Global Calculator – spreadsheet user guide

This document is aimed at those who wish to gain a detailed insight into the underlying Global Calculator Excel spreadsheet. It is best read by referring to the Spreadsheet when such references are made. It is aimed at non-experts, but contains a technical annex for competent Excel users.

This document begins with on overview of how information flows between worksheets and then outlines the broad content of each of the sheets. Useful Excel tips are given in ANNEX A, which should help users to understand the more complex calculations. This document supports the detailed guidance notes that are already included within the Excel spreadsheet.

Contents

Overview of the Global Calculator modelling approach

The Global Calculator allows users to explore the options for reducing global emissions associated with land, food and energy systems to 2050, and to see the cost consequences of these choices to 2050 and the climate consequences to 2100. The Calculator is based in an Excel spreadsheet, which is the topic of this document. All the data, their sources and the calculations are within the spreadsheet, and therefore it is suited to technical experts or non-experts with enough time to interrogate a spreadsheet. For lay users or people with less time, there is a more user-friendly interface called the "webtool" (see www.globalcalculator.org).

The Calculator uses an "engineering" approach to modelling, which means that it models global energy supply and demand by modelling physical units such as land, cars and power plants. This contrasts with economic approaches to modelling, which tend to abstract the world's energy system into complex supply and demand equations to model outcomes using assumptions on economic behaviour and prices.

The Global Calculator is a scenario tool, which means that the user can explore "what if" questions, such as "what if there were no nuclear power globally?". The user makes choices on the deployment, adoption and use of different technologies and their characteristics. For example, the user can choose how far people drive, the proportion of cars that are electric and the efficiency of these cars. The user has 40 of these choices (called "levers") - these represent the most important determinants of global emissions. Often these levers have "sub levers" (they determine multiple parameters), which are visible in the spreadsheet only.

The Calculator models energy at a global level; it does not represent different countries, although regional considerations have been taken into account in the setting of the model's parameters. For example, the lever on passenger travel considers what is possible in different types of city and rural area. This high level, global modelling approach is taken to ensure simplicity and to allow the modelling to work within a single Excel workbook without using complex functions such as "VBA" (Visual Basic for Applications is the programming language in Excel).

The data and modelling in the spreadsheet is organised into different "sectors". A sector is a convenient way of organising the world for modelling purposes. For example, "cars" and "buses" are similar enough to be grouped together but sufficiently different to "boilers" and "air conditioners" to be grouped separately from these. So, the former are grouped within the "transport" sector and the latter are grouped in the "buildings" sector. Sectors are broadly independent of each other (see the exceptions outlined below).

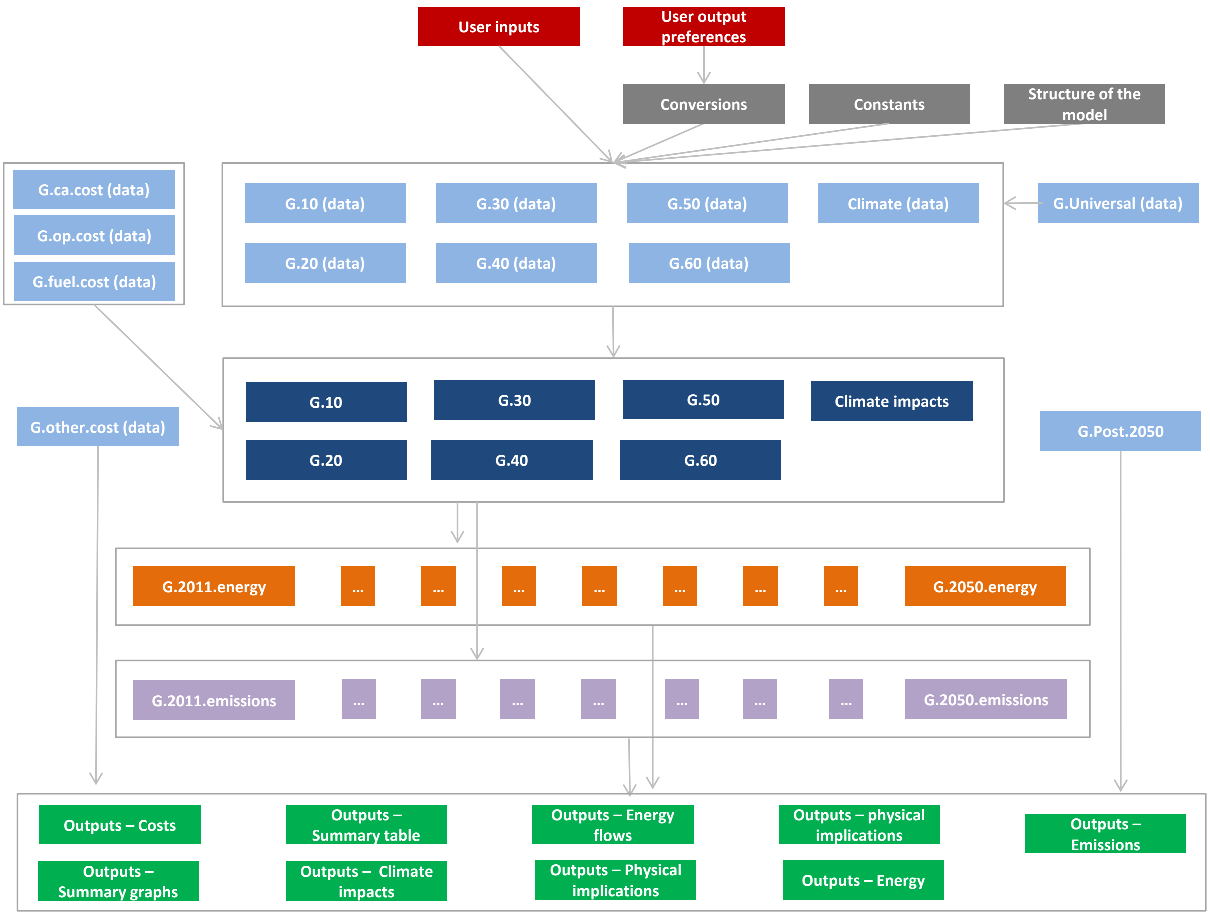
The Calculator has around 240 “technologies”. A technology is anything that uses or produces energy. Sometimes a “technology” in the Calculator is a grouping of similar real world technologies. For example, there is only one type of internal combustion engine urban motorbike in the model, whereas in the real world there are many different motorbikes. The reason is to ensure simplicity in the modelling whilst characterising the real world in a way that allows users to explore the main drivers of global emissions.

An important principle of the Calculator is that it captures all energy transformations; energy cannot be created or destroyed. Therefore each technology has a net energy balance of zero. An example is that a power station may “take in” gaseous hydrocarbons and give out “losses” and “electricity”, which sum to zero.

Structure of spreadsheet

Figure 1 below provides a high level summary of the structure of the Global Calculator Excel workbook. The boxes correspond to sheets in the workbook, the colours of the boxes correspond to the colours of the sheet "tabs", and the arrows show the flow of information.

Figure 1: the sheets in the Excel workbook



The Global Calculator Excel spreadsheet works as follows:

- The user chooses their pathway in the "**user inputs**" sheet. This contains the 40 or so "levers", within column E. These choices feed through into the "**G… (data)**" sheets (e.g. "**G.10 (data)**" and "**G.20 (data)**"), and are used to select the corresponding data for those choices
- The user also chooses their unit preferences in the "**user output preferences**" sheet. For example, they can view energy in EJ or kWh.
    - These unit choices are drawn into the "**conversions**" sheet, which converts the units in the other worksheets into the units chosen by the user.

- The light blue sheets "**… (data)**" have the input data needed to estimate the energy and physical implications (e.g. number of cars, number of wind turbines) of each sector. The sheets are as follows:
    - **G.10 (data):** transport input data
    - **G.20 (data)**: buildings input data
    - **G.30 (data)**: manufacturing input data
    - **G.40 (data):** electricity generation input data
    - **G.50 (data):** fuels input data
    - **G.60 (data):** land, food and input bioenergy data
    - **Climate (data):** this has the input data to calculate the climate impacts
- The dark blue sheets "**G…**" and "**Climate impacts**" contain the outputs from each sector as follows:
    - **G.10**: transport energy implications, emissions, physical implications (e.g. number of vehicles) and costs
    - **G.20:** buildings energy implications, emissions, physical implications (e.g. number of boilers) and costs
    - **G.30**: manufacturing energy implications, emissions and costs
    - **G.40**: electricity generation energy implications, emissions, physical implications (e.g. number of wind turbines) and costs
    - **G.50**: fuel supply and emissions
    - **G.60**: land, food and bioenergy energy, emissions and physical implications (e.g. land use)
    - **Climate impacts**: the climate implications
- The "**G… (data)**" sheets and "**G…**" sheets also draw data from:
    - "**G.Universal (data)**": this contains data on population and urbanisation, which are universal to sectors
    - "**Constants**": this contains physical constants such as the emissions factors for fuels
    - "**Structure of the model**": this contains the names of the sectors, technologies, energy vectors, and emissions, and their corresponding codes and descriptions
- The orange sheets "**G…..energy**" draw in the energy implications from each of the dark blue "**G…**" sheets. These orange sheets summarise the energy balances for each of the years modelled in the Calculator, split by sectors and technologies. The years in the model are 2011, 2015, 2020, 2025, 2030, 2035, 2040, 2045 and 2050.
- The light purple sheets "**G……emissions**" draw in the emission implications from each of the dark blue "**G…**" sheets. These light purple sheets summarise the emissions for each of the years modelled in the Calculator, split by sectors and

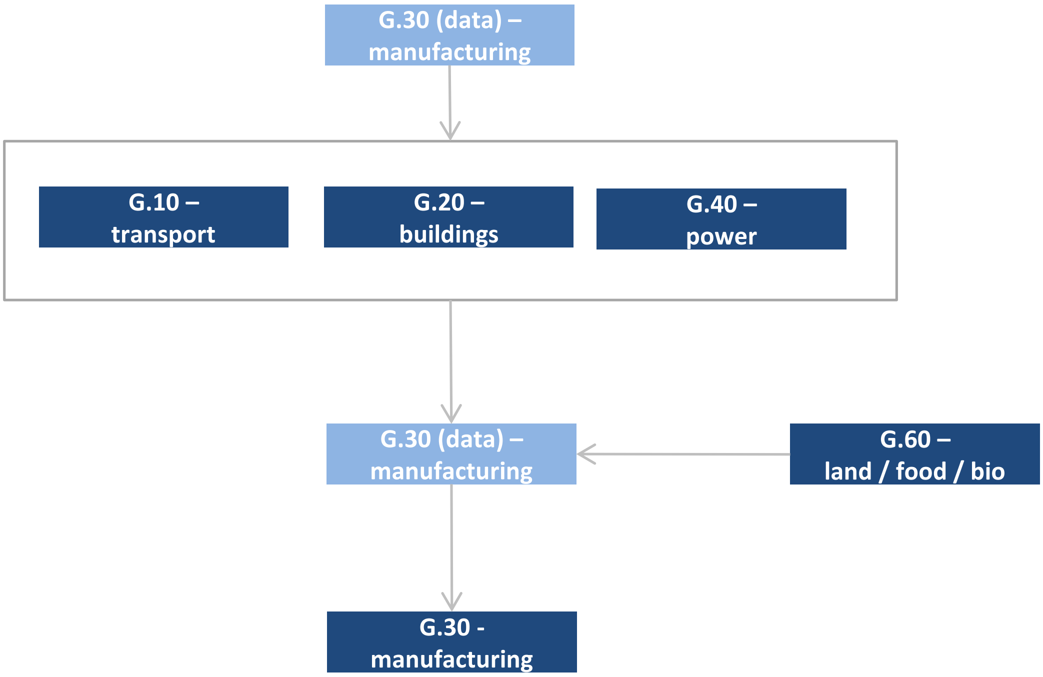
technologies. The years in the global Calculator are 2011, 2015, 2020, 2025, 2030, 2035, 2040, 2045 and 2050.

