Energy (Methodology)

Introduction

Carbon Visuals is a data visualisation studio that specialises in scientifically accurate visualisations that reach non-specialist audiences by making abstract numbers 'real' in a visually engaging way.

Carbon Visuals made a film called *Energy* for the World Business Council for Sustainable Development (WBCSD). The film demonstrates graphically how significant fossil fuel use is today, and will continue to be for decades to come and so makes a case for carbon capture and storage.

This document provides references for data the film refers to and details of calculations, etc.

Contents

Summary

The world gets through a lot of fossil fuels:

- 7,896.4 million metric tons of coal in 2013 (21.6 million metric tons per day, 250 metric tons per second)

- 91,330,895 barrels of oil per day in 2013 (168 m^3 per second)

- 3,347.63 billion m^3 of natural gas in 2013 (9.2 km^3 per day, 106,082 m^3 per second)

This film tries to make those numbers physically meaningful – to make the quantities 'real'; more than 'just numbers'. All the graphics in the film are based on real quantities.

- The coal we use each day would form a pile 236 metres high and 673 metres across. We could fill a volume the size of the UN Secretariat Building with coal every 17 minutes.

- At the rate we use oil, we could fill an Olympic swimming pool every 15 seconds. We could fill a volume the size of the UN Secretariat Building with oil every 30 minutes.

- The rate at which we use natural gas is equivalent to gas travelling along a pipe with an internal diameter of 60 metres at hurricane speeds (135 km/h / 84 mph). We could fill a volume the size of the UN Secretariat Building with natural gas in under 3 seconds. We use a cubic kilometre of gas every 2 hours 37 minutes and a cubic mile of the stuff every 10 hours 54 minutes.

The world's use of fossil fuels is increasing, not decreasing. Renewable energy will help, but it cannot keep up with the demand for energy. The International Renewable Energy Agency's most optimistic road-map suggests that renewables will not displace fossil fuels for decades, which is a problem because we are adding carbon dioxide to the atmosphere at an increasing rate.

- In 2012 we added over 39 billion metric tons of carbon dioxide to the atmosphere. That's 1,237 metric tons a second. It is like a 'bubble' of carbon dioxide gas 108 metres across entering the atmosphere every second of every day. We could fill a volume the size of the UN Secretariat Building with our carbon dioxide emissions in less than half a second. We could fill it 133 times a minute. The pile of one metric ton spheres in the film, which represents one day's emissions, is 3.7 km high (2.3 miles) and 7.4 km across (4.6 miles).

To keep global warming below 2 °C we can afford to emit no more than 1 trillion metric tons of carbon into the atmosphere (3.66 trillion metric tons of carbon dioxide).

2 °C is a significant figure because if warming is more than this 'positive feedback' effects will make it increasingly hard to control the temperature. For instance, beyond 2 °C, there will be considerably less ice on Earth. Because it is white, ice reflects energy from the sun back out to space. If the ice goes, more energy from the sun will be absorbed by the Earth.

We have already added more than half threshold quantity of 1 trillion metric tons of carbon (up to mid-2014, we have emitted about 582 billion metric tons). If carbon dioxide from fossil fuels continues to enter the atmosphere we will reach 2 °C threshold in a few years. The projected emissions illustrated in the film are based on RCP 4.5, which is one of the four 'Representative Concentration Pathways' used in the Intergovernmental Panel on Climate Change's Fifth Assessment Report.

Carbon capture and storage means we can use the energy of fossil fuels without adding carbon to the atmosphere. Because fossil fuels will remain a significant part of the world's energy economy for decades to come, carbon capture and storage is an essential part of any plan to keep global warming below 2 °C.

Some numbers used in calculations below

Seconds in one year: 31,556,925.9936

Molar mass of CO_2: 44.01 g/mol
Molar mass of C: 12.0107 g/mol

Density of air: 1.275 kg/m^3
Density of carbon dioxide gas at standard pressure & 15 °C: 1.87 kg/m^3

