Climate change and the DECC Global Calculator

A software tool to explore the technical and economic feasibility of 'solutions' to global warming

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Energy Group Meeting
European Physical Society

Congresso Società Italiana di Fisica
Roma, Italy 23 September 2015
Revised January 2016

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Executive Summary

This paper aims to assist readers to understand and make use of the **DECC Global Calculator.** It supplements the documentation already provided by UK Department of Energy and Climate Change (DECC) on its website. This software package was developed by an international team of Climate Change and Computer modelling experts under the leadership of DECC, and was made publicly available on its website as an open-source model on 20 September 2013. Since then it has had several published updates, the most recent released on 28 January 2015.

Background This paper begins with a recapitulation of the major political developments which led to the DECC Global Calculator project:

- 1990 Publication of the first report of the Intergovernmental Panel on Climate Change (IPCC), leading to work in the scientific, NGO and national government communities to convince public opinion that anthropogenic climate change is a reality, and to devise and adopt credible policies for mitigating it.
- 2002 The British government publishes a review of UK energy policy, followed by the Stern report in 2006, a White Paper on Nuclear Power in January 2008, and the Climate Change Bill in November 2008, in which the UK committed itself to an 80% reduction in UK GHG emissions by 2050 compared with a 1990 baseline, hoping that this lead, if widely followed, might keep the global rise in mean surface temperature below 2 ^{0}C.
- 2008-11 DECC explored possible strategies for meeting this UK target, and made publicly available a piece of software entitled ‘Pathways to 2050’, allowing any user who so wished to devise his or her own strategy.
- 2013 The British Pugwash Group published a report entitled *Pathways to 2050: three possible UK energy strategies*, in which three independent ‘champions’ used the DECC ‘Pathways to 2050’ software to develop three very different pathways for the UK, described as “high nuclear”, “high renewable” and “intermediate”. All three pathways were claimed to have successfully met three pre-set conditions – that each pathway should:
  - *be based on energy technologies which either already existed, or could reasonably be expected to be brought to sufficient commercial maturity in time for them to be rolled out on the scale required if the UK was to meet its likely energy demands in 2050*
  - *meet the target of 80% GHG reductions by 2050, to which the UK was already legally committed*
  - *have a total cost (capital plus operating costs) between 2010 and 2050 which was comparable with other competing pathways.*

All three pathways arguably met the first two conditions, and each had a total cost of about £3 trillion. However each pathway had at least one potential ‘show-stopper’, so the report advised the UK government to pursue all three pathways until the technical uncertainties had been resolved.

- 2011-14 In the aftermath of the Fukushima disaster in March 2011, there was comparable activity in continental Europe. Germany took the decision to phase out its civil nuclear power in favour of renewables, and this had a strong influence over EU policy-making (as exemplified in its *Energy Roadmap 2050* of 2011 and its *Policy Framework* of January 2013). Only recently have warning voices have been raised (for example in the ‘Position Paper’ of the Energy Group of the European Physical Society) that this policy is putting a serious strain on the economies of continental Europe.
- 2015 In the run-up to the highly significant United Nations Conference on Climate Change (COP21) in Paris in December 2015, a number of organisations have been seeking to prepare a scientific basis for

the political decisions at a global level to be taken at that meeting. Among these has been a Climate Change modelling project undertaken under the leadership of DECC, but with substantial international cooperation, entitled 'the Global Calculator', which has sought to emulate the earlier 'Pathways to 2050' project but now on a global scale, and setting a target of limiting the global average surface temperature rise to 2 ^{0}C by 2100, corresponding to cumulative emissions of ~3000 Gt CO_2e by 2100 (as inferred from the latest IPCC report).

The Global Calculator has been published by DECC in two different forms, aimed at users with different degrees of familiarity with the Excel Spreadsheet software on which both are based:

- For the experienced user, the Calculator is published as an Excel Spreadsheet, downloadable from the DECC website. There is a user guide written by experts for experts, which gives the structure of the various interacting sectors of the Spreadsheet, and outlines its coding standards.
- For the less-experienced user, there is the so-called 'Web Tool' version, which has been designed to permit users with no prior knowledge of Excel coding to get started, and to produce their own global energy pathways by means of a user-friendly input and output interface.

To assist such target users, the present paper gives a **Guide to the 'Web Tool' version of the Global Calculator.** This provides guidance to the user on how to set his/her inputs, which specify a set of values for the 48 'levers' of the chosen Global pathway (listed in Annex 1 below), and how to find the outputs of the Calculator (mostly presented in graphical form) for those lever settings, in a set of histograms and graphs shown on the top half of the screen. These outputs are presented in six chapters, all accessible from the home page.

The Overview chapter has three pages – 'Summary', 'Energy', and 'Emissions'. The Summary histograms only show values for 'today' (usually meaning 2011) and 2050. The Energy and Emissions pages show the evolution of energy supply and demand and emissions in annual steps between these two dates, and give an estimate of the global mean temperature rise in 2100 for the user's chosen levers, with warning flags if the chosen pathway exceeds the target 2 ^{0}C limit (this output is deliberately presented on a fuzzy indicator because of the uncertainties involved). The Energy section also gives access to a Sankey diagram, which shows how energy passes from the nine raw primary energy inputs to the end users, collected together into four "blocks" named 'lifestyle', 'technology & fuels', 'land and food' and 'demographics and long-term': it also indicates the energy losses occurring in the process. The four "block" chapters can be used to set the user-chosen levers in each block.

- The 'costs' chapter gives annual figures between today and 2050, expressed as a multiple of the cost of the 'counterfactual' pathway, which can be chosen by the user in a box on the screen.
- The 'compare' chapter gives a table enabling the user to compare the pathway he/she has constructed with some (but unfortunately not all) of the 'example' pathways provided by DECC. These are pathways which have been sent to the Global Calculator team by interested users, and have been judged to be worthy of inclusion in this release of the software. These example pathways may be helpful to new users looking for a starting point in constructing their own pathway, and can be accessed from the Overview chapter.
- The 'share' chapter explains how users can transmit the set of levers that they have chosen, either from the Web Tool version to their own copy of the Spreadsheet version, or to that of another user.

For the experienced user, the present paper also has a **Guide to the 'Spreadsheet' version of the Calculator,** which is aimed at the user who is already familiar with the use of Excel, and wants to have detailed explanation of the structure of the large family of Spreadsheets involved, and how they exchange information with each other. This Guide is intended to supplement the 'Spreadsheet user guide' published by DECC, which is unfortunately silent on many matters which might be of interest to first-time users of the Calculator. Some of these are identified below.

Help for the user in deciding on 'lever' values for his/her Global Calculator pathway

The Web Tool user is not given much guidance on how to decide on these ~48 settings, apart from the brief drop-down descriptions give in the 'blocks' in the lower half of the home page. The underlying Excel Spreadsheet version is more helpful, having a tab called "Detailed lever guide" which has a column entitled 'Situation today' giving the values of the relevant parameters in 2011, and also has columns giving a 50-word summary of the consequences of selecting one of four integral 'level' values for each lever in 2050 (note that the user is not required to set an integral value for any lever: he/she is free to select an intermediate lever value correct to one decimal place).

Alternatively, the user can at a stroke load an initial set of lever values for a pathway, by selecting one of the 26 '**example pathways**' provided by DECC. In the Web Tool version, this is done by selecting one named pathway from a drop-down list in the Overview chapter. This can then be modified by using the mouse in the relevant "block" chapter. As soon as the user makes a change to any of the 'example' lever values, that pathway becomes the 'user-specified pathway', and the outputs are amended accordingly. In the Spreadsheet version of the Calculator, a table showing the values of all the levers in all the 'example pathways' is given in the 'user inputs' tab. Column E of the same table is labelled 'make your choices here', and the user can copy across values from one of the example pathways into it, using normal Excel procedures.

Given an initial set of lever value choices, the user can then fine-tune this pathway by adjusting the lever values in the light of the outputs obtained from the model. Unfortunately this 'experimental' approach to fine-tuning a pathway is fraught with difficulties because to the very non-linear nature of the model – small changes in the value of one lever can have knock-on consequences for another (or for many other) lever settings, and cause unexpectedly large changes in key outputs, and hence in the overall surface temperature increase. Detecting and understanding these (often non-linear) effects is a skill which the user of the model has to acquire.

Comments on inputs and outputs from all the Example Pathways included in the Global Calculator

In the present paper we give easy access to some parameters from all 26 Example pathways. In Annex 2 we show the 48 lever choices for each Example pathway. In Annex 3 we show a selection of the key outputs for each pathway, listed in the order in which they appear in the Web Tool index. In Annex 4 we show the same data, but with the pathways ordered in order of increasing estimated temperature rise in 2100. It will be seen that the rises range from 0.9 to 6.0 ^{0}C, with only four pathways meeting the temperature rise target of < 2 ^{0}C, and ten having temperature rises exceeding 2.5 ^{0}C, in one case over 6 ^{0}C!

For the purposes of this paper we have selected three pathways, each with an estimated temperature rise below 2.5 ^{0}C, which are representatives (but not necessarily in an optimal way) of three very different global strategies:

1. **High nuclear** strategy. In this case, only one relevant Example pathway is available – the World Nuclear Association's Allegro pathway, which has an installed nuclear capacity of 1870 GWe.
2. **High renewable** strategy. It seems that most of the relevant Examples also have a significant increase in the nuclear component of the overall supply, so we have chosen one, the Climact pathway, which has only 342 GWe of installed nuclear capacity – i.e. roughly the same as its 2011 value – and about 8000 GW of renewable capacity.
3. I**ntermediate** strategy, which includes a significant contribution from Carbon Capture & Storage. From a short list of eight Examples, we have chosen ICEPT, a broadly spread supply strategy, with amounts of electrical energy supply to the grid of 43 EJ of wind, 37 EJ of solar, 17 EJ of nuclear and 10.5 EJ of CCS (sequestering 2 Gt of CO_2)
The energy inputs and outputs, and the resulting temperature rise, for each of these three pathways are summarised in Annex 5. Each of these pathways produces cumulative emissions of around 3000 Gt of CO_2e**.**

Given the rather disappointing temperature rises in our selected pathways, we have made some attempts to improve them by fine-tuning, but have not as yet met with success. This in part reflects the difficulty in finding local optima in highly non-linear systems. However we have identified a number of possible weaknesses in the DECC model, which suggest that it may have scope for further improvement. These include:

- There is some evidence of coding errors in the DECC model: e.g. the Sankey diagrams reveal some failures in the conservation of energy between the input and output channels.
- The treatment of certain elements of the model (e.g. Carbon Capture and Storage (CCS), Afforestation, Bioenergy, Storage and demand shifting) is rather obscure, and not fully explained in the documentation.
- There are not sufficient levers to represent actions taken to cope with intermittency of renewables, or the need for/benefits of storage, backup and electrical interconnections between different geographical regions.
- The methodology of the parts of the software devoted to costing calculations is not made clear.