- All the outputs are then summarised in the green "**outputs – …**" sheets. These sheets contain higher level outputs than in the sheets mentioned above, and contain the data that is used in the Webtool. The output sheets are:
    - "**Outputs – Summary graphs**": this sheet contains a selection of graphs which summarise the user's pathway
    - "**Outputs – Summary table**": this contains some headlines associated with the chosen pathway, by sector. It is used in the "compare" tab in the webtool
    - "**Outputs – Climate impacts**": this summarise the climate impacts
    - "**Outputs – Emissions**": this summarises the greenhouse gas emissions, by sector and by gas, and includes historic data
    - "**Outputs – Energy**": this summarises the energy supply and demand by sector, and includes historic data
    - "**Outputs – Energy flows**": this provides data for the Sankey diagrams in the webtool (graphics that show all energy transformations)
    - "**Outputs – Physical implications**": this provides a summary of the physical implications such as number of vehicles and the output of the manufacturing sector
    - "**Outputs – Costs**": this summarises the costs analysis
    - "**Outputs – Lifestyle**": this sheet provides information on lifestyle, such as appliances per household.
- There are white sheets that contain information not used in calculations. These are:
    - "Front page": an introduction to the tool
    - "Contents": a sheet with "hyperlinks" that take the user directly to other sheets in the workbook
    - "User guide": a high-level overview of the spreadsheet
    - "Detailed lever guides": descriptions of each of the levers
    - "Lever graphs": data and graphs of the data behind the levers in the spreadsheet
    - "Webtool graphs": data for the output graphs in the webtool
    - "Data for webtool": this sheet shows where data in webtool can be found in the spreadsheet.

Interactions between sectors

The sectors in the Calculator are broadly independent. For example, activity in the buildings sector is independent of activity in the transport sector. However the main exception is with the manufacturing sector (sector 30). This sector "produces" the materials needed for the technologies in the other sectors (for example, the steel for cars). The interactions are outlined in Figure 2 below.

Figure 2: the interactions between sectors in the Excel workbook



The interactions between sectors work as follows:

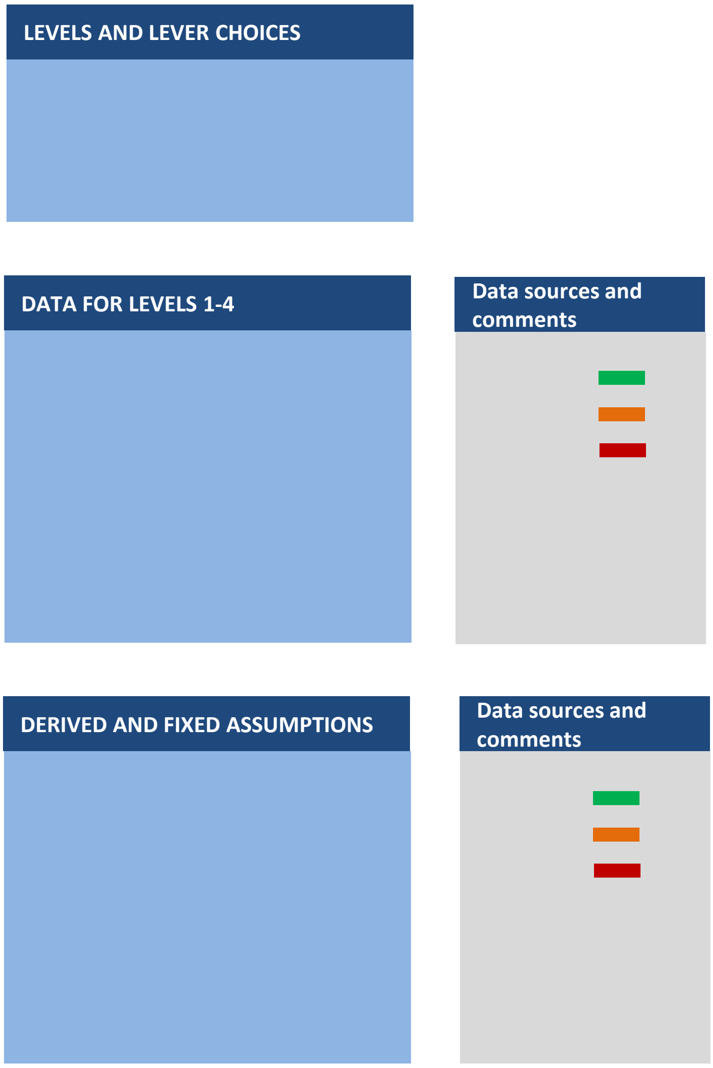
- "G.30 (data)" is the sheet that contains manufacturing data, including data on the lifespans of technologies. These lifespans are chosen by the user using the "product lifespan & demand" lever. The lifespan data are taken into "G.10", "G.20" and "G.40" to determine the number of new units of technology that must be produced each year for these sectors (transport, buildings and electricity generation). This information on number of new units is used to estimate costs.
- The total number of new units of technology given in "G.10", "G.20" and "G.40" are fed back to "G.30 (data)". For example, "G.10" provides information on the number of new cars and trains that must be produced. "G.20" provides information on the number of appliances and floor area of buildings to be produced. "G.40" provides information on the number of wind turbines to be produced. Units of technologies are aggregated into products in "G.30 (data)", and these products demand materials, such as steel. These materials are also "produced" in the "G.30 (data)" sheet.
- "G.60" (the land, food and bioenergy outputs sheet) provides input data into "G.30 (data)" on the change in fertiliser demand. Fertilisers are then produced in the manufacturing sector.

Note in particular that **there are no interactions between the climate outcome and other sectors**. In reality it is likely that a large change in global climate would result in significant impacts to other sectors including crop yields, renewable energy, heating and cooling requirements in homes. Additionally, the impacts of climate change would impose costs, either of damage or of adaptation. **These impacts and costs are not accounted for in any way**, either in the levers or in the spreadsheet model. Please see the caveats document for more information on what the Global Calculator does not do.

Structure of "G… (data)" sheets

Each of the input data sheets for the sectors ("G.10 (data)", "G.20 (data)", "G.30 (data)", "G.40 (data)", "G.50 (data)" and "G.60 (data)") follow the same broad structure. Data should be read from top to bottom, as this is the direction that the calculations flow. Where data for more than one year are presented, this should be read chronologically from left to right in a given row. Each column corresponds to a given year. The sheet structure is outlined below in Figure 3.

Figure 3: structure of each sector's data sheets



"LEVELS AND LEVER CHOICES": this contains the user's lever choices (from the "user inputs" sheet)

"DATA FOR LEVELS 1-4": this contains the data for each lever. To the right hand side of this are the sources, which are given indicative quality ratings of red, amber or green (see explanation below)

"DERIVED AND FIXED ASSUMPTIONS": contains the user's chosen lever trajectories. It uses the lever choices to "look up" the desired data from the levels 1-4. It also contains "fixed assumptions" (data which cannot be altered by the user) and combines data using basic operations (e.g. multiplications). The data in this section are used to estimate the implications in the "G…x" sheets

How are data sources rated?

In the "**G… (data)**" sheets, data sources are rated red, amber or green. Generally the classification works as follows:

- **Green data**: published, credible and recent (the last two or three years) source. The data is relevant to what is being modelled.
- **Amber data**: published but not recent (the last two or three years) source or the data is not quite relevant to what is being modelled.
- **Red data**: not published, not credible, subject to high uncertainty or not recent (the last two or three years)

Energy vectors

A final important modelling convention for the user to understand before examining the "**G…**" sheets relates to "energy vectors".

Energy vectors are a means of categorising energy into different types. Vectors enable quantities of energy to be organised and passed through the various calculation stages of the model in a simple, logical fashion.

The idea of vectors is perhaps best explained by way of an example. A commonly used vector within the model is vector E.02, which is used to represent quantities of electricity that are generated for delivery to the grid. All of the supply sectors that model the electricity generation by various technologies (e.g. solar, wind, nuclear) all assign the quantity of electricity generated to this specific vector (E.02). This allows the generation total across all the technologies to be calculated easily, simply by summing all the quantities assigned to this specific vector together.

The calculator makes use of three separate independent vector categorisations:

1. Uses
2. Primary sources
3. Secondary sources
4. Losses / oversupply

The **uses** vectors represent broad categories of demand, for example industry, road transport, heating and cooling. They are used to show energy demand / use from these aspects of the economy. The uses categorisation is 'MECE' (Mutually Exclusive (there is no overlap between them) and Collectively Exhaustive (all areas of demand fit into one of the available categories)), so that in total they sum to total demand.

The **primary sources** vectors are, as the name suggests, used to represent all sources of primary input energy. The categories included cover everything from fossil fuel reserves (e.g. coal, oil and gas) to renewables (e.g. wind, solar and wave). Again, these vectors are

MECE, so all primary energy sources can be represented by one of the available categories, but only one. Primary energy is the first appearance of a form of energy (e.g. oil reserves are primary energy, diesel for cars is not).

The **secondary sources** vectors are less easily defined. They represent all intermediate stages of energy between the primary sources and the final uses vectors. The closest description of the secondary sources vectors is “usable fuel types” (in the calculator, electricity is treated like a fuel). The secondary source vectors include some energy sources that might be converted prior to consumption. For example, crude oil is converted into oil, and both of these are secondary sources.

As mentioned above, relevant vectors sum to zero for each technology. For example, onshore wind generates electricity, as shown in vector E.02. This is balanced with an equal quantity of primary input energy, using the R.02 “Wind” primary sources vector. The input energy is denoted by the use of a negative value, which results in all the technologies having a balancing of 0. This treatment was inspired by the “double entry” book keeping system used in financial accounting, where all entries have an equal but opposite entry associated with them.

Within the calculator, the vector system can be most easily observed in the energy “year” sheets (e.g. “G.2015.energy”). Here the full categorisation of all four vector types is set out, forming the column headings for the energy balance tables. In combination with the full sector categorisation, which constitutes the row headings, the year sheets provide a full overview of all energy types across the complete energy system. The year sheets also demonstrate the principle that energy cannot be created or destroyed, but only converted to another type; all energy inputs are given negative values, while outputs are given positive values, resulting in a system total of zero.

An almost identical approach is used in the emissions “year” sheets (e.g. “G.2015.emissions”) to organise the emissions data. Here the categories used are the standard IPCC emissions sectors, along with additional categories to specifically record the emissions captured by CCS and greenhouse gas removal technologies.

Sector sheets: data and calculations

This section outlines the broad contents of the "G.xx (data)" sheets, which contain the input data and intermediate calculations by sector.

Transport (sector 10)

The transport data and calculations are contained in the sheets "G.10 (data)" and "G.10" respectively.

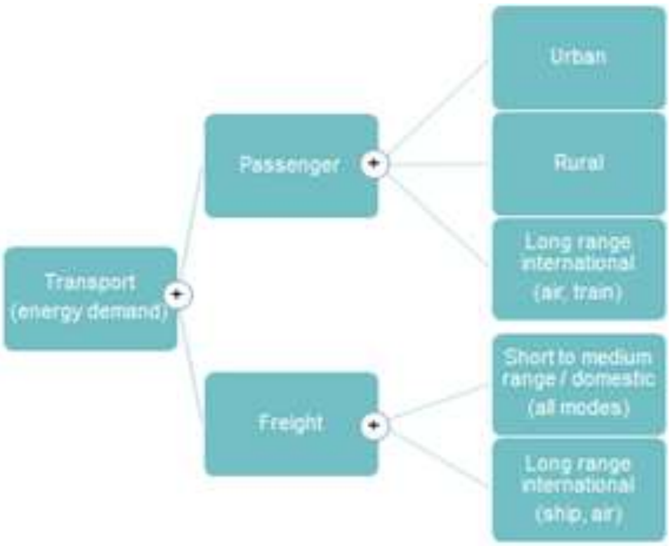
Sheet "G.10 (data)"

This worksheet includes all the data required for the calculation of transport energy and greenhouse gas emissions. For a first overview of the spreadsheet use the "group" function on the left hand side of the sheet to view the structure (just click the plus or minus symbols to expand the groups).

This worksheet is split in two main sections: the 1st section captures all raw data, all 1-4 trajectories for all levers; the 2nd section has all the derived data, for example the lever choices for each lever, as well as some of the required calculations.

Each of these 2 sections is structured as illustrated in Figure 4 below, between passenger and freight transport, and within these, between urban, rural and long range international travel.