The packing density of randomly arranged spheres: 0.64

United Nations Secretariat Building

Height: 153.9 metres
Width: 88.0 metres
Depth: 22.0 metres

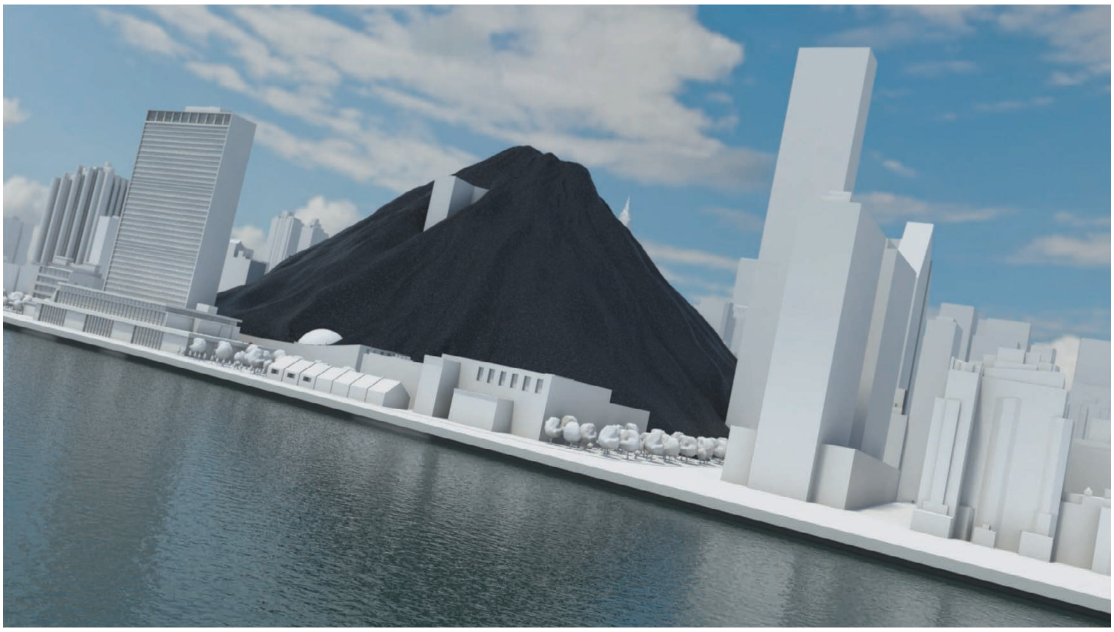
Volume: 297,950.4 m^3

Olympic swimming pool

Length: 50 metres
Width: 25 metres
Depth: 2 metres

Volume: 2,500 m^3

Coal



Total production 2013: 7,896.4 Mt (BP Statistical Review, 2014: Workbook)

Equivalent to:

21,619,627 tonnes per day
250 tonnes per second

Calculating the height and width of a pile of coal requires:

- The bulk density of coal (to determine the total volume of the pile)
- The angle of repose[1] for coal
- The precise shape of the pile

We can deal with the last of these (precise shape) by creating a pile-like shape and scaling it to have the correct volume.

Accounting for different types of coal

The BP data does not break down how much of that coal is 'brown coal'. Because brown coal has a lower bulk density the proportion is important for estimating the size of the pile. However, according to Coal Facts 2013, 12% of coal production in 2012 was brown coal. Based on the trend visible in Coal Facts publications going back to 2005 it is reasonable to assume that the figure for 2013 is somewhere around 11% or 12%. We have assumed it to be 12%.

[1] For a definition of 'angle of repose' see: http://en.wikipedia.org/wiki/Angle_of_repose

The range of densities of the brown coal we assume to be an average of the ranges for bituminous coal and lignite. The ranges are already quite large so this assumption does not have a significant effect on the calculation.

Bulk density for coal

The range of values for bulk density are taken from the Engineering Toolbox: www.engineeringtoolbox.com/classification-coal-d_164.html

The range for the 2013 mix has been calculated with reference to the assumptions above (Accounting for different types of coal).

	Bulk density min (kg/m^3)	**Bulk density mean (kg/m^3)**	Bulk density max (kg/m^3)
Anthracite	800.0	**864.5**	929.0
Bituminous	673.0	**793.0**	913.0
Lignite	641.0	**753.0**	865.0
2013 mix:	782.8	853.5	924.2

Angle of repose for coal

According to Wolfram Alpha Knowledge Base, the angle of repose for broken bituminous coal and anthracite is 35°.
www.wolframalpha.com/input/?i=coal+angle+of+repose

Dimensions of pile

The dimensions of a pile of daily coal will be in the following range:

	Min	**Mean bulk density**	Max
Total volume of coal (m^3)	23,392,801	**25,329,959**	27,616,916
Height of pile (metres)	229	**236**	243
Diameter of pile (metres)	655	**673**	693

Above: sketch showing the range of pile heights corresponding to the range of bulk densities for coal, with United Nations Secretariat Building for scale (height of outer pile: 243 metres; height of inner pile: 229 metres)

The actual volume of the pile in the video is 25,765,180 m^3 (which is within 2% of the target value for mean bulk density and comfortably within the range). Its actual height is 237 metres. We have used these values to calculate the dimensions of similarly shaped piles with different volumes. This can be most easily understood as a two-step process: 1) find the volume of a similarly shaped pile that is precisely 1 metre high; 2) use the cube root of the ratio of this volume and the target volume to scale the 1 metre pile.

Volume of pile at 1 metre high:

$$V_1 = \frac{V}{h^3}$$

Where V is the volume of the pile and h is the height of the pile.

In the case of the pile in the film, V_1 is 1.9355 m^3.

To scale the pile to another target volume, we use the following formula:

$$Height\ scaling = \left(\frac{V}{V_1}\right)^{\frac{1}{3}}$$

Where V is the total volume of coal and V_1 is the volume of the shape of the pile when it is scaled to be 1 metre high.