In conclusion, we note that the authors of the Calculator have not really addressed the issues which British Pugwash faced when considering a 'Pathway to 2050' for the UK in isolation. In that paper, we found that each of the three pathways had at least one potential 'showstopper' of a technical or economic nature, which might rule it out, so urgent action was required to continue R&D on all three pathways until their technical and economic feasibility have been established.

We should add that since the present paper was presented at the Rome Conference in September 2015, the Paris conference (COP21) mentioned above has enabled the world-wide community to reach some highly encouraging conclusions on the urgent need for significant reductions in Greenhouse Gas Emissions, and to set some challenging targets for the resulting global mean surface temperature rise to below 2 ^{0}C. We have reviewed our paper in the light of this development, and made a few minor changes. However our main conclusion – on the need for more work within the relevant international scientific, technical and governmental bodies to devise and implement workable strategies to reach this target – remains essentially unchanged.

Climate change and the DECC Global Calculator

Introduction

In the 25 years since the Intergovernmental Panel on Climate Change (IPCC) published its first report[1], the international scientific community has made strenuous, and increasingly successful, efforts to convince public opinion that anthropogenic climate change is a reality, and to devise credible policies for mitigating it. National governments have responded to the growing public concern on this subject, and a number of concrete measures have been adopted at the national, regional and international level.

The British government took an early lead, publishing a review of UK energy policy in 2002[2], the Stern report in 2006[3], a White Paper on Nuclear Power in January 2008[4], and the Climate Change Bill in November 2008[5], which set out the world's first long-term legally binding framework for tackling the dangers of climate change.

In parallel with this activity at the UK level, the EU passed the Treaty of Lisbon in 2007[6], which eventually became law in 2009. After this relatively slow start, it published its *Energy Roadmap 2050* in 2011[7] and a *Policy framework for climate and energy in the period 2020 to 2030* in January 2014[8].

At the international level, leadership has been provided by the Intergovernmental Panel on Climate Change, which has published its findings in 1990, 1992, 1995, 2001, 2007 and 2014.

All this activity at the institutional level has been accompanied by an enormous increase in the volume of scientific, engineering and energy systems analyses published in the literature. Initially, this work was dominated by the need to have accurate figures for the growth of 'Greenhouse Gas' (GHG) emissions over the recent decades, and to use these to provide forecasts of the consequential rise in the global average surface temperature during the coming decades. More recently, the emphasis has shifted to strategies for mitigating the growth in emissions, and their consequences.

In the early days, mitigation studies were largely focused on means of achieving a specified reduction in national, regional or global GHG emissions. The UK took a lead by committing itself to an 80% reduction in UK GHG emissions by 2050 compared with a baseline figure of 783.1 Mt CO_2e for 1990. This reduction was judged to be approximately compatible, if reproduced elsewhere in the world, with keeping the rise in mean surface temperature below about 2 ^{0}C in 2050.

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1 http://www.ipcc.ch/ipccreports/1992%20IPCC%20Supplement/IPCC_1990_and_1992_Assessments/English/ipcc_90_92_assessments_far_overview.pdf

2 http://webarchive.nationalarchives.gov.uk/+/http://www.cabinetoffice.gov.uk/media/cabinetoffice/strategy/assets/theenergyreview.pdf

3 http://webarchive.nationalarchives.gov.uk/+/http://www.hm-treasury.gov.uk/independent_reviews/stern_review_economics_climate_change/stern_review_report.cfm

4 http://webarchive.nationalarchives.gov.uk/+/http://www.berr.gov.uk/files/file43006.pdf

5 http://www.decc.gov.uk/en/content/cms/legislation/cc_act_08/cc_act_08.aspx

6 http://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:12007L/TXT&rid=1

7 *Energy Roadmap 2050*, COM(2011) 885, EC Brussels, 15 Dec. 2011 http://ec.europa.eu/smart-regulation/impact/ia_carried_out/docs/ia_2011/sec_2011_1565_en.pdf

8 *A policy framework for climate and energy in the period 2020 to 2030*, COM(2014) 015, EC Brussels, 22 Jan. 2014 http://ec.europa.eu/smart-regulation/impact/ia_carried_out/docs/ia_2014/swd_2014_0015_en.pdf

During the period 2008-2011, the Department of Energy & Climate Change (DECC) undertook extensive studies of possible strategies for meeting this target, and encountered widely divergent views on what UK strategy would be optimal. It therefore developed, and made publicly available a piece of software entitled **'Pathways to 2050'**[9] which would enable any user who so wished to devise his or her own UK strategy, and compute the emissions which would result. A number of NGOs and academic bodies took up the challenge, and published their findings. Among these was a study published by the British Pugwash Group in February 2013 entitled *Pathways to 2050: three possible UK energy strategies*[10]. In this report, three independent 'champions' used the DECC 'Pathways to 2050' software to develop three very different pathways, described as "high nuclear", "high renewable" and "intermediate" respectively. All three pathways met the pre-conditions set by British Pugwash – that the pathway should:

- be based on energy technologies which either already existed, or could reasonably be expected to be brought to sufficient commercial maturity in time for them to be rolled out on the scale required if the UK was to meet its likely energy demands in 2050
- meet the target GHG reductions by 2050 to which the UK was already legally committed
- have a total cost (capital plus operating costs) between now and 2050 which was comparable with other competing pathways.

In the event, all three pathways arguably met the first two conditions, and each had a total cost which was close to the cost of the other two (about £3 trillion each). However each pathway had at least one potential 'show-stopper', so the report advised the government to pursue all three pathways until the current technical uncertainties had been resolved.

In parallel with this UK activity, there has been comparable activity in continental Europe, much of which has been dominated by the decision of Germany, in the aftermath of the Fukushima disaster in March 2011, to phase out civil nuclear power in favour of renewable energy. This policy has been energetically pursued by the German government, and has had a strong influence over EU policy-making (as exemplified in the *Energy Roadmap 2050* of 2011[7] and the *Policy Framework* of January 2013[8]). Only recently has it been recognised that this policy is putting a serious strain on the economies of continental Europe, and warning voices have been raised within the political and NGO communities. In particular the Energy Group of the European Physical Society has issued a 'Position Paper'[11] and a summary of its argument, putting it in the context of global energy policy, was published at the EPS Energy Science & Technology conference in May 2015[12].

In the run-up to the highly significant United Nations Conference on Climate Change in Paris in December 2015[13], a number of organisations have been seeking to prepare a scientific basis for the political decisions at a global level which they hoped would be reached at that meeting. Among these has been a project undertaken under the auspices of:

•The UK Department of Energy and Climate Change (DECC)
•The EU Climate Knowledge and Innovation Community (Climate – KIC)
•International Energy Agency

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[9] https://www.gov.uk/government/publications/2050-pathways-calculator-with-costs
[10] http://britishpugwash.org/wp/wp-content/uploads/2013/02/British-Pugwash-Pathways-to-2050-small.pdf
[11] The Position of the Energy Group of the EPS http://www.nature.com/nature/journal/v525/n7568/full/525187b.html also at http://www.epsnews.eu/2015/07/eps-energy-group-position-paper/
[12] EPS Energy Science & Technology conference, Karlsruhe, May 2015 paper 1.09-4 Josef Ongena & Christopher Watson
[13] http://unfccc.int/resource/docs/2015/cop21/eng/l09r01.pdf

•World Resources Institute
•Energy Research Institute of the National Development and Reform Commission and Energy R&D International (China)
•Ernst & Young – India (EY India)
•London School of Economics
•Imperial College London
•Climact
•Climate Media Factory

This project, entitled '**the Global Calculator**', has sought to emulate some of the principles underlying the earlier 'Pathways to 2050' project undertaken by DECC in 2012. The history of this ambitious new project, and the list of individual participants involved in its execution, is given in footnote[14]. In this new software package, the energy system under design is that of the whole world, and the target is no longer simply to reduce emissions, but to limit the global average surface temperature rise to 2 ^{0}C by 2100. This change in emphasis has been made possible by the rapid development in global climate modelling during 2010-15, which now permits reasonably reliable forecasts of temperature rises to be derived from emission forecasts. The project nevertheless recognises that these temperature forecasts have error bars, and of course global average forecasts are far from being sufficient to forecast local consequences of such averages. An outline of the Climate Science modelling used in this part of the Global Calculator is described in the Spreadsheet user guide pp 35-47[15]. The choice of a 'target' of 2 ^{0}C rise by 2100 is admittedly slightly arbitrary – it is broadly in line with the objective set in Article 2 of the United Nations Framework Convention on Climate Change (UNFCCC)[16] , and (as argued by DECC in [17] on pp 12-13) pathways with a significantly higher temperature rise by 2100 have a number of serious socio-economic and environmental drawbacks. The 2 ^{0}C figure corresponds to cumulative emissions of ~3000 Gt CO_2e by 2100, as inferred from Figure SPM-10 of the IPCC report AR5 WG1.

The Global Calculator is a public domain software package which has been published in two different forms, aimed at users with different degrees of familiarity with the Excel Spreadsheet software on which both are based. For the experienced user, the Calculator is published as an **Excel Spreadsheet**, which can be downloaded by the user from the DECC website[18]. This is an evolving piece of software, which has currently (at 25/8/15) reached version V3.99.2, and the user is well advised to retain a master copy of the version that he/she is using before making modifications to it. There is a user guide written by experts for experts, published at [15], which gives the structure of the various interacting sectors of the Spreadsheet, and gives some clues about the software coding standards which it embodies.

For the less-experienced user, there is the so-called **'Web Tool' version**, which has been designed to permit users with no prior knowledge of Excel coding to get started, and to produce their own global energy pathways by means of a user-friendly input and output interface. This version in fact makes extensive use of the underlying Spreadsheet software, but this is largely concealed from the user. The Web Tool can be

[14] http://www.globalcalculator.org/
[15] http://www.globalcalculator.org/sites/default/files/GC%20spreadsheet%20user%20guide.pdf
[16] https://unfccc.int/resource/docs/convkp/conveng.pdf
[17] http://uncached-site.globalcalculator.org/sites/default/files/Prosperous%20living%20for%20the%20world%20in%202050%20-%20insights%20from%20the%20Global%20Calculator_0.pdf
[18] https://www.gov.uk/government/publications/the-global-calculator

accessed at[19]. Surprisingly, there is no published user guide for this version – the intention has been to make the software entirely self-explanatory. However a new user may find the following notes helpful.

Guide to the 'Web Tool' version of the Global Calculator

The Web Tool user is invited to provide inputs to the model, in the form of a set of values for 48 'levers' (listed in Annex 1 below) which specify the characteristics of the 'user-specified' Global pathway. The Calculator then provides outputs using those 'lever' settings, in a set of histograms and graphs shown on the top half of the screen. These outputs show the evolution of global energy supply and demand and emissions in annual steps between 2010 and 2050, and give an estimate of the global mean temperature rise in 2100. The user of the Web Tool version is not given much guidance on how to decide on these 48 settings. Implicitly, the user is simply encouraged to make a choice and see what consequences emerge in the outputs. Relevant Web Tool outputs can be obtained by selecting the appropriate "block" ('lifestyle' etc.) from the bar at the top of the screen, and looking at the output histograms and graphs shown in the upper half of the screen.