Figure 4: high level structure of the transport sector



In the 1st section, by ungrouping the first level of the "passenger transport" section, you will see the various trajectories which are detailed in the spreadsheet: passenger travel demand, modal shares, occupancies, technology shares, efficiencies and ownership.

If you ungroup each of these categories, you will find the data for each of these parameters, split across urban, rural and international travel. Mostly these sections of the spreadsheet include one table with the base year data, and another with the rate of growth of each parameter for each 5-year period up to 2050.

The same logic applies to the 2nd section with all the derived data. As mentioned, it includes the lever choices for each lever, as well as some of the required calculations. Here is an example of a calculation in this section: table “G.10.assumptions.travel.by.mode” multiplies the total resulting travel demand (“G.10.assumptions.total.travel.demand”) by the resulting modal shares (“G.10.assumptions.mode.shares”).

Sheet “G.10”

This worksheet includes 4 types of table; those which compute energy, those which compute greenhouse gas emissions, those which compute physical implications (e.g. the stock of cars or the number of new cars produced to satisfy the stock) and those which compute costs. These tables use data from the following sheets: “G.10 (data)”; “G.cap.cost (data)”; G.op.cost (data)”, and; “G.30 (data)”.

The energy table includes both the demand side of transport (which end use it refers to - road, rail, aviation or water transport); and another on the supply side (which energy vector does it use - e.g. electricity). The sum of these two must always be equal to 0, as demand and supply must be matched.

The emissions table includes the 3 largest types of GHG emissions: CO_2, CH_4 and N_2O. It simply computes the amount of emissions based on the amount of energy use and the emissions factors.

The cost tables include capital and operating costs (fuel costs are only computed at a global level).

Buildings (sector 20)

The buildings data and calculations are contained in the sheets “G.20 (data)” and “G.20” respectively.

Sheet “G.20 (data)”

This worksheet includes all the data for calculating buildings energy demand and greenhouse gas emissions. Buildings are modelled in two broad parts, residential and non-residential. In the residential part, it contains four sub-sectors:

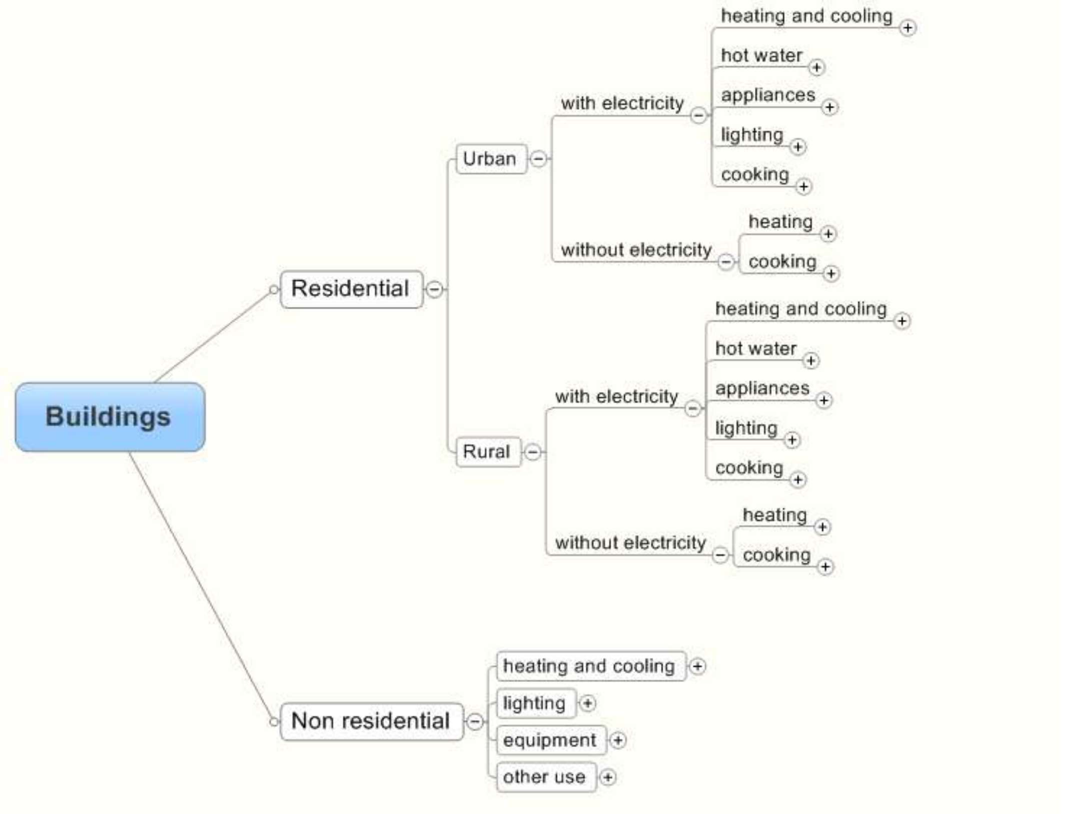
- urban residents with access to electricity
- urban residents without access to electricity
- rural residents with access to electricity
- rural residents without access to electricity

These four categories aim to capture the main differences between residents around the world, whilst keeping the tool simple enough for non-experts to use and interrogate.

In the spreadsheet, we model six kinds of energy consumption behaviour for the residential sector: heating, cooling, hot water, appliances, lighting and cooking. For non-residential: heating, cooling, lighting, equipment and other use (see

Figure 5).

Figure 5: structure of the buildings sector



All the energy consumption calculations are in “G.20 (data)” along with explanations of the formula.

Sheet “G.20”

This worksheet includes the calculation of buildings’ energy implications, greenhouse gas emissions and costs.

For the first part, it just refers to the results from “G.20 (data)”. For the second part, we use a very simple function to calculate the emissions. For the third part, we calculate both capital and operating costs. There is a very important hint for users - this worksheet references “G.30 (data)”, which supplies lifespan data for calculating the costs.

Manufacturing (sector 30)

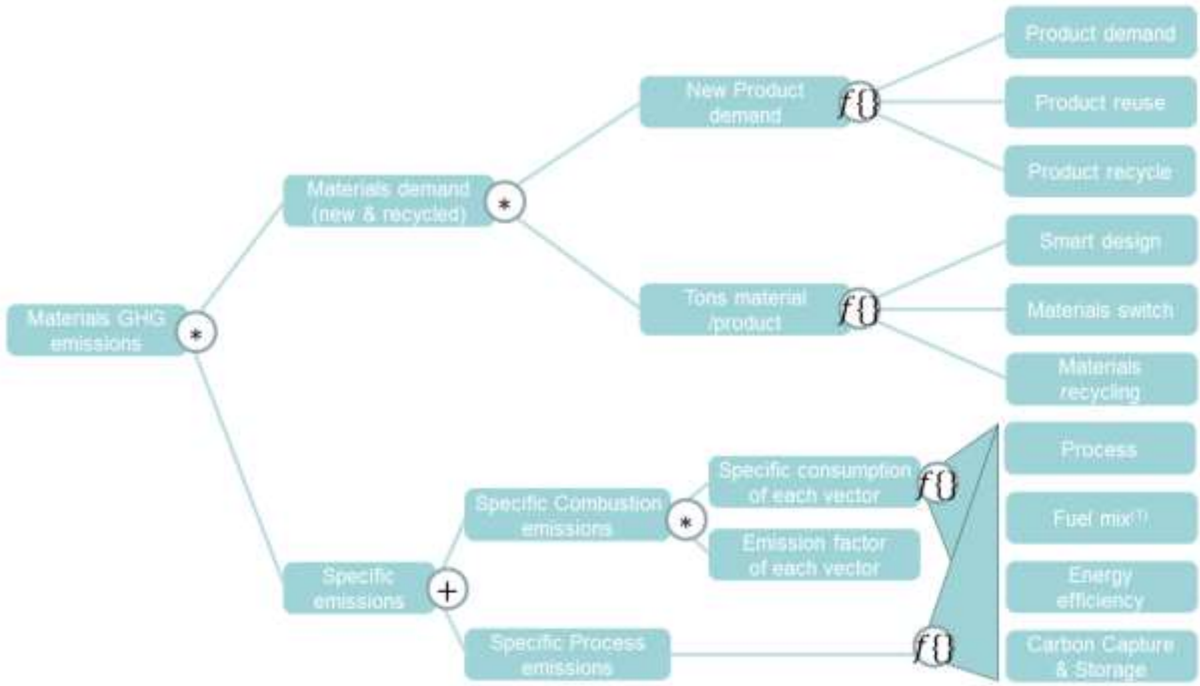
The manufacturing data and calculations are contained in the sheets "G.30 (data)" and "G.30" respectively.

Sheet "G.30 (data)"

This worksheet includes all the data required for the calculation of materials' energy, greenhouse gas (GHG) emissions and costs. For a first overview of the spreadsheet, use the "group" function.

The model performs the analysis starting from the demand for products, and then assesses materials demand for these products. From this, impacts are calculated in terms of emissions, energy consumption, and resource use. For the emissions, the high level rationale is illustrated on Figure 6. This is followed for each product and each material type.

Figure 6: manufacturing greenhouse gas emission tree



Note: (1) The fuel mix does not influence the specific process emissions

To model this, the worksheet is split in 2 main sections : a 1st section captures all raw data, all 1-4 trajectories for all levers; and a 2nd section has all the derived data, for example the lever choices for each lever, as well as some of the required calculations.

Each of these 2 sections is structured as illustrated in Figure 4 below, with 3 lever groups:

1) the product demand,
2) the materials demand per product, and
3) the carbon intensity of material production.

There are 10 lever families structured along each of these lever groups.

Figure 7: high level structure of materials modelling

Lever groups	Lever families	Lever descriptions
Product demand [1]	• Reduce (Product demand) • Reuse • Recycle	• End consumer demand of products • Solutions for sharing the product amongst different users • Product recycling
Material demand per product	• Smart design • Materials switch • Materials recycling	• Amount & type of materials required to supply the products (includes new product types and substitution materials) • Materials recycling potential
Carbon intensity of material production	• Process change • Energy efficiency • Fuel switch • Carbon capture and storage	• Production CO_2 intensity of various improvements levers in each industry (~60improvements types)

NOTE: (1) these levers don't apply in the materials analysis when the product demand is defined by the other sectors

Table descriptions in the data section

The following section describes the sequence of tables in the model, each is accessible by ungrouping (clicking the "+" sign on the left).

Product demand	The first table describes the change in the **new product demand** versus 2011. It covers the demand (also called **reduce**), the **reuse** and the **recycling** of materials potentials.
Materials demand per product	The second table describes the change in the link between product demand and **material demand**. **Smarter designs** enable us to produce products with the same characteristics yet using less material. **Materials switch** describes the reduction in materials requirement for a same product (because of smarter design). **Recycling** describes the portion of materials which can be obtained through a recycling process (thereby not requiring new resources)
Carbon intensity of material production	The third part (5 tables) describes the **carbon intensity of the materials production**. • The **Process improvement** table describes the energy consumption reduction possible by switching to more optimised processes (e.g. from Classic Oxygen Steel to HIsarna Oxygen steel). Each time a process

	improvement is performed, it adds a different material demand category. • The **Alternative fuels** table describes the switches between energy vectors (e.g. coal substitution by biomass). • The **Combined Heat and Power** table describes the reduction potential of network electricity (the additional gas used to make the CHPs function is assessed in the derived assumptions). • The **Energy efficiency** table describes the energy consumption reduction which can be obtained through energy efficiency measures (excluding process improvements, alternative fuels and CHPs). • The **Carbon Capture and Storage (CCS)** table describes the percentage of emissions captured by the CCS technology.

More details on how to interpret the data, the sources and the assumptions are available in the Excel workbook. Please note only modelling information is detailed here, not the underlying choices regarding the technologies chosen or the various ambitions. This information is available in the technical appendixes at www.globalcalculator.org.

Please note these are applied in a sequential order (e.g. the energy efficiency potential is modelled after processes have been improved, fuels have been switched and combined heat and power has been installed).

Table descriptions in the fixed and derived assumptions section

A first set of **fixed assumptions** describes the 2011 situation in terms of product demand, materials demand, energy consumption and GHG emissions.