Time to fill United Nations Secretariat Building

$$Time\ to\ fill\ UN\ Building = \frac{volume\ of\ building}{volume\ of\ coal\ consumed\ per\ second}$$

The time it would take to fill the UN Building fits into the following range:

	Min	**Mean bulk density**	Max
Volume of coal per second (m^3/s)	270.75	**293.17**	319.64
Time to fill UN Building	18m 20s	**16m 56s**	15m 32s

Oil

Volume of a barrel: 42 US gallons = 158.987 litres

Global oil consumption in 2013: 91,330,895 barrels per day (BP Statistical Review, 2014: Workbook)

Equivalent to:

14,520,452,022 litres per day

168,061 litres per second

Time to fill UN Building = 29 m 33 s

Time to fill an Olympic swimming pool = 14.9 seconds

A pipe with diameter 3 metres has cross-section area 7.07 m^2 ($A = \pi r^2$)

$$Exit\ speed\ of\ oil = \frac{volume\ of\ oil\ per\ second}{area\ of\ exit\ hole}$$

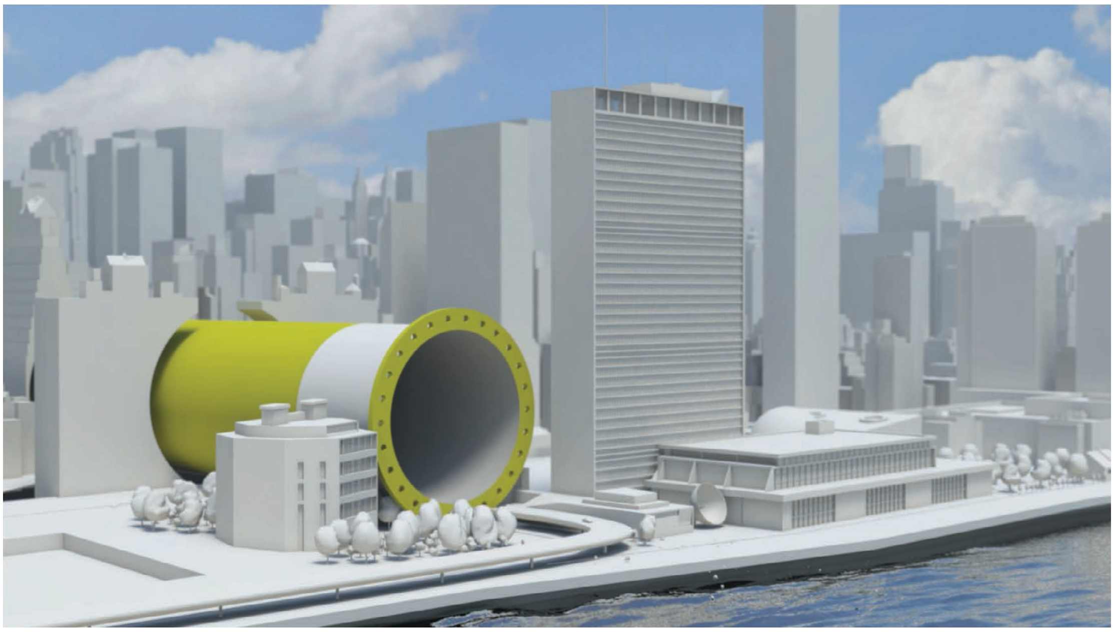
Exit speed of oil = 23.78 m/s (86 km/h or 53 mph)

Checking the fluid simulation looks right

$$Horizontal\ distance\ travelled\ before\ hitting\ pool = u\sqrt{\frac{2h}{g}}$$

Where *u* is the exit speed, *h* is the height of the pipe above the bottom of the pool (3 metres) and *g* is the acceleration due to gravity (9.8 m/s^2).
Thus the bottom of the plume of oil would hit the pool 18.6 metres from the end of the pipe.

Natural Gas



Global gas consumption 2013: 3,347.63 billion m^3/year (BP Statistical Review, 2014: Workbook)

Equivalent to:

106,082 m^3/s

9.2 km^3/day
2.2 mi^3/day

Time to fill UN Building = 2.81 seconds

Time for one km^3: 2 hours 37 minutes
Time for one mi^3: 10 hours 54 minutes

A pipe with diameter 60 metres has cross-section area 2,827 m^2
($A = \pi r^2$)

$$Exit\ speed\ of\ gas = \frac{volume\ of\ gas\ per\ second}{area\ of\ exit\ hole}$$

Exit speed of gas = 37.52 m/s (135 km/h or 84 mph)

Renewable energy projections

The International Renewable Energy Agency (IRENA) predicts that 'business as usual' would result in the share of energy from renewables growing to 21% in 2030 (IRENA 2014, p 19). Its roadmap however, sees renewables' share growing faster: reaching up to 36% in 2030 (IRENA 2014, p 12). The film uses IRENA's projection for Total Final Energy Consumption (IRENA 2014, p 17) and its optimistic 36% figure. Growth of renewables is still too slow to keep global warming below 2 °C.