The underlying Excel Spreadsheet version provides slightly more help to the user. This Spreadsheet has a tab called 'Detailed lever guides' which has a column entitled 'Situation today' giving the values of all the relevant parameters in 2011, and also provides columns (one column giving a 20-word summary and another giving a 50-word summary for each integral value) which explain in broad outline the consequences of selecting that value for each lever in 2050. These columns do not have space to give any real insight into why the consequences are as reported. However some further clue is provided by the Web Tool if the user points the screen arrow at one of the four boxes shown for each lever, which leads to a brief drop-down message. The reason for this rather laconic guidance becomes clear if one examines the text of the Excel version user guide[15]. Decisions on the setting for any one lever can have knock-on consequences for another (or for many other) lever settings. So no simple explanation of all the consequences of making any one setting is possible.

Most of the output information provided by the Web Tool (using the six chapter headings shown at the top of the page) is fairly self-explanatory, but is rather limited in extent, and the user seeking more detail may have to go to the Spreadsheet version, which gives much more detail. However the Web Tool outputs are sufficient for many purposes. Its overview chapter has three sections – 'Summary', 'Energy', and 'Emissions'. The Summary histograms only show 'today' (usually meaning 2011) and 2050. Further clues about the evolution between these two dates is given in the 'Energy' and 'Emissions' sections which have graphs of energy supply and demand and emissions, showing annual steps. A useful source of further information in the Energy section is the Sankey diagram, which shows how energy passes from the nine raw primary inputs to the end uses under each of the four "blocks", and also indicates energy losses in the process. The energy flow on each pathway is shown on the screen if the arrow is pointed to it using the mouse.

Another useful table, which can be selected by pointing to the 'Example pathways' link, is the list of the 26 pathways which have been sent to the Global Calculator team by interested users, and are judged to be worthy of inclusion in this release of the software. These example pathways may be helpful to new users looking for a starting point in constructing their own pathway, and they are discussed further below. Descriptions of the 26 'example pathways' can be found in[20].

[19] http://www.globalcalculator.org/ and press the 'Access the Global Calculator' button
[20] http://www.globalcalculator.org/pathways

Some of the headline figures which are given need some elucidation. The 'Global mean temperature rise in 2100' is shown on a 'thermometer', which is a very fuzzy indicator. This is deliberate, and emphasises the uncertainties in forecasting temperature rises so far ahead. Various drop-down warnings about the range of outcomes are shown in all three sections.

The four "block" chapters give useful output details on some of the key levers in each block.

The 'costs' chapter gives annual figures between today and 2050, expressed as a multiple of the cost of the 'counterfactual' pathway, which can be chosen by the user in a box near the top of the screen. A useful drop-down page on how costs are calculated can be accessed here. Further information about the basis of the cost figures is given in[21].

The 'compare' chapter gives a useful table enabling the user to compare the pathway he/she has constructed with some (but unfortunately not all) of the 'example' pathways.

The 'share' chapter explains how users can transmit the set of levers that they have chosen, either from the Web Tool version to their own copy of the Spreadsheet version, or to that of another user. This transmission can be effected either by cutting and pasting a column of lever values presented in a box, or by copying the url shown. The Web Tool does not make clear whether transmission in the opposite direction is possible (but see below).

Guide to the 'Spreadsheet' version of the Global Calculator

Users seeking more information about the Spreadsheet version of the software may find it helpful to consult the 48-page 'Spreadsheet user guide'[15]. That guide is aimed at the user who is already expert on the use of Excel, and wants to have detailed explanation of the structure of the large family of Spreadsheets involved, and how they exchange information with each other. Detailed flowcharts are given, and an indication of the way in which the various Excel calculations are made. There is also a helpful Annex explaining how some of the more advanced Excel software features are used. However that 'user guide' is silent on many matters of concern to the inexperienced user. Some of these are identified below.

How to design a user-specified pathway

The table shown in Annex 1 lists the 48 levers used in the current version of the Global Calculator V3.99.2 (at 28/8/15). This number is five more than the number in the previous version V3.47.9, emphasising the fact that the Global Calculator is still evolving. The 'current situation' column in Annex 1 gives the values of the relevant parameters in 2011, and the task of the user is to indicate his/her judgment of the way in which these parameters will change between now and 2050, by assigning a value to the corresponding lever. A 50-word explanation of the way in which the Global Calculator will interpret the user's lever setting for each integral value is given in the Spreadsheet's 'Detailed lever guides' tab columns X to AA. (The user is not required to set an integral value for any lever: he/she is free to interpolate between these integral values, and select an intermediate lever value correct to one decimal place). The explanations can help guide the user to choose a personal set of lever values: this set is described in the Web Tool as the 'user-specified'

[21] *Prosperous living for the world in 2050: insights from the Global Calculator* https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/398596/Global_calc_report_WEB.pdf

pathway. Alternatively, the user can proceed by amending one of the 26 'example pathways' (see below): once he/she has started doing so, this automatically becomes the 'user-specified' pathway.

Inputting the user-specified values of the 48 levers

Inputting the user's chosen lever values can be done within the Web Tool using the mouse, but the process is slow and cumbersome (especially for non-integral values), and the user may find it more convenient to type the chosen figure into the Spreadsheet version (in column E of the 'user inputs' tab), and then transfer the whole user-specified pathway from the Spreadsheet to the Web Tool version (the procedures which can be used to do so are explained below). The Spreadsheet procedure has the advantage that the complete column of user-specified lever settings is shown adjacent to column D, which gives a brief name for each lever.

Access to the lever values chosen in the 26 'example pathways'

There are two means by which the user can access the lever values in an 'example pathway'. Within the Web Tool, the user can find an index of the 26 currently available pathways by clicking the 'example pathways' box at the centre of the 'overview' page of the Web Tool. By clicking one entry in that index, that pathway becomes the 'selected' pathway, and is reported accordingly on the screen. As soon as the user makes a change to any of the lever values, (using the mouse in the relevant 'block' section of the home screen), that pathway becomes the 'user-specified pathway', and is reported accordingly.

Alternatively, within the Spreadsheet version of the Calculator, a table showing the values of all the levers in all the 'example pathways' is presented in columns H to AE of the 'user inputs' tab. (For some reason the figures for the two WNA pathways are not included, but these can be transferred from the Web Tool version using the 'share' facility – see below). Column E of the same table is labelled 'make your choices here', and the user can specify the values in this column either by typing in the values or by copying across individual values or ranges of values from one of the 'example pathways' using normal Excel procedures.

Transfer of pathway lever values between the Spreadsheet and Web Tool versions

There are several reasons why the user may wish to transfer lever values between the two versions of the Calculator:

- The user may wish to save a 'user-specified' pathway, once specified, so that he/she can use it again (or modify it) at a later date. There is no obvious way to do this within the Web Tool
- The user may wish to take advantage of the very user-friendly outputs from the Web Tool version, some of which are not available in the Spreadsheet version (e.g. the Sankey diagram)
- The user may wish to access outputs which are available in the Spreadsheet but not in the Web Tool version
- The user may wish to transfer a user-specified pathway to another user, either by e-mail or by publishing it in a computer-accessible form
- The more advanced user may wish to understand, and possibly amend, how output values presented in either version are calculated, and may therefore require access to the Excel software concerned, or to create new output presentations which may be helpful.

To transfer a 'user-specified' pathway from the Web Tool to the Spreadsheet version, use can be made of the 'share' chapter of the Web Tool, which provides (a) a url which will immediately be recognised by the

Spreadsheet version on his/her own computer or on another computer on which the Spreadsheet software has been loaded and (b) a column of lever values which can be copied into column E of the Spreadsheet version, and will then define that pathway within the Spreadsheet. The data in column E can also be saved, either by saving the whole Spreadsheet immediately, or by copying column E across to a vacant column (from AI onwards) in the 'user input' tab, and saving the Spreadsheet at the end of a session. It is unfortunately less obvious how to transfer a 'user-specified' pathway in the opposite direction. Copying Column E from the Spreadsheet into the corresponding column in the 'share' chapter of the Web Tool does not cause this to become the 'user-specified' pathway in the Web Tool. However if a user has created a pathway in the Web Tool and wishes to save it so as to make it available for further work or to make it available to another user, a convenient procedure is to record its url (which can be found on the Web Tool's 'share' chapter screen). This url, prefixed with the usual http://tool.globalcalculator.org/, can be used in the user's browser to relaunch the Web Tool, with the user-created pathway already selected. If this url has not been recorded, the only procedure which these authors have made to work is to identify the changes which have been made to one of the example pathways, and make the same changes manually (using the mouse) in the Web Tool. The resulting 'user-specified' pathway can then be used to generate the Web Tool outputs for that pathway (including the Sankey diagram and the url).

Outputs from the Calculator for a selected pathway

A useful presentation of the outputs in graphical form is the Sankey diagram, available only from the Web Tool version, which is obtained by clicking summary>energy>Sankey. Within this diagram, the magnitude of the energy flow in EJ along any one channel can be seen by clicking that channel in the diagram. These values are unfortunately not printable. A few key outputs in tabular form are given for the user-specified pathway and for a subset of the example pathways (seven in all) in the 'Compare' chapter of the Web Tool. Unfortunately this subset does not include many of those that might be of interest to new users.

The Spreadsheet version gives a much larger range of outputs, most of which can be accessed in the 'Lever graphs' or other tabs of the spreadsheet. Tables containing the numerical values which are used to construct the Web Tool graphs are given in the 'Web Tool graphs' tab, mostly at 5-year intervals. Tables giving a lot of further summary data are given in the 'Outputs' tabs with green labels. Particularly useful is the 'Outputs-Emissions' tab, which gives a breakdown of the emissions by type (CO_2, methane etc.) and by source (fuel combustion, agriculture, land use etc). Some of the later tabs are rather sparsely populated, suggesting that there is still 'work in progress' here.

A cautionary note

The Calculator gives the user the option of recalculating all the values in all the Spreadsheets either immediately after any change has been made to any formula, or only at user-specified intervals. Since the process of recalculating is quite time-consuming (often taking over a minute), the default setting is to do so only when the user so specifies (by pressing the key F9 or the 'calculate' button at the bottom left corner of the screen). Although this default is generally sensible, it is liable to mislead a user who normally uses Excel in the 'immediate calculation' mode, because it leads to numbers on the screen in certain cells which have not yet been recalculated and may therefore be quite wrong. For example if the user tries to sum all the columns in a Spreadsheet table, by using the procedure of entering the summation formula in the first column, and then 'copying it across', leaving Excel to amend the formula for subsequent columns, the formula will be amended correctly, but the amended formula will only be acted on after the whole

Spreadsheet has been recalculated. To change the default, the user should follow the sequence file>formulas>calculation options and choose between ‘automatic’ and ‘manual’.

