.4 |
| **"Likely" range (66%)** | 901.2 - 1,999.0 | 4.8 - 8.2 | 2.3 - 4.9 |
| **"Very likely" range (90%)** | 763.3 - 2,196.9 | 4.3 - 8.8 | 1.5 - 6.1 |
| **Full range** | 432.9 - 2,440.5 | 3.2 - 9.2 | 0.6 - 8.8 |
| (IPCC 2014 WGIII) | | | |
| **Median value** | 1,584.1 | 7.4 | -[a] |
| **Median range (50%)** | 1,369.4 - 1,700.7 | 7.2 - 7.6 | 3.7 - 4.8 |
| **"Very likely" range (90%)** | 1,099.4 - 2,056.5 | 6.2 - 8.8 | 2.5 - 7.8 |
| **Full range** | 921.5 - 2,498.2 | 5.3 - 9.3 | -[a] |

[a] The IPCC-AR5[1] does not report the full range nor the median value for temperature increase by 2100 of the review of baseline scenarios.

**Supplementary Table 4: Summary statistics of climate outcomes for the year 2100**

| | **Mean** | **s.d.** | **c.v.** |
|---|---|---|---|
| **Total cumulative $CO_2$ emissions (GtC)** | 1,298 ±15 | 466 | 0.36 |
| **Total radiative forcing ($W/m^2$)** | 6.18 ±0.05 | 1.44 | 0.23 |
| **Temperature (°C)** | 3.57 ±0.04 | 1.37 | 0.38 |

Mean with standard error, standard deviation (s.d.) and coefficient of variation (c.v.).

**Supplementary Table 5: Selected quantile estimates of outputs Y for the year 2100 (95% confidence interval in parentheses)**

| **Quantile** | **0.01** | **0.05** | **0.1** | **0.5** | **0.9** | **0.95** | **0.99** |
|---|---|---|---|---|---|---|---|
| **Total cumulative $CO_2$ emissions (GtC)** | 599 (515 - 657) | 763 (737 - 785) | 837 (810 - 861) | 1,147 (1,114 - 1,172) | 2,110 (2,091 - 2,140) | 2,197 (2,166 - 2,221) | 2,292 (2,272 - 2,356) |
| **Total radiative forcing ($W/m^2$)** | 3.88 (3.66 - 4.02) | 4.38 (4.26 - 4.44) | 4.62 (4.51 - 4.71) | 5.74 (5.67 - 5.84) | 8.65 (8.56 - 8.71) | 8.87 (8.81 - 8.91) | 9.11 (9.03 - 9.2) |
| **Temperature change (°C)** | 1.06 (0.88 - 1.11) | 1.5 (1.35 - 1.6) | 1.89 (1.78 - 2.02) | 3.42 (3.35 - 3.51) | 5.4 (5.22 - 5.56) | 6.06 (5.87 - 6.2) | 7.41 (7.12 - 8.03) |

**Supplementary Table 6: Uranium RURR levels and associated probability derived from the Nuclear Energy Agency estimates[6]**

| Levels | RURR (EJ) | Description | Prob. |
|---|---|---|---|
| 1 | 3,023 | Identified resources (RAR+IR) recoverables at a cost < USD 260/kgU | 36% |
| 2 | 4,212 | Level 1 +<br>Prognosticated resources recovables at a cost < USD 260/kgU | 31% |
| 3 | 5,829 | Level 2 +<br>Speculative resources (undiscovered resources in unknown provinces) recovables at a cost < USD 260/kgU | 25% |
| 4 | 10,668 | Level 3 +<br>Speculative resources and reported unconventional resources with cost unasigned | 7% |

RAR and IR stand for reasonable assured resources and inferred resources. Prob. refers to probability.

**Supplementary Table 7: Change in reserve and resource estimates compared to 1997 (1997⇔100%) by energy source from the updated IPCC range from Rogner et al. (2012)[11] in comparison to the previous assessment by Rogner (1997)[8]**

| | **Reserves** | | **Resources** | | **Total** | |
|---|---|---|---|---|---|---|
| | min | MAX | min | MAX | min | MAX |
| Oil | 62% | 95% | 77% | 104% | 79% | 105% |
| Conventional | 78% | 121% | 69% | 101% | 90% | 118% |
| Unconventional | 49% | 73% | 80% | 105% | 71% | 95% |
| Gas | 180% | 532% | 140% | 387% | 152% | 418% |
| Conventional | 85% | 120% | 62% | 76% | 78% | 97% |
| Unconventional | 250% | 835% | 182% | 551% | 200% | 627% |
| Coal | 41% | 50% | 290% | 433% | 212% | 312% |

Minimum and maximum values refer to the ranges provided by Rogner et al. (2012).[11]

## 6. Supplementary Electronic Material

We provide an Excel file (URR-resources_Input-Data_Capellan-Perez et al.xls) as Supplementary Electronic Material with the URR estimates applied in the analysis in terms of primary energy (EJ) for the following fuels: oil (conventional & unconventional), natural gas (conventional & unconventional), coal and uranium. Data are derived from Dale (2012),[17] Mohr et al., (2015)[16] and (NEA, 2012).[6]

The XML files for running GCAM and the R scripts applied in the uncertainty and sensitivity analyses are available upon request.

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