Projections vary greatly, but IRENA's analysis and roadmap are very broadly in line with other projections such as Shell's Scenarios (Shell, 2014). In 2030, Shell's 'Oceans' scenario puts renewables' share of Total Primary Energy Demand at only 16%. In Oceans, renewables do not contribute as much as 36% until 2060 (Shell, 2014, p 83). In terms of energy from renewables, Shell's Oceans scenario is only about 30% lower than IRENA's roadmap – not less than half of it.

However, Oceans' figures relate to Total Primary Energy Demand (TPED) and IRENA's to Total Final Energy Consumption (TFEC) so the two figures are not easy to compare. Oceans' projection for TPED in 2030 is 777 EJ as opposed to IRENA's 471 EJ projection for TFEC (IRENA 2014, p 17).

	Energy from renewables in 2030 (Exajoules)	Share of total energy in 2030 (TPED or TFEC)
Shell's Oceans scenario	124	16%
IRENA's roadmap	Up to 170	Up to 36%

The World Wide Fund for Nature's *Energy Report* (WWF 2011) maps out a pathway that could result in 100% renewable energy by 2050. However, the purpose of the *Energy Report* is to demonstrate that the goal is feasible; it is not an exercise in prediction of what will actually happen.

The slow growth of renewables is discussed in Shell's Scenarios document in a section titled 'Is 100% renewable energy possible?' (Note **Error! Bookmark not defined.**, page 69). The conclusion of this section argues that a zero emissions energy system would be far easier to achieve than 100% renewable energy system:

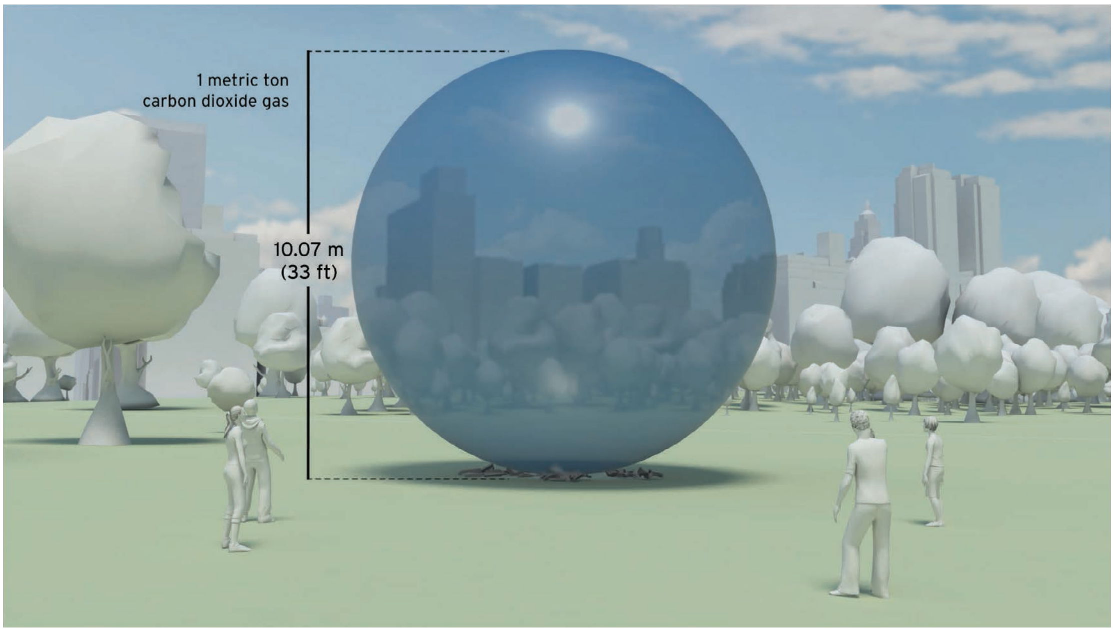
> Optimism for a completely renewable future needs to be tempered by an appreciation of the significant technological, geographical, and market practicalities, let alone the political and societal challenge required. Yet if the optimism is directed towards a zero-emission energy system, including the successful deployment of CCS and biomass combinations, then that appears a distinctly more feasible option than a 100% renewable energy system.

Table adapted from Shell's 'Summary Quantification Tables', *New Lens Scenarios* (Note **Error! Bookmark not defined.**, page 83):

Oceans Scenario: Total primary energy by source: exajoules / year (10^{18} joules / year)