Comments on outputs from the DECC’s ‘Example Pathways’

We have noted that there are some weaknesses in the ‘compare’ chapter of the Web Tool outputs, so in this paper we give a more complete comparison of all 26 Example Pathways. An Excel table giving the lever values for all 48 levers for all 26 Example pathways is given in Annex 2. An Excel table giving selected input and output parameters for all 26 Example pathways, listed in the order in which they appear in both the Web Tool and the Spreadsheet version (but adding back in the two World Nuclear Association pathways which are for some reason omitted from the Spreadsheet version) is given in Annex 3. In Annex 4, the Annex 3 table is sorted by the temperature increase in 2100 which is forecast by each pathway. We would like to draw attention to the following points:

1. The order in which these examples are presented within the Calculator is rather arbitrary. The first four are ‘in-house’ pathways, designed by the team which created the Calculator to exhibit four quite radically different pathways which can almost meet the goal of a rise in surface temperature of less than 2 ^{0}C by 2100. In fact none of them quite meets that target (the estimated rises lie in the range 2.15 to 2.45 ^{0}C), but all four have a 50% chance of keeping the temperature rise below 2.5 ^{0}C.

- The ‘Distributed effort’ pathway seeks to spread the task of decarbonising the system fairly evenly across all sectors - lifestyle, transport, buildings & electricity generation
- The ‘Consumer reluctance’ pathway avoids imposing major new technologies on consumers
- The ‘Low action on forests’ pathway excludes the expansion of afforested land (which would otherwise greatly assist in achieving the 2 ^{0}C target), and thus makes necessary a higher level of electrification
- The ‘Consumer activism’ pathway responds sympathetically to know consumer concerns (nuclear waste, GM crops, industrial farming practices, excessive car ownership, energy-intensive farming).

The remainder reflect the preoccupations of the various organisations that designed them. As seen in Annex 4 , only four of the Example pathways actually give estimated temperature rises below 2 ^{0}C, and these four all have features which reduce their credibility – notably large proposed changes in dietary patterns (reduced average per capita consumption of calories and red meat), and large improvements in agricultural practices. At the other end of the scale, ten of the pathways have temperature rises exceeding 2.5 ^{0}C, in one case by over 6 ^{0}C! The remaining 12 pathways almost all rely on a mixture of renewable technologies and consumer restraint to keep the temperature rise within bounds.

For the purposes of this paper, we have followed the practice adopted in the British Pugwash study on UK Energy policy, and we have selected three pathways which represent (but not necessarily in an optimal way) three very different global strategies:

1. **High nuclear** strategy. In this case, only one relevant Example pathway is available – the World Nuclear Association’s Allegro pathway, which has an installed nuclear capacity of 1870 GWe, with an assumed 85% load factor, giving 1589 GWav or 49 EJ/year delivered to the grid.

2. **High renewable** strategy. Most of the Examples also have a significant increase in the nuclear component of the overall supply, so we have chosen the Climact pathway which has only 342 GWe of installed nuclear capacity – i.e. roughly the same as its 2011 value – and about 8000 GW of renewable capacity.

3. An **intermediate** strategy, which includes a significant contribution from CCS. From a short list of eight Examples, we have chosen ICEPT, which has a broadly spread supply portfolio in 2050, with installed capacities of 4231 GW of wind, 4149 GW of solar, 685 GW of nuclear and 988 GW of CCS. The corresponding figures for annual electrical energy supply to the grid are:
43 EJ of wind, 37 EJ of solar, 17 EJ of nuclear and 10.5 EJ of CCS (which sequesters 2 Gt of CO_2)

The urls for these three pathways are:
WNA Allegro:
http://tool.globalcalculator.org/globcalc.html?levers=22qqo223422j2222q33pqt43343oq322223h32333q11111f32211111111/dashboard/en
Climact:
http://tool.globalcalculator.org/globcalc.html?levers=22333333333333333331331fnnnnnn333222222d111112s2211111111/dashboard/en
ICEPT:
http://tool.globalcalculator.org/globcalc.html?levers=22rfzhgw33bee331dzzn2j33p2sn33jy2332322p2f11111232211111111/dashboard/en

A summary table giving some of the most important input and output parameters for these three 'representative' pathways is given in Annex 5. The reader will be able to infer that we have had some difficulty in compiling this summary:

- There is no output table in either the Web Tool or the Spreadsheet versions of the Calculator which gives all the information in a single set of units, and using the same energy conventions. The Calculator has (to our great relief) decided to use a single energy unit (the ExaJoule) for almost all purposes. However in its summary tables, it departs from this convention in places, and uses installed capacity in GW, without specifying the energy form involved or providing easily accessible information about the factors used by the model to convert these to energy actually delivered to the end user (or to the electric grid). We have managed to infer that the energy conventions are:
    - 'Primary supply' figures presented in EJ are normally the annual amounts of energy (mechanical or thermal) provided by that primary source to a generator of electricity. The losses incurred in the subsequent conversion process, and those resulting from equipment down time, intermittency in the availability of renewable sources, and transmission losses between the generator and the user are then accounted for separately. The energy flow between the primary source (which can be calculated with reasonable precision) and the end user is quite complex, and involves the merging and de-merging of energy flow streams
    - The various loss or unavailability figures are calculated by the model using some relatively crude global average figures (which nevertheless distinguish different types or vintages of equipment in a reasonably precise way). These can mostly be discovered by searching the relevant tables in the Spreadsheet version, but little explanation is given about the way in which these global averages have been derived.
    - The net energy flows are then merged into three relatively distinct blocks – energy supplied direct to the end user (e.g. as fuel for transport or home heating), input to electric generation facilities, and losses. Supplies to the end user are then broken down into four main blocks (buildings, manufacture, transport and agriculture), with at most a small number of end users which are not so readily classified. There are minor complications such as energy converted to hydrogen, district heating, and carbon capture and storage facilities, which do not readily fit into

this simple scheme. However the broad outline is well presented in the Sankey diagrams shown in Annex 6. In these diagrams, the magnitude of the energy flow is approximately represented by the width of the flow path, but can be quantified if the user wishes by pointing the mouse arrow at the flowline, and reading the number shown on the screen (there is unfortunately no easy way to print these numbers out).

    - In theory the sum of the primary supply figures should equal the sum of the end user outputs, after taking account of the conversion losses, which are gathered together as one extra 'end user' called 'losses'. As Annex 5 shows, the Calculator does in some approximation represent the law of the conservation of energy. Discrepancies are at the 2% level. It is not easy to pin down the source of these discrepancies, since the Calculator does not output a table giving the discrepancy on any individual flow line (unlike the UK Pathways to 2050 Calculator, which did). It is perhaps significant that the two Sankey diagrams generated by the Web Tool for each pathway – one more detailed than the other – do not exactly agree on many of the figures. The Calculator wisely informs the reader in its notes that the Sankey diagrams are "work in progress".
- The information output on emissions, and on the implications of these for the global climate, are also not brought together except at the most global level.
    - The calculation of emissions of CO_2 and the other main Greenhouse Gases are undertaken in considerable detail in the Spreadsheet version (see the tab labelled G.2050 emissions) which has a table running to 387 lines showing how this is done for each type of facility. This table is unfortunately rather sparsely populated, and the user may find the information given in the tab 'Outputs-Emissions' more helpful (see especially the summary table in lines 27-54). The Spreadsheet unfortunately lacks a clear explanation of the way in which either the Carbon Capture and Storage figure or the Bioenergy credit figure are calculated, though an expert on Excel programming may get some enlightenment from lines 4238 to 4330 of the 'Lever graphs' tab. CCS does not feature in the Sankey diagrams, and bioenergy is not given a detailed breakdown.
    - The total emissions of GHGs are presented on a quinquennial basis, and are summed to give two cumulative figures – one up to 2050 and one (more speculative) up to 2100, assuming that the trends over the 15 years up to 2050 can be extrapolated to 2100. The summary output in the Web Tool version gives the annual figure for the year 2050 and the cumulative figure up to 2100. These are shown for our three 'representative' pathways in Annex 5.
    - The implications of these (hopefully reasonably accurate) figures for GHG emissions up to 2100 are the starting point for estimates of the global average rise in temperature. As noted earlier, these estimates have considerable 'error bars' attached. Nevertheless, they try to take account of the most recent guidance from the IPCC. The numbers shown in Annex 5 for the three 'representative pathways' are the average of the range of values reported in both the Summary table on the first page of the Web Tool and also in the 'Outputs – Climate Impact tab of the Spreadsheet version, which gives more detail on how the figures for the four main greenhouse gases are aggregated.
    - We do not claim that the three 'representative' pathways have been optimised in any way, and although we have made some initial attempts to 'improve' each of them so as to get its estimated temperature rise below the target of 2 ^{0}C, this has so far been without success (see below). However we do not regard the difference between them as being significant – in each case the average value quoted is within one standard deviation of 2 ^{0}C.

Limitations of the current version of the Calculator

In our attempts to 'improve' the 'representative' pathways we have encountered a number of limitations of the Calculator in its present form. These are not presented in any critical spirit – they are essentially suggestions for further improvements in later versions.

1. The Calculator uses a number of advanced Excel functions, for reasons which are explained in Annex A of the Spreadsheet user guide. Those reasons are cogent, but they result in much of the coding being unintelligible to any but the most expert of Excel users. Other users either have to take the calculations on trust, or need to be provided with comments which explain in lay language what is going on. Many more such comments are needed.

2. In the absence of such comments, the user needs some means of checking whether the results of any given calculation are credible. One obvious check is to ensure that the code is respecting the law of conservation of energy. As mentioned above, the Sankey outputs give some reason to question this. So a table (such as that provided in the Pathways to 2050 software) which flags up any non-conservation would be helpful.

3. The treatment of 'unabated fossil fuel technologies', which is very briefly explained on p24 of the Spreadsheet user guide, remains deeply puzzling to these authors. That paragraph suggests that the Calculator "builds" unabated thermal plants to make good any shortfall in the electricity supply coming from renewable or CCS sources if the system otherwise fails to meet the demand specified by the user. The technical characteristics of this additional plant are defined by a crude formula, and there is no source of clear information about how this procedure has worked in any particular case. It certainly contributes to some unexpected outputs.

4. Equally obscure is the treatment of CCS within the system. The amount of CCS capacity is specified by the user in levers 22 and 25. It is conspicuous that most of the authors of the Example pathways do not venture beyond the level 2 lever setting, and if they do, they stick to integral values. CCS is not mentioned in the Sankey diagrams, and the references to it in the G40 tab are not very illuminating.

5. The treatment of BioEnergy generally, and in particular the Bioenergy credit is not explained. Unlike the 'Pathways to 2050' software, it does not get a separate line entry in the list of Primary energy inputs (eg in the Sankey diagrams).