- The **technology to product** table converts the model "technologies" into product equivalents (for example it converts the "motorbike" technology into the "cars and light trucks" product using an exchange rate that says x motorbikes are equivalent to y cars, in terms of the materials they contain).
- The **amount of product** table lists for the base year (2011) the product demand and the material demand per product.
- The **amount of IEA materials** table enables a sanity check with the materials demand figures provided by the IEA. This table is informative only.
- The **specific consumption** table describes the specific consumption assuming no CHPs are in place (the CHP impact is modelled afterwards).
- The **specific process emissions** table describes the specific process emissions.

Then a set of **derived assumptions** describes how this changes to 2050. Here the same logic is followed as in the data section. However we only list now the values for the chosen trajectory.

<table>
<tr><td>Product demand</td><td>The first table lists the change in new product demand, it is composed of:
• Product demand (also called reduce)
• Product reuse
• Product recycling</td></tr>
<tr><td>Materials demand per product</td><td>The second table describes the change in the link between product demand and material demand. It is composed of
• Smarter design
• Materials switch
• Recycling</td></tr>
<tr><td colspan="2">Following these 2 sections, the key drivers are reassessed (materials demand, energy demand, GHG emissions).</td></tr>
<tr><td rowspan="10">Carbon intensity of material production</td><td>The third part (5 tables) describes the carbon intensity of materials production. Following each table, the key drivers are reassessed each time (materials demand, energy demand, GHG emissions).
The same structure is followed:
• The Process improvement table
(please note only steel is currently modelled)</td></tr>
<tr><td>Following this section, the key drivers are reassessed (materials, energy, GHG emissions)</td></tr>
<tr><td>• The Alternative fuels table</td></tr>
<tr><td>Following this section, the key drivers are reassessed (materials, energy, GHG emissions)</td></tr>
<tr><td>• The Combined Heat and Power table</td></tr>
<tr><td>Following this section, the key drivers are reassessed (materials, energy, GHG emissions)</td></tr>
<tr><td>• The Energy efficiency table</td></tr>
<tr><td>Following this section, the key drivers are reassessed (materials, energy, GHG emissions)</td></tr>
<tr><td>• The Carbon Capture and Storage (CCS) table</td></tr>
<tr><td>Following this section, the key drivers are reassessed (materials, energy, GHG emissions)</td></tr>
</table>

Finally the manufacturing sector includes an analysis of costs. Unlike the other sectors, all capital and operating costs for manufacturing are in the “G.30 (data)” sheet.

Sheet "G.30"

This worksheet includes 2 large tables which compute **energy** and **emissions** for the materials sector based on the data defined in the "G30 (data)" worksheet.

In the energy table, you will find the energy vectors for each of the 15 materials categories.

In the GHG emissions tables, you will find the 3 largest types of GHG emissions: CO_2, CH_4 and N_2O. For each gas, it describes combustion, process and CCS emissions for each of the 15 materials categories.

Emissions are estimated using the energy consumption data and emission factors as follows:

$$Emissions = \left(\sum_{each\ vector} (Energy\ consumption) * (Energy\ Emissions\ factors)\right) + (Process\ emissions)$$

Emissions captured by carbon capture and storage are shown as negative emissions.

Costs, which are calculated in "G.30 (data)", are then summarised in this sheet.

Electricity generation (sector 40)

The electricity generation and calculations are contained in the sheets "G.40 (data)" and "G.40" respectively.

Sheet "G.40 (data)"

"G.40 (data)" includes the installed capacity potential of various renewable, carbon capture and storage and energy storage technologies. Each of these technologies has a level 1 to 4.

Electricity generation is a function of technology deployed, efficiency of the technology and its utilisation. The user determines these parameters using the levers, except when some assumptions are fixed. The levels 1-4 data in the "G.40 (data)" sheet are:

- Installed capacity (renewables, CCS, storage)
- Proportional split of hydrocarbon stations (solid / liquid / gas)
- Split of solid fuel power plants (for example, "ultrasupercritical" or other)
- Split of liquid fuel power plants (for example, efficient vs. inefficient)
- Split of gas fuel power plants (for example, combined cycle gas turbine vs. open cycle gas turbine)
- Change in efficiency of technology
- The size of the peak in demand (used to estimate balancing capacity)
- The use of electric vehicles for electricity storage

An important issue is that electricity from unabated fossil fuel technologies (solid, liquid and gas) is driven by the model (it is "endogenous"). The model sums electricity demand from the user's choices on demand and then sums the electricity supply from the user's choices on renewables and CCS. The Calculator then meets any shortfall in electricity supply by "building" unabated thermal power plants, which supply this electricity shortfall. The user chooses whether these power plants are solid, liquid or gaseous fuelled. The fuel could be bioenergy if supplied by the user (e.g. biomass), or fossil fuel energy (e.g. coal) if there is not enough bioenergy from the user's choices. There is a fixed assumption on the proportional split applied to the CCS technology i.e the % that is gas vs solid fuelled).

This sheet also draws in data on electricity demand for each year, and applies the "peak factor" to this data to estimate the electricity demand peak for each year. Using data on availability factors for generation technologies, it estimates the necessary backup capacity to meet this demand peak. This backup capacity is estimated in "G.40".

Sheet "G.40"

This sheet contains:

1. Energy calculations / results: It computes electricity supply from each of the electricity generation technologies. Electricity output from renewables and CCS is

driven by the user, and as explained above, any shortfall is calculated by the model and supplied from unabated thermal power. The efficiency data then are used to compute the primary energy used (e.g. the amount of solid hydrocarbons used in the power plants). If the user's choices in the buildings sector result in the use of heat networks, waste heat is provided from the power plants to this heat network.

2. Emission calculations / results: This estimates emissions by applying emissions factors to the primary energy combusted, where relevant. Emissions include CH_4, CO_2 and N_2O.
3. Physical implications (installed capacity and inflows of new capacity to meet the required installed capacity).
4. Costs.

The electricity grid itself is modelled in sector 50 (fuels).

Fuel production (sector 50)

The “fuels” data and calculations (including electricity distribution) are contained in the sheets “G.50 (data)” and “G.50” respectively.

Sheet “G.50 (data)”

The “G.50 (data)” sheet of Global Calculator spreadsheet contains all the data that is used to calculate the extraction of fossil fuels, accounting for the energy used in the production chain (extraction, processing and distribution of these fuels). It also contains data used to estimate the energy penalty associated with producing biogas from waste and the energy implications of producing methane for the transport sector.

Specifically it contains data on refineries, coal washeries and natural gas liquefaction. It defines levers for hydrogen production (steam methane reformation, coal gasification and electrolysis) and biofuels (solid to solid, liquid or gas, liquid to gas and gas processing).

The levels 1-4 in G.50 (data) sheet are:

- Hydrogen production efficiency
- Hydrogen production method
- Fossil fuel production efficiency (extraction, refining) and biofuel conversion efficiency
- Split in hydrogen production method

The sheet also contains fixed assumptions on:

- The form of energy from waste (solid vs. liquid vs. gas)
- Fossil fuel and electricity distribution losses

Sheet “G.50”

This sheet contains:

1. Energy Calculations / results: it computes hydrocarbon demand coming from global buildings, transport, manufacturing and power sectors for any year (up to 2050). It then assesses the supply of solid, liquid, and gaseous hydrocarbons from bioenergy for these years. Any shortfall between supply and demand for hydrocarbons is met by fossil fuels from this sector. It also computes electricity and fossil fuel distribution losses.
2. Emission Calculations / results: It calculates the associated emissions (CH_4, CO_2 and N_2O).

Figure 8: fossil fuel flow in the model

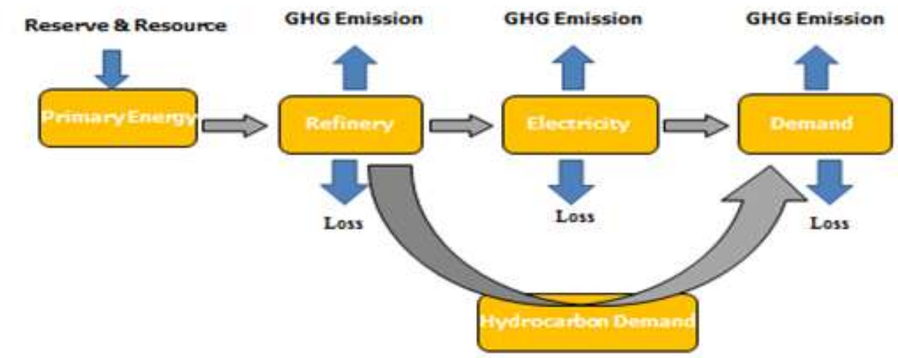
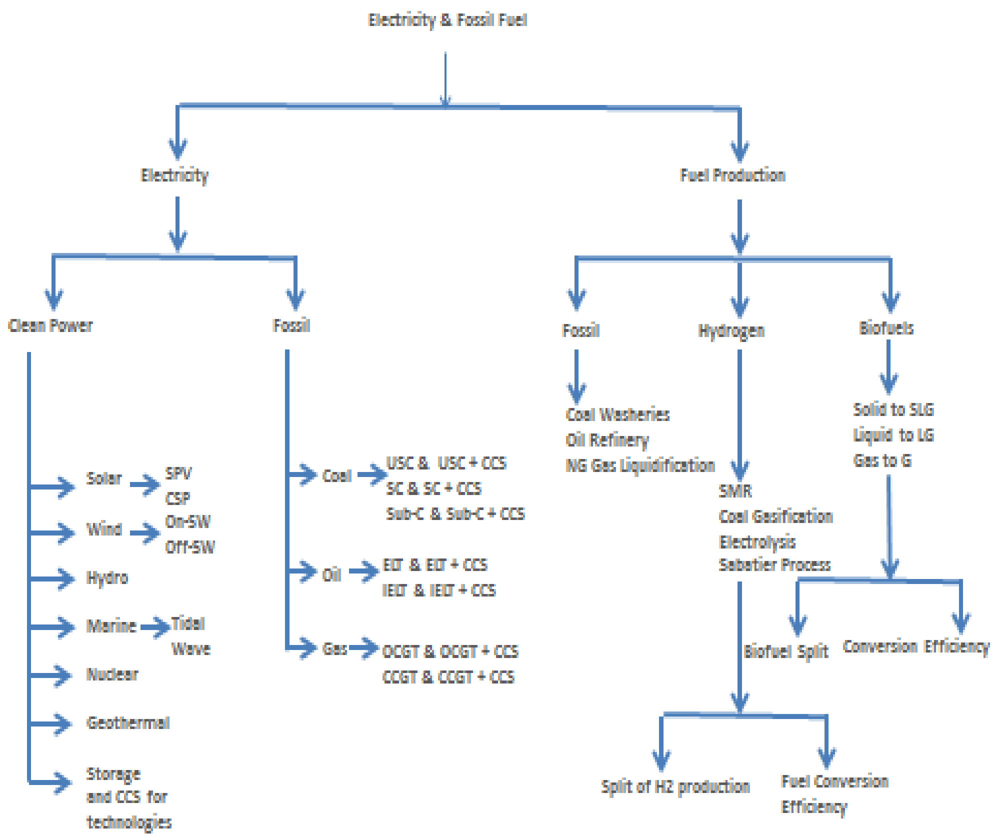