Year	2010	2020	2030	2040	2050	2060
Oil	173.1	196.4	214	221.8	220.7	201.4
Biofuels	2.5	4.6	5.5	7.2	14.2	25.9
Natural Gas	114.8	147.9	169.2	187.3	185.6	175.4
Biomass Gasified	1.3	7.8	19.8	20.4	22.1	26.8
Coal	146.2	202.7	222.3	201.7	218.6	204.2
Biomass/Waste Solids	17.1	18.7	14.1	15.5	17.7	21.4
Biomass Traditional	33.2	28.9	26.9	24.2	24.3	22.5
Nuclear	30.1	33.3	42.1	47.2	52.4	54.7
Hydro-electricity	12.4	13.5	14.8	16.8	18.7	20.6
Geothermal	2.4	5.1	9.7	18.9	26.4	34.1
Solar	0.8	4.4	25.2	70.1	132.6	209.6
Wind	1.2	4.7	13.2	24.7	42.4	59.3
Other Renewables	0	0	0	0	0.1	0.2
Total	**535**	**668**	**777**	**856**	**976**	**1056**
% fossil energy	81%	82%	78%	71%	64%	55%
Total fossil energy	**434.1**	**547**	**605.5**	**610.8**	**624.9**	**581**
Total renewables	**68.4**	**83.1**	**123.7**	**190.6**	**284.3**	**394.5**
% renewables	13%	12%	16%	22%	29%	37%

Carbon dioxide



Carbon dioxide gas at 15 °C and standard pressure has a density of 1.87 kg/m^3. Which means the volume of one metric ton of carbon dioxide gas is 534.76 m^3. The diameter of a sphere is given by the following formula:

$$d = \left(\frac{6V}{\pi}\right)^{\frac{1}{3}}$$

The diameter of a one metric ton sphere is 10.071 metres (about 33 feet).

Physical behaviour

A one metric ton sphere of carbon dioxide gas displaces 534.76 m^3 of air. Its 'excess mass' (its apparent mass when we account for buoyancy) is given by the following equation:

$$m_e = m_{CO_2} - \frac{m_{CO_2} \cdot \rho_{air}}{\rho_{CO_2}}$$

Where m_e is the excess mass, m_{CO2} is the mass of carbon dioxide, ρ_{air} is the density of air and ρ_{CO2} is the density of carbon dioxide. For a one metric ton sphere, this is 318 kg. In other words, it 'feels' like a sphere that is 318 kg (701 US lbs).

When falling through the air, a one metric ton sphere of carbon dioxide gas will accelerate until it reaches a speed at which the force of air resistance matches the force of gravity. This speed, known as the 'terminal velocity', is given by the following equation:

$$v_T = \frac{2m_e g}{\sqrt{A\rho_{air} c_d}}$$

Where v_T is terminal velocity, m_e is the excess mass, g is the acceleration due to gravity, A is the cross-section area of the sphere (79.65 m^2) ρ_{air} is the density of air and c_d is the drag coefficient[2] for a sphere (0.47). For a one metric ton sphere, the terminal velocity is 11.43 $m.s^{-1}$ (41 km/h or 26 mph). That is the speed at which the single sphere is falling when it lands on the furniture in the film.

The film takes some liberties with the physical properties of carbon dioxide spheres in the scene in which spheres fly into the air at a rate of 1,237 a second. The terminal velocity we represent there is actually 86 $m.s^{-1}$ (310 km/h or 192 mph) which is significantly faster than a physically realistic value, but has the advantage of looking right.

What we are interested in representing in this scene is the rate at which carbon dioxide is entering the atmosphere, not the physical properties of fictitious spheres, so the priority is to show the number of spheres appearing in a way that doesn't raise too many other questions. For that reason, looking right trumps being physically realistic.

Emissions

Figures for carbon dioxide emissions use the latest actual values compiled by the Global Carbon Project (Le Quéré, et al, 2013) rather than a projection for current values. The latest year for which data are available is 2012.

Year	Fossil fuel & cement emissions[3] (GtC)	Land use change emissions[4] (GtC)	Total (GtC)
2012	9.67	0.99	10.66

$$Mass\ of\ CO_2 = Mass\ of\ C \times \frac{Molar\ mass\ of\ CO_2}{Molar\ mass\ of\ C}$$

Converting to Gt CO_2:

[2] For a definition of 'drag coefficient' see: http://en.wikipedia.org/wiki/Drag_coefficient

[3] Boden et al 2013. 2012 estimates are based on BP's *Statistical Review of World Energy 2012*.. Emissions from cement production were estimated by CDIAC based on cement production data from the US Geological Survey.

[4] Houghton et al, 2012. The 2012 estimates is an extrapolation as described in Le Quéré et al. 2013

Year	Fossil fuel & cement emissions ($GtCO_2$)	Land use change emissions ($GtCO_2$)	Total ($GtCO_2$)
2012	35.42	3.63	39.05

Average daily emissions in 2012 were 106,902,955 tonnes CO_2 / day.

The angle of repose chosen for a pile of carbon dioxide spheres is 45°. As the spheres are not real, the choice physical properties we give them is arbitrary – it just looks right

Dimensions of Pile

The pile in the film has a volume of approximately.: 90,500,000,000 m^3. This is within 1% of the target volume of 89,323,992,748 m^3 (see below). It is 4,242 metres high.

As with the coal pile above, to calculate the dimensions of similarly shaped piles with different volumes we can use the volume and height of the pile. A similarly shaped pile at 1 metre high has a volume of 1.1858 m^3.