6. The almost complete absence of any reference to variations as between geographical regions, and the consequent need for (and potential benefits of) energy distribution networks (long range grids & pipelines) are hardly mentioned. The word 'oversupply' does appear in the G2050 energy tab, but is not explained.

7. The difficulties in exchanging pathway data between the Web Tool and Spreadsheet versions of the Calculator software are frustrating. In our view, there should either be a significant enhancement in the Web Tool version, so that it is genuinely free-standing, or a considerable improvement in the speed and convenience of making transfers of user-generated data from the Spreadsheet version to the Web Tool. Ideally, entry of user data into the Web Tool by typing it in should be made as easy as in an Excel Spreadsheet. Alternatively the mouse entry system could be made faster and more user-friendly (it takes over a minute to change one lever value at present). There should also be a substantial improvement in the

number and design set of outputs which can be accessed directly within the Web Tool. Sorting out the oddities in the Sankey diagrams should also be a priority.

A "business as usual" scenario should be provided. This could be the standard reference scenario and would permit a comparison of the costs and efforts involved in different user-specified energy plans.

Notwithstanding all these problems, we have made a serious effort to design some new pathways to complement those in the 26 Examples, mostly aimed at producing three illustrative pathways which met the 2 ^{0}C target. Our work consisted largely in treating the Calculator as a black box, and seeking to understand the changes in outputs resulting from experimental changes in the values of the input levers. We encountered several examples of unexpected findings:

- Starting with the WNA Allegro pathway, we changed the nuclear power capacity from level 4 (1870 GW) to level 3 (1030 GW) and made no other change. This only increased the temperature rise from 2.45 to 2.50 ^{0}C, whereas the unabated fossil fuel power increased from 0 to 2204 GW. We had expected a much larger temperature rise from the withdrawal of a large amount of low-carbon primary energy, and the need for back-up fossil fuel power to be at least partially abated by CCS.
- There seem to be a problematic interplay between the Diet levers and electricity production
  - Using the Friends of the Earth model, increasing the 'amount of calories consumed' lever up to 4.0 results in an unexplained warning of oversupply of electricity!
  - Using the ICEPT pathway, switching the 'type of meat' lever from 3 to 4 again results in a warning of oversupply of electricity.
  - Using the WNA Allegro Pathway, switching the 'quantity of meat' lever from 2 to 3 again results in overproduction of electricity.
  - Using the Climact model, switching either the 'quantity of meat' or 'type of meat' lever from 3.0 to 4.0 results in the electricity overproduction message.
- There are not sufficient levers to represent actions taken to cope with intermittency of renewables, or the need for storage, backup and electrical interconnections between different geographical regions. There is one lever 'Storage and demand shifting' with a maximum storage of 1200GW (4.0 lever position). However its impact seems to be negligible.
- There is a set of diagrams, and a set of supporting tables in the 'Outputs-Costs' tab, related to Cost, which are calculated on a basis which is so convoluted that the result is of little value to the average user. In the Web Tool version, there is a high-level summary graph, in which the 'total system cost' (meaning the cumulative capital, operating and fuel costs up to 2050) is presented. In addition some further breakdown is shown in the 'capital, operating, fuel' section. These 'costs', together with a figure for error estimates, are then compared to a reference scenario that can be chosen by the user, and the result is then expressed as a percentage of GDP more or less than that of the chosen reference scenario. A comparison with a "business as usual" scenario (as suggested above), would be more helpful. In addition, estimated absolute costs in pounds or euros evaluated at some specified date should be given. To be relevant, these costs should include the additional cost of maintaining and operating backup power plants, electrical interconnects and storage facilities. One can also question how storage costs are calculated – the influence on the % of GDP of changing the 'storage and demand' lever seems rather small.

In general, it is very difficult to predict the consequences of individual changes in one lever because of the interactions with other levers, or with the effects of rather arbitrary procedures such as those mentioned in paras 3-5 above. An illustration of this difficulty is provided by the two example pathways entitled 'Chatham House – High Meat' and 'Chatham House – Low Meat'. These names give the rather misleading impression that the only difference between the two sets of levers lies in the levers relating to the production and consumption of meat. In fact, the very significant difference in the total emissions of the two pathways (65.9 and 21.3 Gt of CO_2e respectively) is by no means entirely attributable to the different settings of the meat levers. As the table of lever settings in the Spreadsheet version (given in the 'User inputs' tab, columns AD and AE) shows, there are several other lever settings which also differ significantly – notably those relating to nuclear power, CCS abated fossil fuel combustion, electrification of transport and building heating. An indication of the eventual consequences of these settings for the emissions is give in the Outputs – emissions tab column X lines 46-54. One conspicuous contribution, though less than half of the total difference in emissions, comes from a large increase on the area of afforestation, made possible by the release of agricultural land no longer required to support meat production.

Conclusions

The Global Calculator is possibly the best attempt published to date which seeks to model the production and use of energy in our modern global society, and its influence on climate. Although there is still a great deal of improvement possible, notably in the documentation of its inner clockwork, it exhibits many of the complexities in decisions related to climate and energy.

We would like to see this model enhanced so that it can be used with confidence by the general public, or at least by those who have some basic knowledge of spreadsheet software. But perhaps even so it is too complex? Is there a danger that it would be used to draw over-hasty conclusions? Perhaps it could be the starting point for a much simpler version, which would at least give the public a feel for the intricacies in decision-making, and enable them to check out assertions made by politicians and the mass media? If that were possible, it would be a most useful contribution to the debate.

One main conclusion which we have drawn from using this tool as it stands is that is it not at all simple to keep within the 2 ^{0}C goal, unless one is prepared to make draconic changes in the global system of energy production and use, in the insulation and heating of houses, in public and private transport, forestry, global dietary practices and agriculture etc. The need for such changes will be intensified by the growth in the global population, and by the trend towards evening-up the standard of living of the whole global population. Most of these pressures are familiar to politicians, planners and voters alike, even by those who prefer to turn a blind eye to them. But the Calculator already has a few insights to offer which may be found surprising:

1. The relative impact of different levers on CO_2 emissions and the rise in temperature.

Looking at the table of lever values selected in the 26 Example pathways (Annex 2), it is striking that the overall average lever value is about 2.2, with a relatively minor variations between the different 'blocks' from 1.9 for traffic to 2.4 for land/food/bioenergy. Thus most of the pathway authors, in their efforts to minimise the rise in temperature, have had to propose measures which the creators of the Calculator regard as lying between 'ambitious but achievable' and 'very ambitious but achievable'. No one group of measures is generally perceived to be much more worthwhile than the others. The implication is that the final choice of strategy to save the planet will have to be a political one, since any one of the very diverse technical solutions (e.g. ranging from the high nuclear to the high renewable ones) could probably be made to work.

2. The authors of the Calculator have not really addressed the issues which British Pugwash faced when considering a 'Pathway to 2050' for the UK in isolation. We found that each of the three pathways which we considered had at least one potential 'showstopper' which might rule it out, and that urgent action was required to continue R&D on all three pathways until their technical feasibility was established. The Calculator essentially assumes that any technical problems with any of the proposed pathways could be solved on the relevant timescale. Most of the Pugwash 'showstoppers' were either economic or related to the timescale for developing and proving new technology at the Gigawatt level. These issues are not really considered in this model or the associated documentation.

3. The authors of the Calculator have published their own 'insights from the Global Calculator'[22].
Their conclusion is that 'Prosperous living for the world in 2050' is fully possible, but it will require the global community:

- to transform the technologies and fuels we use: for example, the amount of CO_2 emitted per unit of electricity generated globally needs to fall by at least 90% by 2050. Also, the proportion of households that heat their homes using electric or zero-carbon sources should rise from 5% today to 25-50% globally by 2050.
- to make smarter use of our limited land resources: in particular, we must protect and expand our forests globally by around 5-15% by 2050 because forests act as a valuable carbon sink.
- to ensure that these changes are rolled out: strong leadership from businesses, civil society and politicians is essential to support urgent action to cut emissions through an ambitious global deal in the December 2015 United Nations Framework Convention on Climate Change (UNFCCC) negotiations.

We can certainly endorse all of these conclusions.

[22] https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/398596/Global_calc_report_WEB.pdf

ANNEXES

Annex 1 List of the 48 levers of the model, together with their current values

Lever No	Description	Situation today (data taken from Global Calculator V3.99.2)
1	Global population	In 2011 the world population was around 6.97 billion.
2	Urbanisation	In 2011, 52% of the world's population lived in urban areas.
3	Passenger distance	In 2011, the weighted average distance travelled per person was around 9200 km / year
4	Freight distance	In 2011 freight travelled 85 trillion tonne-km
5	Mode	In 2011, 38% of all domestic km travelled by urban passengers were by car
6	Occupancy and load	In 2011 the average urban car carried 1.6 people
7	Car own or hire	In 2011 the average urban car travelled 15,000 km/year, with little use of hired, shared or self-driving vehicles
8	Efficiency	In 2011 the average urban passenger car used 8.6 litres/100 km
9	Electric and hydrogen	In 2011 5% of global fleet used hybrid technology, 0.2% used 100% electric cars and very few used hydrogen
10	Building size	Average urban house floor area was 92 m^2 per household: service buildings 5 m^2per capita
11	Temperature & hot water use	Winter: 17.5^{0}C for urban and 13 ^{0}C for rural residential, 20 ^{0}C for non-residential. Summer figures were 26.5, 29 and 23 ^{0}C. Hot water demand was 18263 litres/year/capita
12	Lighting, cooking & appliance use	Average household has 1 fridge, 0.8 clothes-washers, 0.3 dishwashers, 0.3 clothes dryers, 1.6 TVs and 20 lightbulbs
13	Building insulation	The average heat loss coefficient for buildings was 16.9 GW/Mha^{0}C
14	Temperature, cooking & lighting technology	Heating technology mix was 2% solid boiler, 14% liquid boiler, 55% gas boiler, 2% heat pumps, 8% electric heater, 0% solar, 2% micro CHP, 17% district heating. Lighting: 72% incandescent, 3% halogen, 25% CFLs, 0% LEDs
15	Appliance efficiency	Average appliance use: fridge 100W, dishwasher 1500W, clothes washer 700W, clothes dryer 1500W, TV 250W, miscellaneous 100W
16	Product lifespan	In 2011 the average lifespan of an urban 4-wheeled car with an internal combustion engine was 12.5 years
17	Design, material switch & recycling	In 2011 Production required 1.5 Gt of crude steel, 0.1 Gt of aluminium, 0.7 Gt of chemicals, 0.6 Gt of paper, 0.8 Gt of timber, 0.3 Gt of cement, 1Gt of other materials
18	Iron, steel & aluminium	Specific emissions: 1.97 $GtCO_2$/Gt of steel, 0.9 for Al
19	Chemicals	Specific emissions: 1.09 $GtCO_2$/Gt of materials
20	Paper and other	Specific emissions: 0.95 $GtCO_2$/Gt of paper, other materials 2.2
21	Cement	Specific emissions: 0.41 $GtCO_2$/Gt of materials
22	Carbon capture and storage (ind.)	In 2011 zero
23	Coal / oil / gas	In 2011, 61% of total fossil power supplied was by coal/biomass, 7% by liquid, 32% by gas
24	Fossil fuel efficiency	In 2011 8% of coal-fired stations used ultra-supercritical technology, 17% supercritical and 75% subcritical technology: of liquid fuelled, 30% were >50% efficient, 70% <50%: of gas-fuelled, 35% were open cycle 65% combined cycle.
25	Carbon capture and storage (power)	In 2011 only small demonstration projects