Figure 9: summary of electricity and fossil fuels in the model



List of acronyms

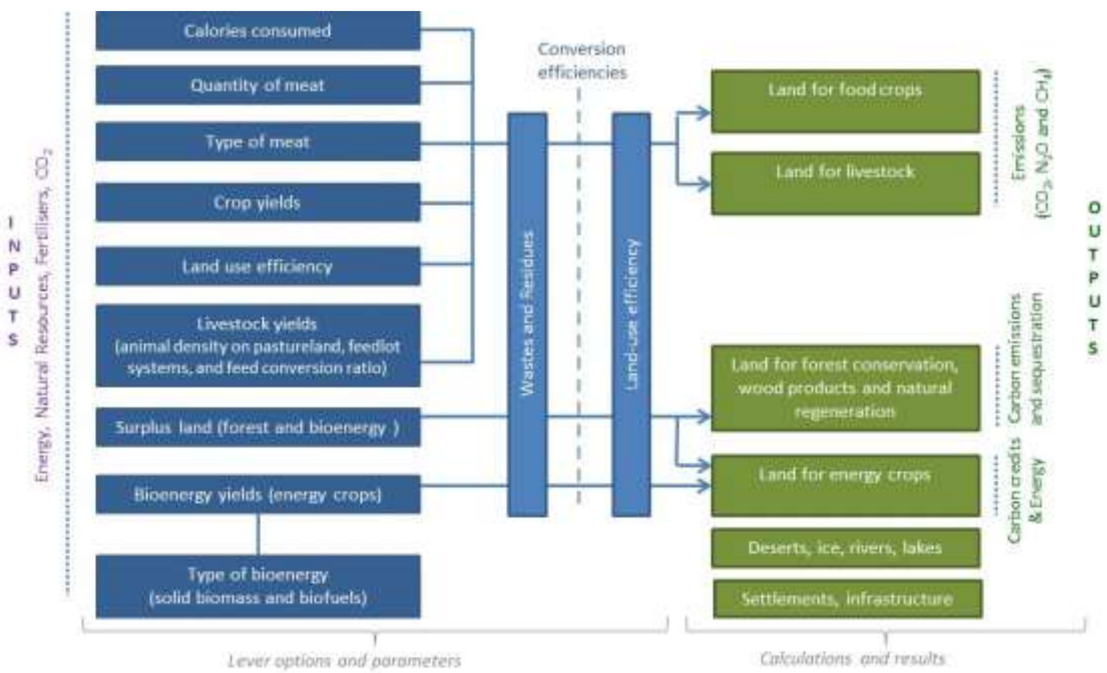
1. SPV= Solar Photovoltaic
2. CSP= Concentrated Solar Power
3. On-SW= Onshore Wind

4. Off-SW= Offshore Wind
5. CCS= Carbon Capture Storage
6. USC= Ultra Supercritical
7. SC= Supercritical
8. Sub-C= Subcritical
9. ELT= Efficient Liquid Technology
10. IELT= Inefficient Liquid Technology
11. OCGT= Open cycle gas turbine
12. CCGT= Closed cycle gas turbine
13. NG= Natural Gas
14. SMR= Steam Methane reforming
15. SLG= Solid, Liquid & Gas
16. LG= Liquid & Gas
17. G= Gas
18. H2= Hydrogen

Land, bioenergy, food and greenhouse gas removal (sector 60)

This section provides guidelines for the use of the Land / bio / food / GGR worksheets in the Global Calculator, namely "G.60 (data)" and "G.60". The diagram below (Figure 10) summarises the main levers, land allocation and worksheets for the Land / bio / food / GGR sector.

Figure 10: Driver tree for the land/bio/food sector, global calculator project



Sheet "G.60 (data)"

This worksheet presents all the levers and levels data and estimations, as well as some complementary parameters for the calculations. Right in the beginning of this worksheet there is a section called **Levers and Levels**, in which a table presents a summary of all levers of the Land / bio / food / GGR sector, as well as each level option that was previously chosen by the user in the worksheet 'User Input'. The next section, called **Data for Levels 1-4**, shows a list of all levers with their respective four level options and associated time series. These were estimated with the 2050 endpoint and are based on multiple references cited in two tables on the right side of this worksheet. These side tables include a column for source, links, risks, comments/assumptions/caveats and comment author. The main issues for the section 'Data for Levels 1-4' are described below by lever type.

Calories consumed

This lever models the land demand for food production, along with the levers for the quantity and type of meat, and some efficiency parameters. The values may not be shown in terms of kilocalories if a different energy unit was selected in the 'User Input' worksheet. If the user wishes to change the units, it is necessary to choose the unit of preference in the 'User Input' worksheet and then click on 'calculate' in order to update all the values in the spreadsheet.

Quantity of meat

This lever is aimed at obtaining input values for the future demand of meat in order to estimate the necessary land area (direct and indirect) for livestock production. The total food consumption is a share of meat, plant-based food products, eggs, milk and fish. Thus, after selecting the quantity of meat, the consumption of plant-based products is automatically adjusted to match the selected level of calories consumed. The per capita intake of other food products, such as eggs, milk, animal fat and fish, follow a fixed trend line based on a literature review. Meat has also a significant impact on the protein balance, but for the purpose of the calculator, all estimates were made in energy terms only, and exclude losses.

Type of meat

There are significant differences in meat types (e.g., beef, poultry, pork, lamb, goat meat, fish) in terms of production systems, meat conversion efficiencies, monogastrics and ruminants, and the necessary land for producing the respective meat type. Thus, the future global average consumption of each meat type also varies by 2050, depending on the level effort chosen by the user, who can select a higher or lower share of meat from ruminant animals (bovines, sheep and goats) vs. monogastric animals (pigs and chicken). Ruminants are usually associated with higher GHG emissions than monogastrics, particularly because of the methane produced from the enteric fermentation.

Crop yields

This lever affects the need for land resources for producing food, i.e., the greater the productivity, the smaller the area necessary for producing a certain amount of food, such as grains, fruits and vegetables. It is challenging to predict crop yield potentials accurately, particularly because of the complexity of estimating biotechnology potentials, future use of water and fertilisers, and positive and negative impacts of climate change on agriculture. The trajectories are not based on composed rates (exponential), but on different linear trends from the base year. There is no looping effect of climate change on crop yields, due to methodological reasons of the calculator, but the user can selected a pessimistic growth rate of productivity (e.g., level 1) in order to simulate an adverse climate impact. It is also possible to change the lever 'land use efficiency' to simulate the impact of climate change on the future availability of productive land resources (e.g., a higher level of desertification).

Livestock (grain/residues fed)

The production of meat necessary to satisfy future demands represents a major challenge for land use change in the coming decades. The land for achieving such levels of production is calculated based on the type of diet, which gives the amount of meat needed for the projected demand and the livestock yield growth. Thus, through a substantial yield increase, less area would be used for livestock production and more area would be available for other purposes, e.g., the production of grains, natural regeneration, planted forests, or energy crops. As noted, the demand of milk, egg, fish, and other animal products are modelled separately, as a fixed assumption based on global trends from a literature review.

This lever is related to the use of confined and semi-confined systems, instead of grass-fed schemes. A higher use of feedlot, for example, would require more feed from the crop areas and less pasturelands. The conversion efficiency of meat also varies according to the type of animal under feedlot. This conversion is also known as the Feed Conversion Ratio (FCR), which is the percentage of feed that is converted into edible meat. FCR varies according to the type of animal, genetics and feed quality.

Livestock (pasture fed)

This lever reflects the possibility of increasing the number of grass-fed animals (ruminants, i.e., cattle, sheep and goats) per unit of area (e.g., hectares), i.e., the concentration of animals on pastureland. Such increase is associated with the carrying capacity of pasture, which depends on pasture yields and the availability of pasture lands. This lever is also impacted by changes in the Feed Conversion Ratio (FCR) per type of animal in pasture systems.

Bioenergy yields

In the agricultural stage, the yield growth potential of energy crops (e.g., sugarcane, maize, wheat, oil palm, oilseed rape, eucalyptus, miscanthus, poplar) was assumed to be slightly higher than those of ordinary crops aimed at supplying the food market. This is because this lever also assumes a change in the energy crop mix, for example, a higher use of energy-efficient crops (in net primary production terms) instead of low-efficiency crops for energy production, which would indirectly affect the total average bioenergy yield growth by 2050. Thus, energy-crop yield growth may also be affected by the potential progress of some key technologies, e.g., lignocellulosic ethanol, Fischer-Tropsch diesel. For example, a certain crop could be genetically improved to produce more cellulose and hemicellulose.

Industrial efficiencies for converting waste into solid, liquid or gaseous fuels were addressed in other sectors of the Global Calculator. Modern bioenergy is considered as a renewable energy source in the calculator, because its expansion is not in competition with food production. It is also worth noting that algae is not represented in this lever, given that it is aimed at estimating the land use change for bioenergy production, and algae may not significantly affect land use change. In addition, algae is still a technology in process, with many uncertainties about its large-scale commercial implementation by 2050.

Bioenergy types (solid or liquid)

The potential expansion of dedicated energy crops on surplus land can be allocated towards a higher proportion of producing solid biomass (e.g., pellets, wood chips, charcoal) or liquid fuels (e.g., ethanol, biodiesel, biokerosene), which have different efficiencies for energy conversion. This lever also indirectly affects how bioenergy is consumed (e.g., for heating, power generation, transport) in different sectors of the calculator. This lever excludes traditional biomass, which is mostly solid and modelled in the buildings sector.

Surplus land (forest & bioenergy)

Land use change is determined by a hierarchy of land use types, the first use being for food production. Then, if there is remaining land after meeting the food demand (crop and livestock), such area could be allocated for forests (planted or naturally regenerated) and natural grasslands, and/or for an expansion of energy crops, with different levels of ambition. It is assumed that the current forest (in the absence of deforestation for food production) and bioenergy (dedicated energy crops) lands would remain used, but augmented by some proportion of the potential remaining areas. Therefore, this lever is about the use of freed up land, after meeting the global food supply, which is determined by the user’s choices. Land cannot be taken from deserts, ice sheet and ice caps as these are considered as unproductive, at least on a relevant scale for the purposes of the global calculator. Land for settlements and infrastructure also increases by 2050, but under a fixed trend based on literature review.

Land-use efficiency

This lever presents a novel concept to address different land use interactions in the Global Calculator, which are not covered as changes to yields. Ideally, there would be a large number of new levers to better reflect the complexity behind land use changes, but even with them it would be difficult to make very accurate global projections, because of the lack of comprehensive and robust global datasets. Thus, this lever aims to address issues like the land-use change effects from agro-livestock-forestry schemes (and any combinations thereof), and multi-cropping systems, e.g., dual-cropping (e.g., a summer crop followed by a winter crop in a same year), triple-cropping (e.g., starting with a summer crop, then a second summer crop of short cycle, followed by a winter crop).

In order to simplify this analysis, this lever has four levels of effort which represent an abatement potential on land use, i.e., less or more land would be necessary than initially estimated from the previous levers for the production of food, meat and bioenergy. This lever is necessary because the model is based on global actual area, instead of harvested area, i.e., it represents an additional effect on agricultural yield growth, given that land-use can be maximised (e.g., having more crops per year in a same area). However, climate change effects and the over use of land can also damage its productivity, for example, due to erosion, soil degradation and desertification process. Therefore, land-use efficiency also includes negative impacts in the level options, i.e., a case where it would be necessary to use more land than initially estimated to attain the same level of food supply.

Wastes and residues

This lever involves two main groups of tables in the worksheet "G.60 (data)". The first shows the amount on-farm (e.g., crops left overs, such as straws and leaves), and post-farm (from food production to the consumer and disposal) wastes and residues. The second presents the proportion that is collected from on-farm and post-farms wastes and residues.

Each of them has four levels of effort, which were then combined into a single lever. There are also two further supporting parameters: 'waste from animals', i.e., manure and tallow, which gives the energy production from animal waste; and 'waste per person', which presents the energy potential from waste treatment, i.e., sewage or landfills. Both parameters are presented in the section 'derived and fixed assumptions', worksheet "G.60 (data)". Residues can be collected for both bioenergy and animal feed.

Speculative Greenhouse Gas Removal (GGR) technologies

GGR comprises a number of technologies that aim to remove greenhouse gases from the atmosphere and thereby mitigate the anthropogenic global warming effect. GGR is presented as a set of speculative measures in the online version of the calculator in a separate tab. GGR is also known as Carbon Dioxide Removals (CDR) or Negative Emissions Technologies (NETs). It represents only a part of geoengineering technologies, which also includes Solar Radiation Management (SRM). However, SRM is outside of the scope of this project, given that it is not aimed at removing carbon, but rather changing the albedo effects and consequently also the balance of radiative forcing, which affects global warming. Geoengineering is a controversial and speculative issue, and the international debate on this issue is in its infancy, currently often polarised between those categorically against it and those in favour of its development.

There are many risks and uncertainties associated with GGR, which vary depending on the technology type, its scale, public acceptance, energy penalty and environmental impacts. Despite concerted research efforts and a recent increase in scientific publications on GGR technologies and governance, there is no comprehensive and robust database that could be referenced in the calculator. Most of the GGR technologies were never tested on a large scale and therefore their potential results are questionable and speculative. However, GGR may become an important extreme option for climate change mitigation, especially if the current mitigation efforts are not sufficient. Thus, GGR technologies and their estimated GHG emission reduction potentials were included in the calculator, but due to the high level of uncertainties associated with GGR, these technologies should not be viewed as equivalent to the other GHG mitigation measures included in the calculator.