The packing density of randomly arranged spheres is 0.64. (This means a in a volume containing randomly arranged spheres, 64% of the volume will be taken up by spheres and 36% will be the spaces in between the spheres.)

We can calculate the height scaling for the pile of spheres in the same way we calculated the scaling for the pile of coal, but the volume to use is not the total volume of CO_2 gas, but rather the volume of all the spheres plus the spaces in between the sphere. The equation is:

$$Height\ scaling = \left(\frac{V_{co_2}/0.64}{V_1}\right)^{\frac{1}{3}}$$

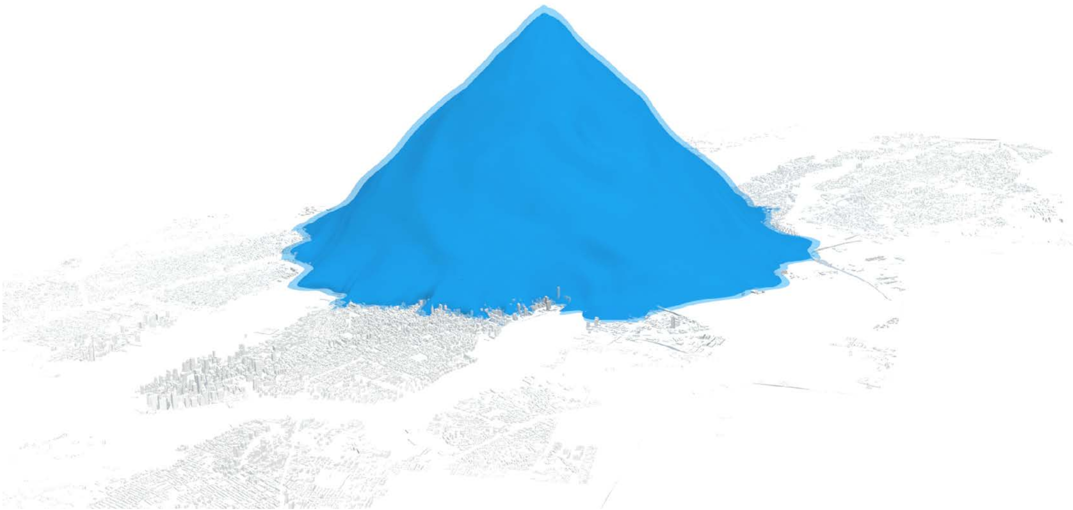
Where V_{CO2} is the total volume of CO_2 and, as before, V_1 is the volume of the pile shape at a height of 1 metre.

The time to fill the United Nations Secretariat building is given by the following equation:

$$Time\ to\ fill\ UN\ Building = \frac{volume\ of\ building}{volume\ of\ gas\ emitted\ per\ second}$$

The Global Carbon Project figures have error bounds of 5%, which gives the following range for the values for spheres per second, time to fill the UN Building and height of the daily pile:

	min (-5%)	2012 value	max (+5%)
2012 CO_2 emissions (tonnes/second)	1,175	1,237	1,299
2012 time to fill UN Bldg (seconds)	0.47	0.45	0.43
2012 height of daily pile (metres)	4,152	4,223	4,293



Sketch showing the range of pile heights corresponding to the range of values for the 2013 emissions, with New York City for scale (outer pile: 4,293 metres; inner pile: 4,152 metres). The pile in the film is between these extremes.

Historic emissions

To illustrate historic emissions we used CDIAC data taken from Global Carbon Budget 2013 v2.4. The aim in this very short animation is merely to give a rough sense of the way emissions have accelerated since 1750. The final value (2014) is taken from the Trillionth Tonne tool (www.trillionthtonne.org).

Year	fossil fuel and cement emissions (GtC)	land-use change emissions (GtC)	Cumulative emissions (GtC)	As percentage of 1 trillion tonnes C
1760	0.003	-	0.030	0%
1770	0.003	-	0.060	0%
1780	0.004	-	0.100	0%
1790	0.005	-	0.150	0%
1800	0.008	-	0.215	0%
1810	0.010	-	0.310	0%
1820	0.014	-	0.435	0%
1830	0.024	-	0.608	0%
1840	0.033	-	0.879	0%
1850	0.054	0.525	1.833	0%
1860	0.091	0.614	8.617	1%
1870	0.147	0.498	15.136	2%
1880	0.236	0.625	22.923	2%
1890	0.356	0.665	32.327	3%
1900	0.534	0.652	43.125	4%
1910	0.819	0.861	58.034	6%
1920	0.932	0.673	74.048	7%
1930	1.053	0.765	91.222	9%
1940	1.299	0.864	110.180	11%
1950	1.630	1.054	133.133	13%
1960	2.569	1.461	168.749	17%
1970	4.053	1.531	216.461	22%
1980	5.315	1.243	277.644	28%
1990	6.127	1.444	347.704	35%
2000	6.765	1.412	427.133	43%
2010	9.167	0.855	517.893	52%
2014			582.291	58%

2° limit

To represent 1 trillion metric tons of carbon we illustrate the volume that carbon dioxide gas equivalent to 1 trillion metric tons C, at 15 °C and standard pressure would occupy. The volume of that much carbon dioxide gas is 1,959,483 km^3. It would fit in a cube with sides 125,135 metres (77.8 miles).