26	Nuclear	In 2011 global nuclear capacity was 364 GW
27	Wind	in 2011 234 GW of onshore wind capacity (in 83 countries) and 4 GW of offshore capacity
28	Hydroelectric	in 2011 global hydroelectric capacity was 970 GW
29	Marine	in 2011 there was 0.5 GW of tidal power, but there is a pipeline of projects coming in early 2020s
30	Solar	in 2011 there was 71.3 GW of installed solar capacity (69.7 GW photovoltaic, 1.6 GW of concentrated solar)
31	Geothermal	in 2011 global geothermal capacity was 11.56 GW (centred in 24 countries). Large potential in 'ring of fire' around the Pacific Ocean
32	Storage and demand shifting	in 2011 there was 120 GW of installed capacity of electricity storage plants (mostly in OECD). There is a large need for interconnects to enable peak demand to be met by intermittent renewable technologies elsewhere (solar & wind)
33	Calories consumed	in 2011 Average consumption was 2180 kcal/person/day, but with strong regional variations
34	Quantity of meat	in 2011 global average meat consumption was 187 kcal/person/day, but this is increasing, particularly in the developing world
35	Type of meat	in 2011 22% was beef, lamb and goat, 78% pork, chicken & other poultry
36	Crop yields	Between 1987 and 2007 yields increased globally by 1.9% pa, but since then growth rate has decreased. Currently the average food energy yield is 0.1 W/m^2
37	Land-use efficiency	Scope for smarter land-use techniques such as multi-cropping and integrated agro-livestock-forestry schemes to increase productivity
38	Livestock (grains/residues fed)	Scope for moving livestock from pastureland into feedlots (confined systems that are more efficient at converting food to meat) and using more efficient breeds of animal e.g. in 2011, around 6% of cattle meat was produced from feedlots.
39	Livestock (pasture fed)	Currently cattle density is 0.6 animals/hectare, and 3.1 animals/hectare for sheep & goats.
40	Bioenergy yields	Currently the average biocrop yield is 0.4 W/m^2 , equivalent to 6.7 dry tonnes/hectare for woody energy crops
41	Solid or liquid	Currently 60% of biofuels are solid (eg wood chips) and 40% liquid (bioethanol and biodiesel)
42	Surplus land (forest & bioenergy)	Land not required for food production could be used for growing biocrops or for regeneration of forests & grassland
43	Biochar	In 2011 biochar technology was not used to remove CO_2 from the atmosphere
44	Direct air capture	In 2011 direct air capture was not used to remove CO_2 from the atmosphere
45	Ocean fertilisation	In 2011 ocean fertilisation was not used
46	Enhanced weathering (oceanic)	Technically demonstrated (eg in submarines), but not yet used on a large scale
47	Enhanced weathering (terrestrial)	Nationally approved experiments inconclusive
48	Wastes and residues	Estimated 25% of energy content of total food production is wasted (e.g. through damage in transit, improper storage, or consumers throwing it away), and wasted on-farm residues are equivalent to a further 100%, but are not easily collected

Annex 2 Lever choices for 26 Example Pathways

Level	Description		Distr ffort	Cons eluc	Low orest	Cons activ	IEA 6DS	IEA 4DS	IEA 2DS	Shell Mou	Shell Ocea	Frien Earth	Mott McD	Clim-act	IC-EPT	RCP 8.5	RCP 6.0	RCP 2.6	TIAM 4DS	TIAM 2DS	WEC Jazz	WEC Symp	Vegn	Camb	Chat low	Chat high	WNA Alleg	WNA Largo
1	Global population		2	2	2	2	2	2	2	2.2	2.2	3	2	2	2	1.6	2.2	2.5	2.1	2.1	2.7	1.9	2	2.5	2	2	2	2
2	Urbanisation		2	2	2	2	2	2	2	2	2	2	2	2	2	3	1.9	1	2	2	1.8	2.3	2	2.5	2	2	2	2
3	Passenger distance		2.7	2.7	2.7	2.7	2.7	2.7	2.7	2	1	3	3	3	2.7	1	1.5	2.6	3	3.2	2.7	2.7	2	2.8	2.7	2.7	2.6	2.6
4	Freight distance		1.5	1.5	1.5	1.5	1.5	1.5	1.5	2.1	1.3	3	3.8	3	1.5	1	1.5	2.1	3.3	3.5	1.5	1.5	2	3	1.5	1.5	2.6	2.6
5	Mode		2.4	2.4	2.4	3	2.4	2.4	3.5	3	2	4	3	3	3.5	1	1.5	2	1.8	2	2.3	3.3	1.9	2.5	2.4	3.5	2.4	2.4
6	Occupancy and load		1.4	1.4	1.4	2	1.4	1.4	1.7	2	2	4	2	3	1.7	1	1.4	2	1.8	2	1.4	1.6	1.9	3	1.4	1.7	2	2
7	Car own or hire		2	2	2	2.4	2	2	1.6	2	2.2	3	2	3	1.6	1	1.4	2	1.8	2	2	2	1.9	2	2	1.6	2	2
8	Efficiency		2.8	2.8	3	3	1.4	1.8	2.8	1	3	4	3.8	3	3.2	1	1.3	2.3	2.6	3.8	1.1	2	2	2.5	1.8	2.8	3	3
9	Electric and hydrogen		2.8	2	3	3	1	1.1	1.8	3.2	2.1	4	2	3	3	1	1.1	2	2.5	3.7	1.1	2.5	1	3	1.1	1.8	4	3
10	Building size		3	3	3	3	3	3	3	4	3	3	3.8	3	3	1	2.2	1.5	1.8	2.5	2	2.4	2	2.5	3	3	2	2
11	Temperature & hot water use		1.1	1.1	1.1	1.1	1.1	1.1	1.1	2	2	3	3	3	1.1	1	2.2	1.5	2	2.5	1.1	1.1	2	3	1.1	1.1	2	2
12	Lighting, cooking & appliance use		1.4	1.4	1.4	1.4	1.4	1.4	1.4	1	1	4	3	3	1.4	1	2.4	1.5	2.5	3	1.3	1.3	2	3	1.4	1.4	1.9	1.9
13	Building insulation		2.8	2	3	3	1	1.2	1.4	1	1	4	2	3	1.4	1	2.8	1.2	2	2.5	1	1.4	1.6	3	1.2	1.4	2	2.9
14	Temperature, cooking, lighting		2.8	2	3	3	1	1.3	3	1.5	2.5	4	2.5	3	3	1	2.6	1.9	1.5	3.8	1	2.4	1.5	3	1.3	3	2	3
15	Appliance efficiency		2.8	3	3	3	1	1.3	3	3	4	4	3.8	3	3	1	2.7	1.6	1	3	1	2.4	1.6	3	1.3	3	2	3
16	Product lifespan		1	1	1	2	1	1	1	1	1	4	2.5	3	1	1	2	2.9	1.2	1.5	1	1	1.4	2.5	1	1	2	2
17	Design, material switch & recycling		2.8	2	3	3	1.2	1.4	1.9	2	2	4	1.3	3	1.3	1.2	1.9	3	1.5	2	1.9	3.5	1.1	2	1.3	1.3	2.6	2.6
18	Iron, steel & aluminium		2.8	3	3	2	2	2.5	3.3	3	3	3	3.5	3	3.5	1	1.9	2.8	2	3.9	3.3	3.5	1.5	2.6	2.7	3.5	3	2.6
19	Chemicals		2.8	3	3	2	1.2	2	3	3	3	3	3.5	3	3.5	1.1	2	2.9	2.5	3.2	3	3.5	1	2.6	1	3.5	3	2.6
20	Paper and other		2.8	3	3	2	2	2.5	3.3	3	3	3	2.3	3	2.3	1	1.9	2.9	2.4	3	3.3	3.5	1.9	2.6	1.7	2.3	2.5	2.5
21	Cement		2.8	3	3	2	1.2	2	2.5	3	3	3	2	3	2	1	1.9	2.9	1.9	3.9	2.5	3	1.6	2.6	1.7	2	2.6	2.6
22	Carbon capture and storage (ind.)		2.8	3	3	2	1	1.2	3	2.5	1.2	1	2	1	1.9	1	1	3.7	1	3.8	1.1	2.1	1	1.5	1.2	1.9	2.9	2
23	Coal / oil / gas		2.8	3	3	3	2.3	2.5	3.8	2	3	4	2.5	3	3	1.2	2.8	2.5	2	3	1	2	1.8	3	2.5	3.8	4	3
24	Fossil fuel efficiency		2.8	3	3	3	3	3	3	3	4	4	3	3	3	3.4	3	2.5	2.5	2.5	3	3	1.6	3	3	3	3	3
25	Carbon capture & storage (power)		2.8	3	2	3	1	1.4	3	3.5	1.9	1	2	1	2.5	1.1	1	3.7	1	2.1	1.8	3.1	1.2	1.5	1.4	3	3	2
26	Nuclear		2.8	3	2.8	2	1.7	2	3	3	1.7	1	2	1.5	2	1.8	1.1	1.7	2	3.5	1.6	2.6	1.9	2	2	3	4	3
27	Wind		2.8	2.7	3	2	1.5	1.8	2.1	2	2.4	2	2.4	2.3	2.8	1.7	1.6	1.7	1.3	1.6	1.8	1.7	1.6	2.8	1.8	2.1	3	2.6
28	Hydroelectric		2.8	2.7	3	2	1.9	2.1	2.3	1.6	1.6	1	1.5	2.3	2.3	2.4	1	1.6	1.1	1.9	1.7	3.2	1.9	3	2.1	2.3	2.4	2.4
29	Marine		2.8	2.7	3	2	1.3	1.6	2.4	1	1.1	2	1	2.3	3	1.6	1	1	1	1	1.6	2.4	1.4	3	1.6	2.4	2.6	2.6
30	Solar		2.8	2	3	3	1.2	1.5	2.4	3.2	4	3	2.1	2.3	3	1.9	1.4	1.3	2.3	2.9	1.7	3	1.4	1.9	1.5	2.4	3	2.7
31	Geothermal		2.8	2.7	3	2	1.4	1.6	1.9	1.3	1.4	2	1.5	2.3	1.9	1.6	1	1	2.7	3.6	1.8	1.6	1.4	3	1.6	1.9	2	2
32	Storage and demand shifting		2.8	2.7	3	2	1.5	1.8	2.5	3	4	4	2	2.3	3.4	1.8	1	1	1	1	1.7	2.2	1.5	3	1.8	2.5	2	2
33	Calories consumed		2	2	2	2	2	2	2	2	2	2.2	2.5	3	2	2	3	3.4	2.5	3	2	2	3.9	2.5	3	1	2	2
34	Quantity of meat		2	2	2	2.2	2	2	2	2	2	3.4	2.1	3	3	3	3	3	2.5	2.5	2	2	3.9	2	3	1	2	2
35	Type of meat		2	2	2	3	2	2	2	2	2.4	3.2	2.5	3	3	3	3	3.3	2.5	2.5	2	2	3.9	2.9	4	1	3	3
36	Crop yields		2.8	3	2	2	1.7	2.7	3	2	2.5	1	2	2	2	2.8	2	3	2	2	2.5	3	3.9	2	3	3	1.7	1.7
37	Land-use efficiency		2.8	3	3	3	2.5	3	3	3	3	2	2.7	2	3	2.8	1	3	2.5	2.5	2.5	3	3.9	2.5	3	3	3	3
38	Livestock (grains/residues fed)		2.8	3	2	1.5	2	2	3	2.2	2.4	1	2.8	2	2	2.7	3	3	2	2	2	3	1	1	3	3	2	2
39	Livestock (pasture fed)		2.8	3	3	3	3	3	3	2.6	2.6	2.1	2.5	2	2	2	3	3	2	2	3	3	1	2.5	3	3	3	3
40	Bioenergy yields		2.8	3	3	2	3	3	3	2.5	2.5	1	3.6	2	2.5	1.4	1	2.3	2	3	3	3	2.3	2	3	3	3	3
41	Solid or liquid		2.8	3	2	2	1.5	1.9	2	1.5	2.9	2	3.8	2	2	3.6	2	2.5	2.5	2.7	1	1.1	2	1	1.9	2	3	3
42	Surplus land (forest & bioenergy)		2.8	3	3	2	2	3	1.5	3.9	4	1	2	1.3	1.5	2.8	1	3	1.7	1.8	2	1.5	2	2.5	3	1.5	2.6	2.6
43	Biochar		1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
44	Direct air capture		1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
45	Ocean fertilisation		1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
46	Enhanced weathering (oceanic)		1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
47	Enhanced weathering (terrestrial)																											
48	Wastes and residues																											