GGR technologies considered in the global calculator include Biochar, Direct Air Capture (DAC), Enhanced Weathering – Terrestrial (EW-T), Enhanced Weathering – Oceanic (EW-O), and Ocean Fertilisation (OF). GGR is presented in a separate tab of the webtool as something speculative. The total level of effort was estimated based on literature review. Forestry, BECCS (bioenergy with CCS) or Land Use / Soil Carbon Management are indirectly calculated from other sectors in the calculator.

An energy penalty for all GGR technologies was also added in the calculations, as described in the table 'energy inputs for geosequestration' in the section 'derived and fixed assumptions', worksheet "G.60 (data)". The energy used in the process may have different GHG impacts on the net carbon removal, because these impacts depend on the global energy mix generated in the calculator by 2050 according to the user's choices. For example, the electricity used for operating a certain GGR plant will have carbon emissions in line with the energy mix chosen in the calculator, either fossil or renewable intensive.

Sheet "G.60"

This worksheet presents the calculation and results of Land/Bio/Food and GGR sectors, by using the worksheet "G.60 (data)". It features the following sections:

a) Energy calculations / results

This section gives the energy production and demand for land for food crops, livestock, bioenergy and others. It works based on data from energy consumption and production from food, livestock and bioenergy, energy conversion efficiencies, and the land use distributions. It also includes calculations for wastes and GGR. By clicking on each worksheet cell it is possible to follow the variables and equations used for each calculation.

b) Emissions calculations / results

These calculations are based on the emission factors for land by type of greenhouse gas presented in the worksheet "G.60(data)", as well as the food, meat and bioenergy production, and the land distributions for meeting them. Thus, it is possible to estimate the emissions by type of land. The gases considered in the calculations are CO_2, N_2O and CH_4, which represent the main GHG gases related to "Agriculture, Forest and Other Land Use" (AFOLU).

As for forest conservation areas, deforestation results in CO_2 emissions, whilst afforestation/reforestation means CO_2 sequestration from the atmosphere through photosynthesis, particularly during the forest establishment stage. Mature forests also act as carbon sinks. Temporal variations were also considered in the forest recovery.

Regarding bioenergy emissions, national GHG inventories usually accounts for its emissions in an indirect manner. In theory, the growing biomass captures equivalent levels of CO_2, which is released back to the atmosphere upon combustion. However, some fossil fuel inputs are usually required in the bioenergy production, distribution and consumption chain. There may be emissions from direct and indirect land use change (dLUC and iLUC) as well. Therefore, in the calculator, emissions related to bioenergy are indirectly estimated, accounting for its emissions in agriculture (including Nitrogen fertilisers), land use change and other sectors of the calculator. This is important to avoid double counting of carbon emissions, because despite bioenergy is not carbon neutral in most cases, its lifecycle emissions are captured elsewhere in a comprehensive global model. Thus, the energy penalty and emissions balance from bioenergy are indirectly measured by different sectors in the Global Calculator. Hence, in this worksheet, there is a CO_2 credit from bioenergy, which are summarised into a table called 'Credit CO_2'.

c) Land use and technology calculations / results

Land use calculations are based on a hierarchy of land use types, because land availability is a finite resource, i.e., land demand for all purposes cannot be higher than the total amount land available on the planet. Thus, after excluding 'other areas' (i.e. deserts, ice cover, rivers, lakes) and areas for 'settlements and infrastructure', first the land necessary to meet food supply is estimated, according to calories consumed, type of diet (quantity and type of meat) and land-efficiency factors. This assumes that food security is prioritised above forest conservation and bioenergy production. Then, land is allocated for other purposes (e.g., natural regeneration, additional planted forest and/or energy crops). If the cropland required to meet the food production is not sufficient, even with agricultural productivity gains, there will be deforestation. Otherwise, the model will generate a surplus land which will be allocated according to the user's choices presented in the worksheet "G.60 (data)".

Climate science

Sheet "Outputs – Climate impacts"

The outputs sheet summarises the main results of the climate science section of the Global Calculator. All temperature rises are quoted relative to a baseline of 1870, or an 1861-1880 average. These are as follows (details of calculations are in the next section):

Global warming – simple model calculations

A range (high and low possible values) of global mean temperature change, based on the IPCC summary of climate model projections, is shown for 2050 and 2100 (rows 10-12 and 15-17). The units are degrees Celsius. If the trajectory generated by the Calculator goes beyond the IPCC assessment, over 8,000 $GtCO_2$, then the output is a warning rather than a numerical value. The first range (rows 10-12) is based on the user-generated CO_2 only, and takes representative values for other gases from the IPCC's Representative Concentration Pathways (RCPs). The second range (rows 15-17) is based on user-generated CO_2, CH_4, N_2O and SO_2 only. Note that the second method shows lower temperature change because it does not include other forcings (halocarbons, VOCs, black carbon, etc.) that are in the RCPs, and because the impact of climate-carbon feedbacks are not included in the Global Temperature Potential values used (more details below). The second method is the one which generates the output that is shown in the web tool visualisation in the January 2015 release of the Global Calculator.

Global warming – evolution over time

These two sections (rows 27-29 and 38-40) show how the global mean temperature changes over time for each of the methods described above. This helps to see whether the figure at 2100 has "levelled off" or whether it is continuing to rise. In both cases a high/low range is shown, with historic actuals for comparison. The second method is the one which generates the output that is shown in the web tool visualisation in the January 2015 release of the Global Calculator.

Basic Physics – a back of the envelope calculation

The cumulative extra energy (row 49) trapped by the increased carbon dioxide levels since pre-industrial (1870) is shown for 2050 and 2100. This could be used for comparison with other energy flows.

The order of magnitude mass of ice that could be melted (row 54), generated by the back-of-the-envelope basic physics calculation, is shown as a fraction of the ice mass of the Greenland ice sheet. This is illustrative only. This is then used to generate an approximate value for the sea level rise due to the melted ice entering the oceans (row 59), and also due to thermal expansion (row 64). These are also illustrative order-of-magnitude figures, not projections or predictions.

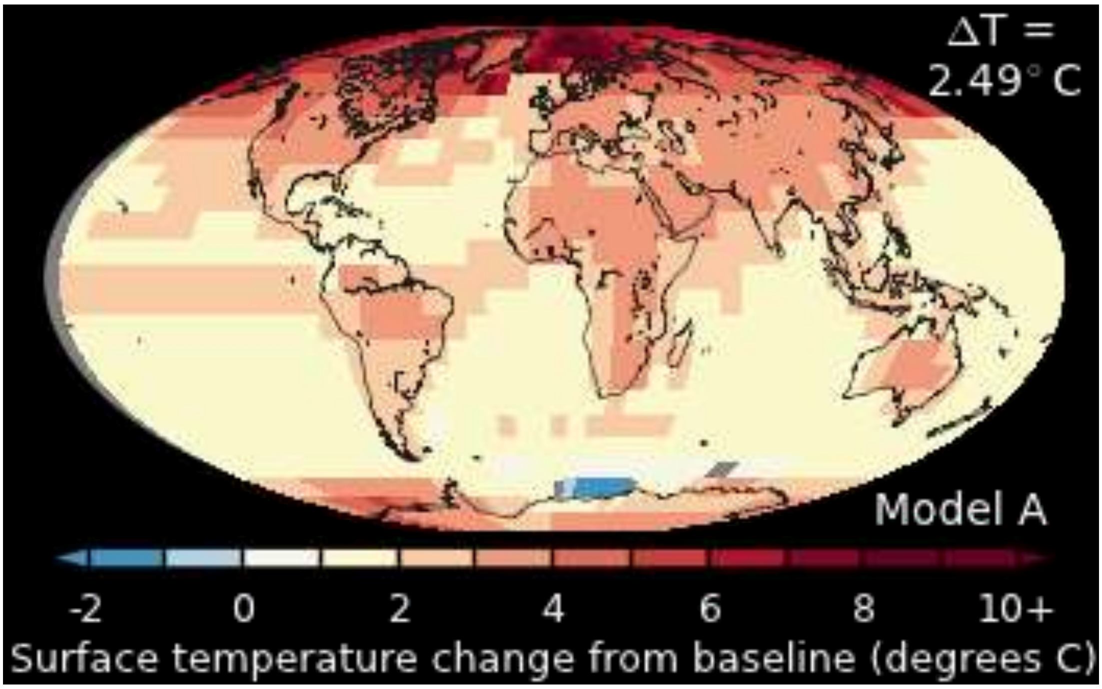
The aim of this section is to demonstrate that we can get an idea of the potential magnitude of the changes to the Earth system using very simple physics. A seemingly small amount of extra CO_2 can trap a large amount of energy.

Animations

The animations are not directly available from the spreadsheet but are selected based on the temperature range generated by the user pathway.

Pictures corresponding to each selected model run have been provided separately in .png format. An example is shown in Figure 11.

Figure 11: example animation frame showing regional temperature changes.



In Figure 11:

- the model used is bcc-csm1 (consistently “Model A” – see list below)
- the time period shown is 2090-2109 (around central year 2100)
- the scenario is RCP4.5
- all data plotted are regridded from the model native resolution to T15 truncation
- all data are twenty-year average surface temperatures for the grid point, minus the model’s own 1861-1880 average at that grid point
- The projection used is a Mollweide equal-area projection.

Areas where the signal (change in 20-year average temperature) is less than the "noise" (standard deviation of internal model variability in 20-year average temperature over a long unforced run) have been greyed out to indicate lack of statistical significance. Data on the average internal variability, as used by the IPCC, was kindly provided by Jan Sedlacek of the ETH, Zurich for both temperature and precipitation.

The animation frames are created in the following way:

- Calculate the baseline temperature for each model (1861-1880 average);
- Select experiments to use: only the r1i1p1 runs, for all available models, for all available RCP scenarios (including extensions to 2300 where these have been done);
- For each experiment, for each 20-year period (2010-2019, 2020-2039, 2030-2049, etc), calculate the change in global mean temperature (ΔGMT) at that period relative to the baseline of the model, and the regional changes in temperatures also relative to the model baseline;
- Plot the regional changes on a T15 grid (lower resolution that the original model);
- Grey out areas where the change is "not significant" (is less than the internal variability, as used by the IPCC);
- Save the regional changes as a picture, and note down the corresponding ΔGMT.

For each animation, the frames are selected in the following way, given a temperature range of X-Y:

- The range is divided into 8 bins and 2 model runs are chosen within each bin, such that
    - No experiment is repeated (an "experiment" is a model run with the same model and same forcing scenario, e.g. HadGEM2 RCP8.5). Thus we may not choose two consecutive time steps of the same model run, but we could choose the same model running two different scenarios;
    - The frame chosen is the closest available to 2100. Where many runs are available this will typically be the 2090-2109 time step, but if few are available then another time step may be chosen. This is consistent with the rationale for the IPCC figure SPM-10, on which the method is based.
- If no frame is available with a global mean temperature within the bin, then a blank map is created with a constant temperature change at the centre of the bin.
- The frames are then arranged in random order and animated.