Proven Reserves

The values for the proven reserves are taken from Table 7.2 in IPCC WG3 AR5 (Chapter 7, page 16), which was originally taken from Rogner et al, 2012

The following table shows the values used and the range (in brackets). The units are exajoules (10^{18} joules) and gigatonnes C (billion metric tons of Carbon).

Reserves

Reserves	EJ	Gt C
Total Coal	19,150 [17,300-21,000]	494 [446-542]
Total Oil	10,930 [8,650-13,210]	219 [173-264]
Total Gas	49,650 [25,100-74,200]	759 [383-1,134]
Total	**79,730 [51,050-108,410]**	**1,471 [1,002-1,940]**

'Reserves' are those quantities able to be recovered under existing economic and operating conditions. Reserves are distinguished from 'Resources', which are quantities for which economic extraction is potentially feasible but unlikely with current economic and operating conditions. Resources are considerably greater than reserves. For more detail on what constitutes 'reserves' in relation to petroleum see SPE & WPC, 1997. The following table represents resources, which are *not* represented in the film:

Resources	EJ	Gt C
Total Coal	363,000 [291,000-435,000]	9,370 [7,510-11,230]
Total Oil	18,200 [15,450-20,950]	365 [309-420]
Total Gas	89,100 [47,400-130,800]	1,362 [724-1,999]
Total	**470,300 [353,850-586,750]**	**11,096 [8,543-13,649]**

Note that the values quoted by the IPCC diverge from the estimates in BP Statistical Review, 2014, which in turn diverge from estimates by the IEA (International Energy Agency 2013(2)). In the following table estimates for reserves taken from the BP Statistical Review Workbook converted to units of Gt C. These have then been compared with the values quoted by the IPCC (above).

Reserves	BP estimate (Gt C)	IPCC estimate (Gt C)	IPCC / BP
Total Coal	665	494	74%
Total Oil	198	219	110%
Total Gas	91	759	834%
Total	**954**	**1,471**	**154%**

The main reason for the divergence is the inclusion of 'unconventional oil' and 'unconventional gas' in the IPCC table. Unconventional gas, which includes gas derived by fracking, is already very significant in the United States and increasingly significant in Europe, Russia and elsewhere, so it makes intuitive sense to include it as a 'reserve'.

Estimates for proved reserves depend crucially on definitions, and so vary widely. However, all estimates for reserves, when converted to units of carbon, indicate that the carbon associated with fossil fuels yet to be used would take cumulative emissions beyond the 1 trillion metric ton threshold if it is allowed to enter the atmosphere.

Projected emissions

The animation of projected emissions is based on Global Carbon Budget 2013 v2.4 and RCP 4.5, which is one of the 4 'Representative Concentration Pathways' used in the IPPC's Fifth Assessment Report. The RCP Database provides estimates for the rate of CO_2 emissions (GtC/year) for 2010, 2020, and subsequent decades to 2100.

http://www.iiasa.ac.at/web-apps/tnt/RcpDb

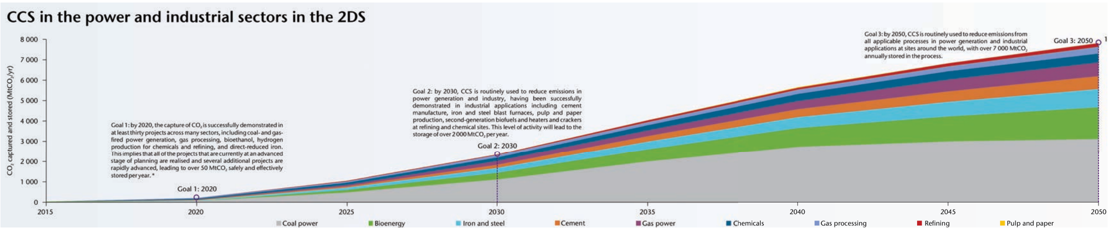
To get cumulative emissions we integrated this series in a very simple way (assuming the points are joined by straight lines). This basic analysis puts the time at which 1 trillion tonnes C is exceeded some time between 2050 and 2055.

The table below uses RCP 4.5 values to extend the table of cumulative emissions above. The values in blue are extrapolations for animation purposes and are not included in calculations. 'Cumulative emissions for period' refers to periods between dates in black – not in blue.

	RCP 4.5 (GtC/yr)	Cumulative emissions for period (GtC)	Cumulative emissions (GtC)
2005	9.167		
2010	9.518	46.71	533.91
2014		39.46	573.37
2015		49.33	583.23
2020	10.212	98.65	632.56
2025		26.73	659.28
2030	11.170	106.91	739.47
2040	11.537	113.53	853.00
2050	11.280	114.08	967.08
2055		52.16	1,019.24
2060	9.585	104.33	1,071.41
2070	7.222	84.04	1,155.44
2080	4.190	57.06	1,212.50
2090	4.220	42.05	1,254.55
2100	4.249	42.34	1,296.89

CCS Growth

The animation in this section is based on IEA's Carbon Capture and Storage Roadmap, and in particular on the main figure in the FoldOut (summary) which shows the rate storage per year between 2015 and 2050.