Annex 3 Outputs from 26 Example Pathways **Energies in EJ except where shown as GW Pathways shown in order of Web Tool index**

	Name of example pathway	Primary Energy Supply in 2050				Total	GW of CCS	Final Energy Demand in 2050				Total	GHG emissions and consequences			
		Nuclear	Heat	Renewables	Fossil	input	Abatement Capacity	Manu-facture	Transport	Buildings	Other	End-use	GHG emissions to 2100: Annual in 2050	GHG emissions to 2100: Cumulative 2100	Estim' Rise 2100	Possible Temp 2100 C
1	Distributed effort	68.1	11.5	309.5	238.4	627.5	1288	183.5	117.9	121	11.7	434.1	18.5	2892	2.25	1.2-3.3
2	Consumer reluctance	72.8	0	72.8	270	415.6	1487	207.2	120.7	129.2	12.1	469.2	19.8	2886	2.25	1.2-3.3
3	Low action on forests	68.1	0	297.4	451.4	816.9	490	175.1	112.4	116.3	12.2	416	20.9	2942	2.35	1.3-3.4
4	Consumer activism	48.9	0	274.6	451.4	774.9	1487	155.7	98.1	116.3	11.6	381.7	19.3	2949	2.15	1.1-3.2
5	IEA 6DS	28.2	0	72.8	731.4	832.4	16	246.5	168.7	180.1	16.1	611.4	84.3	7693	3.95	1.9-6.0
6	IEA 4DS	48.9	12.7	164.2	592.3	818.1	206	230.3	156.2	168.3	13.6	568.4	53.6	5512	3.05	1.5-4.6
7	IEA 2DS	28.2	17.5	248	264.6	558.3	1487	193.7	98.4	135.3	11.4	438.8	15.3	2677	2.10	1.1-3.1
8	Shell mountains	72.8	12.3	226.4	368.2	679.7	2594	192.8	142.9	130.7	13	479.4	32.2	3613	2.70	1.5-3.9
9	Shell oceans	35.5	15.9	410.8	285.3	747.5	443	208.9	134.1	119.6	12.4	475	28.2	3501	2.65	1.5-3.8
10	Friends of the Earth	0	6.8	211.3	75.2	293.3	1188	66.8	47.8	60.7	11.4	186.7	0.1	2214	1.70	0.8-2.6
11	Mott McDonald	48.9	10.7	239.5	144.7	443.8	490	155.9	74	89.8	10.9	330.6	15.9	2987	2.20	1.2-3.2
12	Climact	26	8.5	218.9	186.1	439.5	16	114.2	82.9	89.9	11.1	298.1	17.7	2882	2.15	1.1-3.2
13	ICEPT	48.9	17.5	279.4	274.8	620.6	988	214.2	87.4	135.3	12.7	449.6	19	2768	2.10	1.1-3.1
14	RCP 8.5	40.1	16.2	218.6	984	1259	63	349.8	255	230.3	17.7	852.8	88.3	8582	6.00	high
15	RCP 6	5.5	10.2	72.8	451.4	539.9	16	201.5	203.1	108.1	14.8	527.5	52.1	5598	3.00	1.4-4.6
16	RCP 2.6	35.5	15.6	221.7	445	717.8	3036	157.7	131	167.5	11.1	467.3	16.2	2766	1.60	0.6-2.6
17	TIAM UCL 4DS	48.9	10.1	182.2	586.5	827.7	16	213.6	113.7	151	13.6	491.9	58	5939	3.25	1.6-4.9
18	TIAM UCL 2DS	102.1	12.8	262.1	210.7	587.7	590	143.3	99.7	116.7	12.8	372.5	15	2999	2.15	1.1-3.2
19	WEC/PSI-Jazz	30.8	12.7	187.6	600.7	831.8	395	191.4	171.9	180.2	13.4	556.9	54.6	5634	3.00	1.4-4.6
20	WEC/PSI-Symphony	63.3	16.3	250.2	288.1	617.9	1708	145.4	121.5	150.4	11.3	428.6	20.9	3095	2.25	1.2-3.3
21	The Vegan Society	44.5	12.1	298.3	563.7	918.6	111	242.3	160.2	150.7	10.5	563.7	18.9	2798	0.90	-0.1-+1.9
22	Cambridge Architectural Soc	48.9	8.2	236.8	203.6	497.5	253	142.3	97.3	85.1	11	335.7	22.8	3193	2.40	1.3-3.5
23	Chatham House - low meat	48.9	12.7	309.9	463.4	834.9	206	246.4	156.2	168.3	12.9	583.8	21.3	3584	1.85	0.7-3.0
24	Chatham House - high meat	72.8	17.5	209.2	333.1	632.6	1487	213.3	98.4	135.3	12.2	459.2	65.9	6460	4.00	2.2-5.8
25	World Nuclear Assn (Allegro)	131.1	11.9	258.2	240.8	642	1487	170.7	96.8	136.1	13.2	416.8	22.5	3003	2.45	1.4-3.5
26	World Nuclear Assn (Largo)	72.8	11.1	235.5	253.5	572.9	490	168.3	102.1	112.9	12.9	396.2	27.5	2950	2.55	1.5-3.6

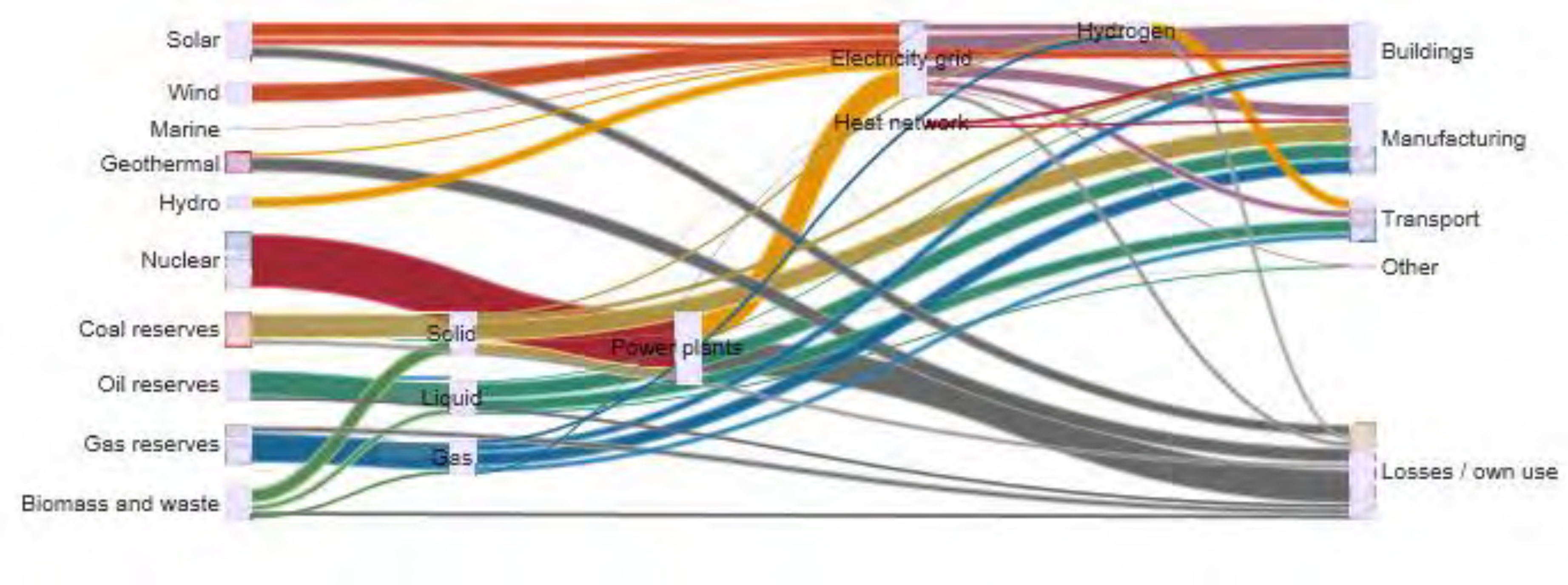
Annex 4 Outputs from 26 Pathways **Energies in EJ except where shown as GW Pathways listed in order of increasing temperature rise**