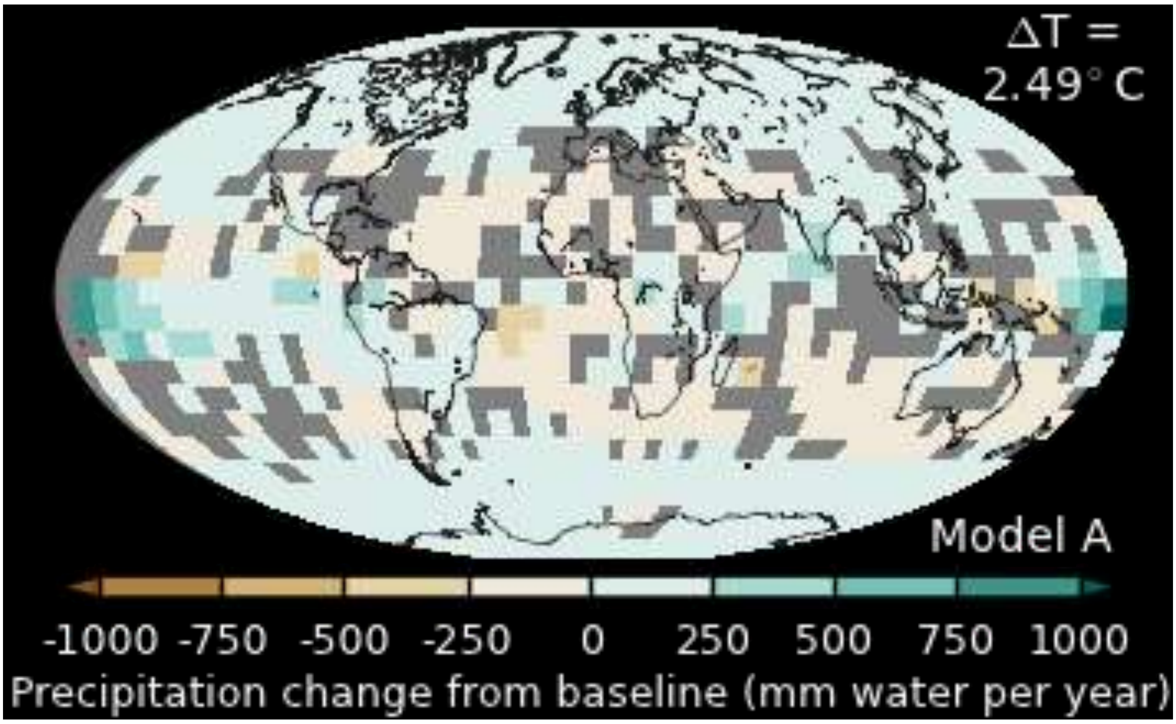
The animations created from a series of such images, for a given global mean temperature range, demonstrate that:

a) simulations show considerable diversity, especially for small regions;
b) there is a robust pattern of land warming more than the oceans;

c) there is a robust pattern of the Arctic regions warming more than the equator.

Similarly, animations for global precipitation projections are provided. An example frame is shown here:

Figure 12: An example animation frame showing regional precipitation changes.



The same formatting is used as for the temperature animation. The same method has been used to grey out areas where the signal is less than the "noise" (internal model variability).

The animations created from a series of such images, for a given global mean temperature range, demonstrate that:

a) simulations show very wide diversity, especially for small regions;
b) there is a robust pattern of greater total change near the equator, but there is not always consensus about the direction of that change.

We acknowledge the World Climate Research Programme's Working Group on Coupled Modelling, which is responsible for CMIP, and we thank the climate modelling groups for producing and making available their model output. For CMIP the U.S. Department of Energy's Program for Climate Model Diagnosis and Intercomparison provides coordinating support and led development of software infrastructure in partnership with the Global Organization for Earth System Science Portals.

Sheet "Climate impacts"

The climate impacts worksheet contains the calculations both for the back-of-the-envelope illustrations and to select the climate model results for viewing. The "Basic Physics" calculations are based upon work presented by Dr Arnaud Czaja in a Grantham Discussion Paper entitled "A consideration of the forcings of climate change using simple physics", published by the Grantham Institute for Climate Change, Imperial College London, 2011. (Any errors in the implementation, however, are the responsibility of the Global Calculator team).

Emissions

Carbon dioxide emissions in each 5-year period (row 9), and cumulative emissions since pre-industrial (row 10), are taken from the "**Outputs - Emissions**" worksheet, which summarises the emissions generated by all of the Calculator sectors.

The first calculation (row 11) uses the CO_2 atmospheric fraction assumption (user input, see Climate data below) to find the total quantity of CO_2 remaining in the atmosphere (the rest is not explicitly modelled, but is taken up by the oceans and by terrestrial vegetation). This quantity is used only in the "Basic Physics" calculations and does not contribute to the temperature range calculation for the thermometer graphic.

Back-of-the-envelope heat flux

CO_2 concentrations (row 20) are historical up to 2010, and are then projected using a linear relationship between the small extra quantity of CO_2 and the change in atmospheric concentration (CDIAC).

The instantaneous additional heat flux (row 21) resulting from this change in CO_2 concentration is calculated using the logarithmic relationship between CO_2 concentration and radiative forcing, with a coefficient of 3.71 based on the latest IPCC report (IPCC AR5 WG1, section 12.3.1.3). The total energy is shown first in Joules per square metre (row 22) of surface, and then integrated over:

1. The total surface area of ice sheets;
2. The total surface area of oceans;
3. The whole planet surface area.

For each of these areas, the heat is shown for 5-year periods (rows 23-25) and then as a cumulative quantity since pre-industrial (rows 27-29). In order to calculate the cumulative totals pre-1960, a linear interpolation is used assuming a value of 0 in 1870. This will be a slight overestimate and could be corrected using historical values, although the influence is likely to be minimal.

Back-of-the-envelope impacts

Additional heat has many impacts on the earth system. In this section we consider the order of magnitude effect that would be generated if all of the extra heat falling on the ice surface went into melting, and if all of the extra heat falling on the ocean surface went into thermal expansion via heating of the seawater. These approximations are crude but illustrative.

The approximate mass of ice melted (row 37) is calculated by dividing the total available energy by the latent heat needed to melt a unit of ice. This additional (fresh) water is converted into sea level rise (row 38) by dividing the water volume by the (present) area of the ocean surface.

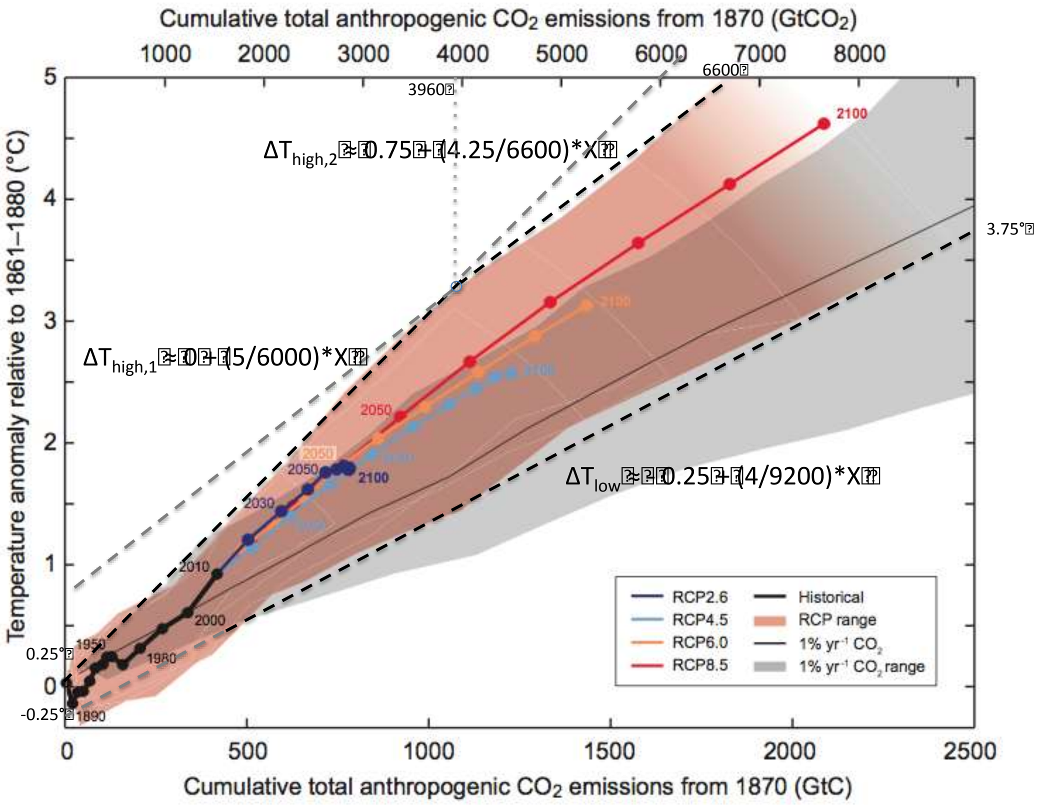
Approximate sea level rise due to thermal expansion (row 39) is calculated using the relationship derived in Box 4 of Czaja, 2011, again by finding the volume change and dividing by the (present) area of ocean surface.

These results are illustrative only, and will be clearly labelled as such.

Climate model output (CO2 only, with representative non-CO2 forcings)

Global mean temperature change for the given level of cumulative CO_2 emissions is calculated based on Figure SPM.10 of the IPCC AR5 WG1 report (2013), using the pink shaded range which is based on model runs using scenarios which include representative non-CO_2 forcings in addition to the stated cumulative CO_2 emissions. The equations used are shown here in Figure 13, superimposed onto IPCC Figure SPM-10. Note that the use of two lines rather than a single fit for the high end of the range is mainly done to match this output with the 2 degrees cumulative emissions target. This calculation is NOT linked to the web tool graphics but is provided as a comparison to the second method described below.

Figure 13: Straight lines (dashed) fitted to IPCC AR5 WG1 figure SPM-10, to calculate RCP range based on CO_2 emissions (top axis) but with representative levels of non-CO_2 forcings (pink shaded range).



For each 5-year period, a high/low range is given (rows 48-50) based on this diagram, and a halfway point also stated. The relationship summarised here is assessed by the IPCC to hold only for cumulative emissions less than 8,000 GtCO2. Beyond this, the Calculator output is simply a warning ("warning - range exceeds IPCC assessment"). The IPCC also state that this relationship does not hold after the peak in temperature, but this version of the Calculator does not check for that condition.

An inflated uncertainty range reflecting the IPCC's judgement about their confidence in model data is given by increasing the range symmetrically by a factor of 1.645, shown in rows 54-56. This is the scaling factor between a 66% confidence interval (IPCC: "likely") of a Gaussian distribution and a 90% confidence interval (IPCC: "very likely"). This implements the "confidence in models" user selection.

Note again that this method is NOT linked to the January 2015 version of the Global Calculator web tool and is provided only as a reference calculation for the interested spreadsheet user within the spreadsheet.

Climate model output (CO_2, CH_4, N_2O, and SO_2 only)

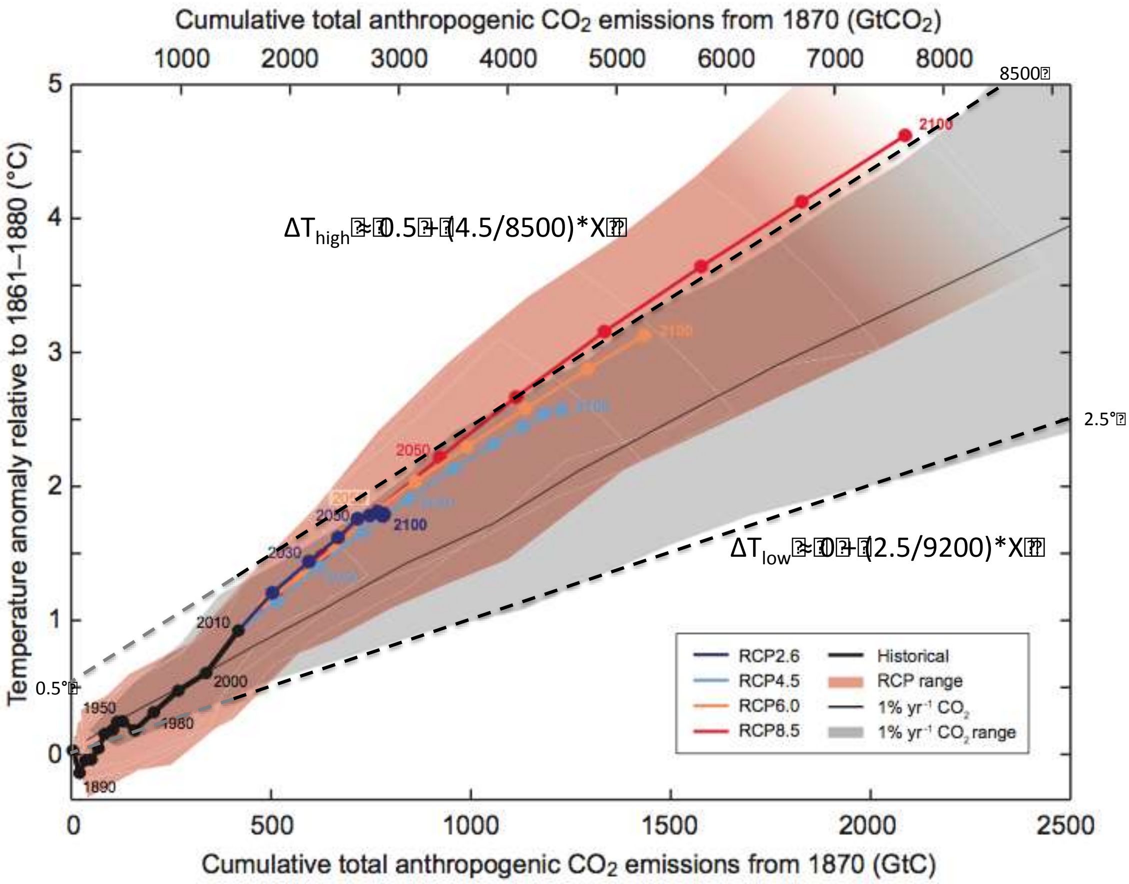
This method IS linked to the web tool.