In the absence of a table of values we measured values directly from the graph and integrated between values in the following way:

$$Carbon\ stored\ in\ period = \frac{(t_2 - t_1)(R_1 + R_2)}{2}$$

Where t_1 is the year at the beginning of the period, t_2 is the year at the end of the period, R_1 is the rate of carbon storage at the beginning of the period and R_2 is the rate at the end of the period.

http://www.iea.org/media/freepublications/technologyroadmaps/EMBARGO_CCS_2013_Roadmap_FoldOut.pdf

Year	Carbon stored per year ($MtCO_2$)	Carbon stored in period ($MtCO_2$)	Cumulative stored carbon ($MtCO_2$)	Cumulative stored carbon (MtC)
2015	40	-	-	-
2020	210	625	625	171
2025	1,060	3,175	3,800	1,037
2030	2,360	8,550	12,350	3,370
2040	5,690	40,250	52,600	14,355
2050	7,870	67,800	120,400	32,858
2055	8,960	42,075	162,475	44,341

For the purpose of the animation we extrapolated to 2055 assuming the same rate of growth as 2040 to 2050.

References

Boden, T. A., Marland, G., and Andres, R. J. 2013, *Global, Regional, and National Fossil-Fuel CO_2 Emissions*, Carbon Dioxide Information Analysis Center (CDIAC) Oak Ridge National Laboratory, U.S. Department of Energy, Oak Ridge, Tenn., U.S.A.

BP Statistical Review of World Energy, June 2014
http://bp.com/statisticalreview

Houghton R.A., House J.I., Pongratz J., van der Werf G.R., DeFries R.S., Hansen M.C., Le Quéré C., and Ramankutty N. (2012) 'Carbon emissions from land use and land-cover change', *Biogeosciences*, 9, 5125-5142.
Doi: 10.5194/bgd-9-835-2012

International Energy Agency 2013(1), *Key World Energy Statistics 2013*,
www.iea.org/publications/freepublications/publication/KeyWorld2013.pdf

International Energy Agency 2013(2), *Resources to Reserves 2013: Oil, Gas and Coal Technologies for the Energy Markets of the Future* (ISBN 978-92-64-08354-7)
http://www.iea.org/w/bookshop/add.aspx?id=447

IPCC WG3 AR5 (final draft postplenary) Chapter 7
http://www.ipcc.ch/report/ar5/wg3/

IRENA, 2013, "Doubling the Global Share of Renewable Energy: A Roadmap to 2030", January 2013, IRENA, Abu Dhabi,
www.irena.org/DocumentDownloads/Publications/IRENA%20REMAP%202030%20working%20paper.pdf.

IRENA, 2014, REmap 2030: A Renewable Energy Roadmap, June 2014. IRENA, Abu Dhabi. www.irena.org/remap

C. Le Quéré, et al, 'Global carbon budget 2013', *Earth Syst. Sci. Data*, 6, 235–263, 2014 www.earth-syst-sci-data.net/6/235/2014/ doi:10.5194/essd-6-235-2014
Data: Global Carbon Budget 2013 Budget v2.4 (July 2014) from Global Carbon Project: http://cdiac.ornl.gov/GCP/ (www.globalcarbonproject.org)

Rogner H.H., R.F. Aguilera, C.L. Archer, R. Bertani, S.C. Bahattacharya, M.B. Dusseault, L. Gagnon, H. Haberl, M. Hoogwijk, A. Johnson, M.L. Rogner, H. Wagner, and V. Yakushev (2012). Chapter 7 – 'Energy resources and potentials'. In: *Global Energy Assessment – Toward a Sustainable Future*. IIASA and Cambridge University Press, Vienna, Austria, and Cambridge, UK (ISBN: 9781107005198).

Shell, *New Lens Scenarios*, 2014
Details: http://www.shell.com/global/future-energy/scenarios/new-lens-scenarios.html

Download: http://s01.static-shell.com/content/dam/shell-new/local/corporate/Scenarios/Downloads/Scenarios_newdoc.pdf

SPE & WPC, 1997 (Society of Petroleum Engineers Inc (SPE). and the Executive Board, World Petroleum Council) Petroleum *Reserves Definitions* http://www.spe.org/industry/docs/Petroleum_Reserves_Definitions_1997.pdf

World Coal Association, *Coal Facts 2013*, http://www.worldcoal.org/resources/coal-statistics/

WWF, 2011 *The energy report: 100% renewable energy by 2050*
ISBN 978-2-940443-26-0
http://wwf.panda.org/what_we_do/footprint/climate_carbon_energy/energy_solutions22/renewable_energy/sustainable_energy_report/