	Name of example pathway	Primary Energy Supply in 2050					GW of CCS	Final Energy Demand in 2050					GHG emissions and consequences			
		Nuclear	**Heat**	**Renewables**	**Fossil**	**Total input**	**Abatement** capacity	**Manufacture**	**Transport**	**Buildings**	**Other**	**Total End-use**	**GHG emissions to 2100** Annual in 2050	Cumulative 2100	**Estim'** Rise 2100	**Possible** Rise C 2100
21	The Vegan Society	44.5	12.1	298.3	563.7	918.6	111	242.3	160.2	150.7	10.5	563.7	18.9	2798	0.90	-0.1-+1.9
16	RCP 2.6	35.5	15.6	221.7	445	717.8	3036	157.7	131	167.5	11.1	467.3	16.2	2766	1.60	0.6-2.6
10	Friends of the Earth	0	6.8	211.3	75.2	293.3	1188	66.8	47.8	60.7	11.4	186.7	0.1	2214	1.70	0.8-2.6
23	Chatham House - low meat	48.9	12.7	309.9	463.4	834.9	206	246.4	156.2	168.3	12.9	583.8	21.3	3584	1.85	0.7-3.0
7	IEA 2DS	28.2	17.5	248	264.6	558.3	1487	193.7	98.4	135.3	11.4	438.8	15.3	2677	2.10	1.1-3.1
13	ICEPT	48.9	17.5	279.4	274.8	620.6	988	214.2	87.4	135.3	12.7	449.6	19	2768	2.10	1.1-3.1
4	Consumer activism	48.9	0	274.6	451.4	774.9	1487	155.7	98.1	116.3	11.6	381.7	19.3	2949	2.15	1.1-3.2
12	Climact	26	8.5	218.9	186.1	439.5	16	114.2	82.9	89.9	11.1	298.1	17.7	2882	2.15	1.1-3.2
18	TIAM UCL 2DS	102.1	12.8	262.1	210.7	587.7	590	143.3	99.7	116.7	12.8	372.5	15	2999	2.15	1.1-3.2
11	Mott McDonald	48.9	10.7	239.5	144.7	443.8	490	155.9	74	89.8	10.9	330.6	15.9	2987	2.20	1.2-3.2
1	Distributed effort	68.1	11.5	309.5	238.4	627.5	1288	183.5	117.9	121	11.7	434.1	18.5	2892	2.25	1.2-3.3
2	Consumer reluctance	72.8	0	72.8	270	415.6	1487	207.2	120.7	129.2	12.1	469.2	19.8	2886	2.25	1.2-3.3
20	WEC/PSI-Symphony	63.3	16.3	250.2	288.1	617.9	1708	145.4	121.5	150.4	11.3	428.6	20.9	3095	2.25	1.2-3.3
3	Low action on forests	68.1	0	297.4	451.4	816.9	490	175.1	112.4	116.3	12.2	416	20.9	2942	2.35	1.3-3.4
22	Cambridge Architectural Soc	48.9	8.2	236.8	203.6	497.5	253	142.3	97.3	85.1	11	335.7	22.8	3193	2.40	1.3-3.5
25	World Nuclear Assn (Allegro)	131.1	11.9	258.2	240.8	642	1487	170.7	96.8	136.1	13.2	416.8	22.5	3003	2.45	1.4-3.5
26	World Nuclear Assn (Largo)	72.8	11.1	235.5	253.5	572.9	490	168.3	102.1	112.9	12.9	396.2	27.5	2950	2.55	1.5-3.6
9	Shell oceans	35.5	15.9	410.8	285.3	747.5	443	208.9	134.1	119.6	12.4	475	28.2	3501	2.65	1.5-3.8
8	Shell mountains	72.8	12.3	226.4	368.2	679.7	2594	192.8	142.9	130.7	13	479.4	32.2	3613	2.70	1.5-3.9
15	RCP 6	5.5	10.2	72.8	451.4	539.9	16	201.5	203.1	108.1	14.8	527.5	52.1	5598	3.00	1.4-4.6
19	WEC/PSI-Jazz	30.8	12.7	187.6	600.7	831.8	395	191.4	171.9	180.2	13.4	556.9	54.6	5634	3.00	1.4-4.6
6	IEA 4DS	48.9	12.7	164.2	592.3	818.1	206	230.3	156.2	168.3	13.6	568.4	53.6	5512	3.05	1.5-4.6
17	TIAM UCL 4DS	48.9	10.1	182.2	586.5	827.7	16	213.6	113.7	151	13.6	491.9	58	5939	3.25	1.6-4.9
5	IEA 6DS	28.2	0	72.8	731.4	832.4	16	246.5	168.7	180.1	16.1	611.4	84.3	7693	3.95	1.9-6.0
24	Chatham House - high meat	72.8	17.5	209.2	333.1	632.6	1487	213.3	98.4	135.3	12.2	459.2	65.9	6460	4.00	2.2-5.8
14	RCP 8.5	40.1	16.2	218.6	984	1259	63	349.8	255	230.3	17.7	852.8	88.3	8582	6.00	high

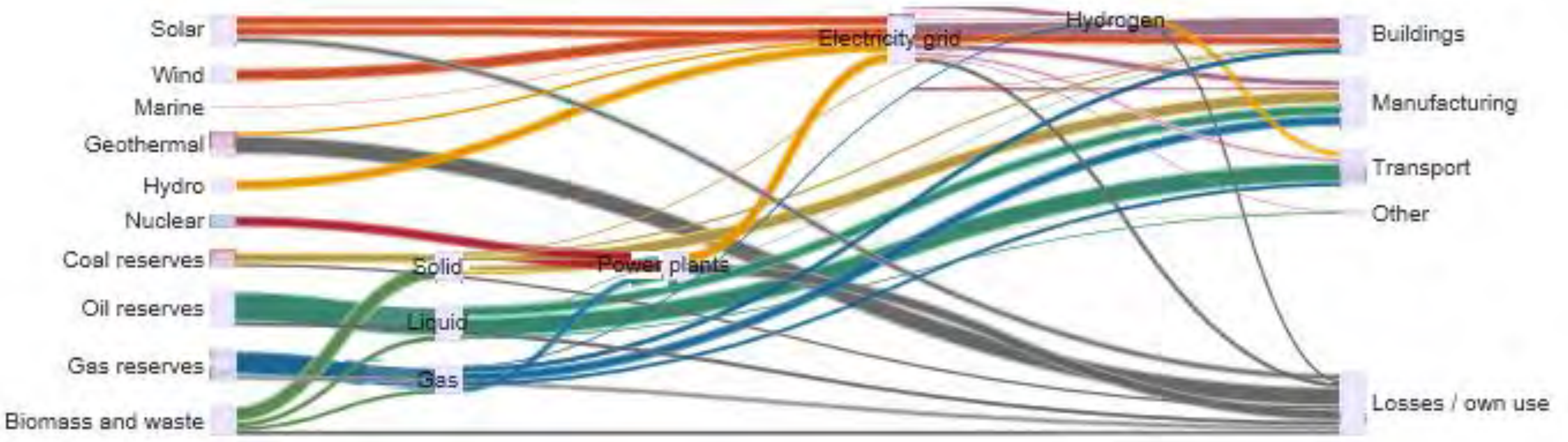
Annex 5 **Web Tool inputs and outputs for three 'representative' pathways**

Energy figures from the 'simple' Sankey diagrams	High nuclear (WNA Allegro)		High renewable (Climact)		Intermediate (ICEPT)	
Energy Inputs (EJ)	**652**		**458**		**646**	
Renewables	**206**	**32%**	**176**	**38%**	**218**	**34%**
Nuclear	**131**	**20%**	**26**	**6%**	**49**	**8%**
Fossil	**240**	**37%**	**187**	**41%**	**274**	**42%**
Biomass	**75**	**11%**	**69**	**15%**	**105**	**16%**
End-use Outputs (EJ)	**640**		**441**		**631**	
Buildings	**136**	**21%**	**90**	**20%**	**135**	**21%**
Manufacturing	**170**	**27%**	**114**	**26%**	**211**	**34%**
Transport	**97**	**15%**	**83**	**19%**	**88**	**14%**
Agriculture	**8**	**1%**	**6**	**1%**	**6**	**1%**
Losses	**229**	**36%**	**148**	**34%**	**191**	**30%**
Emissions (Gt)						
Gt CO_{2e} in 2050	**22.5**		**17.7**		**19**	
Cumulative to 2100	**3003**		**2882**		**2768**	
Temperature rise (^{0}C)	**2.45**		**2.15**		**2.1**	

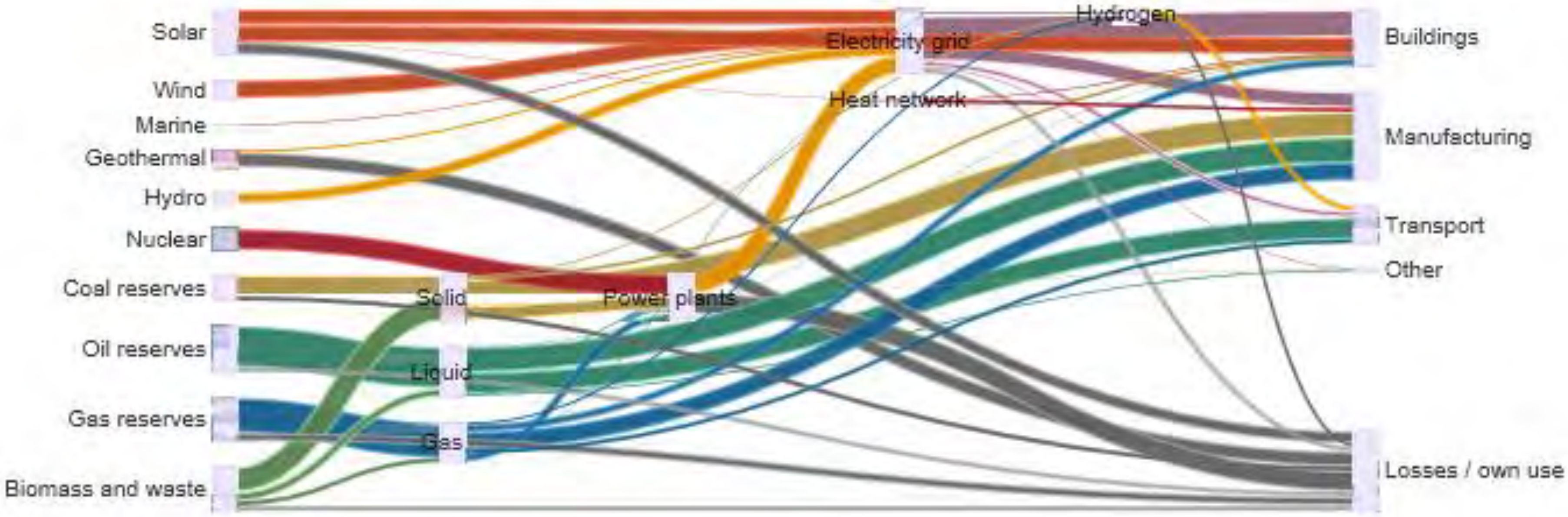
Annex 6.1 High nuclear pathway



Annex 6.2 High Renewables pathway



Annex 6.3 Intermediate pathway



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