This method assumes that the forcings due to CO_2, CH_4, N_2O and SO_2 are the primary contributions to total global mean temperature change, and that they can be added linearly to give an estimate of total change. It is true that these gases are the primary drivers of change, but there are a large number of smaller influences which we do not represent, including other anthropogenic emissions (halocarbons, VOCs, black carbon, etc), changes in solar forcing, and volcanic eruptions. The assumption of linearity is crude and clearly does not hold for large forcings, but is felt to be acceptable here if CO_2 emissions remain within the 8,000 GtCO2 limit, since we look for only a rough estimate. Beyond 8,000 Gt, the output is a warning as above.

Since the Global Calculator pathways can result in very large changes to non-CO_2 greenhouse gas emissions, for example with very large changes in land use, it was decided that the "endogenisation" of non-CO_2 gases was an important feature. The alternative method with representative non-CO_2 gases, not shown on the web tool, is left in the spreadsheet as a reference for the interested user who may disagree with this choice. Note that the two methods typically differ by about half to one degree of global mean temperature, with the second (web tool implemented) method typically being lower. Readers who may jump to conclude that the Global Calculator web tool is over-optimistic about the level of climate change (i.e. underestimating the change) are reminded that due to the extreme level of simplification, all outputs should be taken as a qualitative illustration and not in any way quantitatively reliable.

First, an estimate of global mean temperature change for the given level of cumulative CO_2 emissions is calculated based on Figure SPM.10 of the IPCC AR5 WG1 report (2013), using the grey shaded range, which is based on model runs using scenarios which alter the CO_2 only (other forcings remain constant). The equations used are shown here in Figure 14, superimposed onto IPCC Figure SPM-10.

Figure 14: Straight lines fitted to IPCC AR5 WG1 figure SPM-10, to calculate contribution to global mean temperature change of CO2 only (grey shaded range).



For each 5-year period, a high/low range is given (rows 83-85) based on this diagram, and a halfway point also stated. The linear relationship summarised here is assessed by the IPCC to hold only for cumulative emissions less than 8,000 GtCO2. Beyond this, the Calculator output is simply a warning ("warning - range exceeds IPCC assessment"). The IPCC also state that this relationship does not hold after the peak in temperature, but this version of the Calculator does not check for that condition. This is another simplification.

An inflated uncertainty range reflecting the IPCC's judgement about their confidence in model data is given by increasing the range symmetrically by a factor of 1.645, shown in rows 89-91. This is the scaling factor between a 66% confidence interval (IPCC: "likely") of a Gaussian distribution and a 90% confidence interval (IPCC: "very likely"). This implements the "confidence in models" user selection.

Second, an estimate of the global mean temperature change due to each of the non-CO_2 gases is found by adding up the influence of the emissions in each 5-year period:

$$\Delta T_{gas,2100} = \sum_{j=1990}^{2100} AGTP_{gas,2100-j} \times \text{emissions}_{gas,j}$$

For example, the effect of CH_4 emissions in 2035 on the temperature change at 2100 will be given by the 85-year AGTP of CH4 multiplied by the total emissions of CH_4 in 2035. The AGTP is dependent on time horizon, which is why this sum is needed: we have to add up the differing effects of emissions in 1990, 1995, 2000, … 2090, 2095.

Emissions post-2011 are generated by the user choices, summarised in the Outputs – Emissions worksheet. Historical emissions of CH_4 and N_2O are taken from data provided in the Climate – Data worksheet. Note that for SO_2 we have not included the effect of emissions further back than 1990. This is no problem for SO_2 because the AGTP of this compound declines very rapidly, reflecting the short residence time of sulphates in the atmosphere, so earlier historical emissions have a negligible effect.

Third, the contributions of the four gases are added together and a total given in rows 99-101, for the total global mean temperature change at 2050 and 2100. (Note that a running total for every year up to 2100 is also given in the Impacts – Climate sheet).

Climate (data)

The climate data worksheet contains data relating to the levels of the climate science levers. At the moment, these are:

CO2 atmospheric fraction

This choice is derived from the diagram in IPCC AR5 WG1 Chapter 6, Figure 6.26. A range between 0.3 and 0.74 seems to reflect scientific plausibility. The current value is 0.44+/-0.06. The user chooses a value at 2100 and the spreadsheet interpolates linearly from 0.44 in 2010 to the chosen value in 2100 (rows 40-43).

The IPCC figure does, however, suggest that the range allowed could be made dependent on cumulative emissions, with a higher atmospheric fraction being possible for higher cumulative emissions trajectories. It was decided that this level of complexity was unnecessary for the Calculator, but would be an obvious extension. The lack of this feature effectively omits a type of earth system feedback: if higher emissions pathways are generally accompanied by a higher atmospheric fraction of CO_2, then allowing the user to choose a low atmospheric fraction results in an underestimation of the net change.

Having said that, note that the CO_2 atmospheric fraction is only used in the “basic physics” calculation. It is **not** used for the thermometer graphic. The thermometer graphic is based on IPCC Figure SPM-10 (see discussions above) and therefore includes any earth system feedbacks that are included in the CO_2-only model runs submitted to CMIP5 and used to generate SPM-10.

Confidence in climate models

To improve the user relevance of the Calculator, we wish to take account of the additional uncertainty representing the limitations of the ability of climate models to simulate the Earth system. The lever choices are as follows:

A. Show only raw climate model output range (no change to distributions);
B. IPCC AR5 method (generate distribution based on downgrading uncertainty language, e.g. from “very likely” 90% to “likely” 66%);
C. “I don’t believe the results of climate models at all” (Selecting this option was intended to take the user directly to the Basic Physics page, where it is explained that complex numerical models are not required in order to appreciate that climate change is happening and has the potential to have large impacts. In practice the user has to navigate there by themself).

As described above, the inflated uncertainty range reflecting the IPCC’s judgement about their confidence in model data is given by increasing the range symmetrically by a factor of 1.645, shown in rows 89-91. This is the scaling factor between a 66% confidence interval (IPCC: “likely”) of a Gaussian distribution and a 90% confidence interval (IPCC: “very likely”).

Note that the IPCC specify that their judgement about the downgrading of the uncertainty language applies only to the four RCPs, only at the time horizon of 2100, and only for global mean temperature. In the Global Calculator, for the purposes of practical illustration, we have extended this assumption to any pathway with less than 8,000 $GtCO_2$ (within the bounds of Figure SPM-10), at any time horizon up to 2100, only for global mean temperature. This is intended to be an illustration of the process by which the IPCC account for unmodelled uncertainties, not an accurate quantification of uncertainty bounds; therefore, as before, the actual numerical values generated should not be over-interpreted.

Emissions trajectory assumption

The choice determines how the 2050-2100 emissions trajectory is generated, since the other Calculator sectors only run out to 2050. It was decided that it would be unfeasible to construct sector-specific trajectories further than 2050, because of the great uncertainty in technological developments. The current options for generating emissions pathways are:

- Level 1: emissions are flat from 2050 to 2100
- Level 2: after 2050, emissions change every year by 33% of the average yearly change for the previous 15 year period (unless an absolute lower limit is hit)
- Level 3: after 2050, emissions change every year by 66% of the average yearly change for the previous 15 year period (unless an absolute lower limit is hit)
- Level 4: after 2050, emissions change every year by 100% x the average yearly change for the previous 15 year period (unless an absolute lower limit is hit)

Note that for all but the lowest emission pathways, **the cumulative CO_2 total at 2100 (and hence the temperature impact) is dominated by the area under the curve between 2050-2100, which is produced by this crude assumption rather than by a realistic model**. This could be avoided by presenting emissions and temperature change only up to 2050, but doing so would obscure the long-term nature of the expected climate impacts. The user should be aware that the setting of this lever is in no way related to or limited by the technological development in 2011-2050 and is not an outcome of any technological modelling. The user should therefore satisfy themself that further change beyond the end of the modelled pathway at 2050 would be plausible.

A minimum emissions floor has been suggested (row 59) and chosen arbitrarily.

Cost estimates

This section is included as a placeholder only. Cost estimates are available, for example in the IPCC's Working Group 3. However they require some thought before being added in, because there are several categories of costs which cannot necessarily be calculated or compared meaningfully: adaptation costs, loss and damage, and welfare costs. Comparison with the incremental energy system costs may not be a helpful output for users and requires further consideration. Future updates to the Global Calculator could consider incorporating such estimates.

Absolute Global Temperature Potentials (AGTP)

The GTP for CH_4, N_2O and SO_2 is given in IPCC WG1 Table 8.SM.17 (supplementary material) for time horizons of 10, 20, 50 and 100 years. These are multiplied by the absolute GTP of CO_2 for the corresponding time horizon to give an AGTP for each gas in units of Kelvin per kilogram. The spreadsheet performs a simple linear interpolation between each time horizon to give the AGTP for each gas for 15, 25, 30 years etc. This could be updated with analytical values but the difference would be small. For the 5-year and 0-year horizons (mainly important for short-lived forcings, in this case SO_2), a crude assumption has been made to extend the curve. In this case the division into 5-year segments also results in considerable over-simplification but is unavoidable given the scope of the Calculator.

Other reference data

Historical emissions of CH_4, N_2O and SO_2 are provided for use in the AGTP calculations.

Palaeoclimate temperature records are provided as a context for the recent and projected change in global mean temperature.

Emissions of CO_2, CH_4, and N_2O in the standard Representative Concentration Pathway scenarios (RCPs) used by the IPCC are also provided for context.

Annex A: Excel formulae tips

The Global Calculator spreadsheet combines Excel functions in a way the can look daunting to non-expert Excel users. For example, there are formulae such as the following that can seems long and unwieldy:

=IFERROR(SUMIFS(INDIRECT(B3&"."&$D13&".energy["&This.year&"]"),INDIRECT(B3&"."&$D13&".energy[Technology code]"),$B13,INDIRECT($B$3&"."&$D13&".energy[Energy vector]"),F$6),0)

The spreadsheet makes use of these formulae in order to make the model more robust; the use of functions that "look up" data within "named ranges" of data or "Tables" means there is a lower risk of a function using the wrong data (see below). It also makes it easy to add new technologies with confidence, because they can simply be added to existing "Tables" if they perform the same energy service as another existing technology. This modelling approach also makes it easier to spot errors, as an exact lookup will fail and return "#REF!". The downside is that the formulae slow the calculation of the model, which is why the calculation function is set on "manual" (the user has to press "F9" to re-calculate).

The common functions in the workbook are:

- "=INDEX(*array, row number, column number*)": returns a specific value from a specified array, according to the row and column numbers stipulated in the formulae (often combined with match to find the column / row number)
- "=MATCH(*lookup value, lookup array, match type*)": returns the relative position of a given value within a specified array (for example, the column number in which a technology is located)
- "INDIRECT(*text*)": this creates a cell reference from string (text). For example, using the "&", which joins two separate "strings", you can create a cell reference. "F9" would be given by =INDIRECT("F"&"9")
- "Structured Table References": Excel 2007 and Excel 2010 give users the option to define an array of data as a "Table". This function is useful as it means that columns of tables are given names, using the headings of the table. The way in which cells within a "Table" are referred within formulae is different, and requires the use of square brackets (e.g. =Table1[[#This Row],[Column1]]).