Costs in Global Calculator: methodology paper

The Global Calculator is a relatively simple model of the world's energy, land, food and climate system in the period to 2050. This note summarises the methodology we have used to include costs.

Summary

The Global Calculator estimates the total capital, operating and fuel cost of the global energy system out to 2050. For example, it includes the costs of building and maintaining power stations, wind turbines, heat pumps, boilers, cars, trains, planes, roads, railways and the clean technology used in manufacturing, as well as the fuels, such as fossil fuels and bioenergy, used to power these technologies.

Our methodology for including costs in the Global Calculator has been guided by the principles that it should be simple and as consistent as possible with how other global energy models have done it. Since the Calculator does not have regional detail, we use US costs only. Many of our central estimates are US costs from the TIAM-UCL model. We also have high/low cost ranges.

Principles

The key principles guiding our methodological approach are:

- **Keep it simple!** The key distinguishing feature of the Calculator is its simplicity, so the approach must be as simple as possible and the same for all technologies.
- **Consistent with how other models have done it**. To help us compare our results to other models, it will be helpful to use as consistent as possible a methodology. For that reason, we have kept our methodology as close as possible to that used in the UK / Chinese / Belgian Calculators. These methodologies were deliberately consistent with the MARKAL methodology. We will also be using the TIAM-UCL model for many of our point estimates (see annex A).

Costs coverage

We plan to include the total energy system cost. Specifically, capital, operating and fuel costs for electricity, transport, buildings and manufacturing sectors, as follows:-

- **Electricity generation**: capital cost of building electricity generation technologies; operating costs for this; fossil fuel and bioenergy used in power plants. Nuclear decommissioning costs have been excluded because it is uncertain whether decommissioning would occur before 2050. Costs of improving the efficiency of fossil fuel extraction has also been excluded owing to lack of data. Costs of transmission and distribution are excluded owing to complexity of estimating the required networks.

- **Transport**: capital cost of new passenger vehicles, trains, planes, boats and associated operating costs; fossil fuel consumed by transport; cost of building new transport infrastructure. The cost of transport efficiency improvements have been excluded owing to lack of data. The value of infrastructure and vehicles existing prior to 2011 is excluded.
- **Buildings**: capital cost of boilers, heat pumps and district heating and associated operating costs; cost of fossil fuel or bioenergy used for heating. The cost of insulation and appliance efficiency has been excluded owing to lack of data. The cost of building new houses and the value of building stock existing prior to 2011 is excluded.
- **Manufacturing**: capital and operating costs associated with making manufacturing more energy efficient, fuel switching, move to cleaner technologies (e.g. the cost of fitting CCS) or produce more output. Note that we do not include the cost of buildings used by industry.
- **Opportunity cost**: for all capital expenditure, valued at 3% over the economic life of the asset.

The land costs associated with agriculture and forestry are excluded from the calculations because it would be difficult to get good data on land and agriculture values. Many energy models (including the UK, China and TIAL-UCL model) do not include land costs.

We have also excluded the costs of greenhouse gas removal technologies as these are considered to be speculative.

"Single region cost" approach

Given that the Global Calculator does not have regional detail, we have populated it with costs for just one region: the US. We chose the US because it had the best data availability.

We chose to populate the model with costs for a single region because:

- **Simple and easy to understand**. The results tell us, "if the whole world faced US prices in 2050 then…" This is an easy concept to understand.
- **Good illustration of uncertainty**. There is evidence that there is more uncertainty in costs data within the US than between the US/other regions (e.g. see figure 1 in annex A). Also, we would expect that costs between regions will converge over time so that by 2050 the difference will be less pronounced.

However, users interested in exploring what costs would look like if the whole world faced India, Chinese or Western European prices in 2050 can do so in the Global Calculator spreadsheet. For more information on this functionality, see annex F.

High/low range

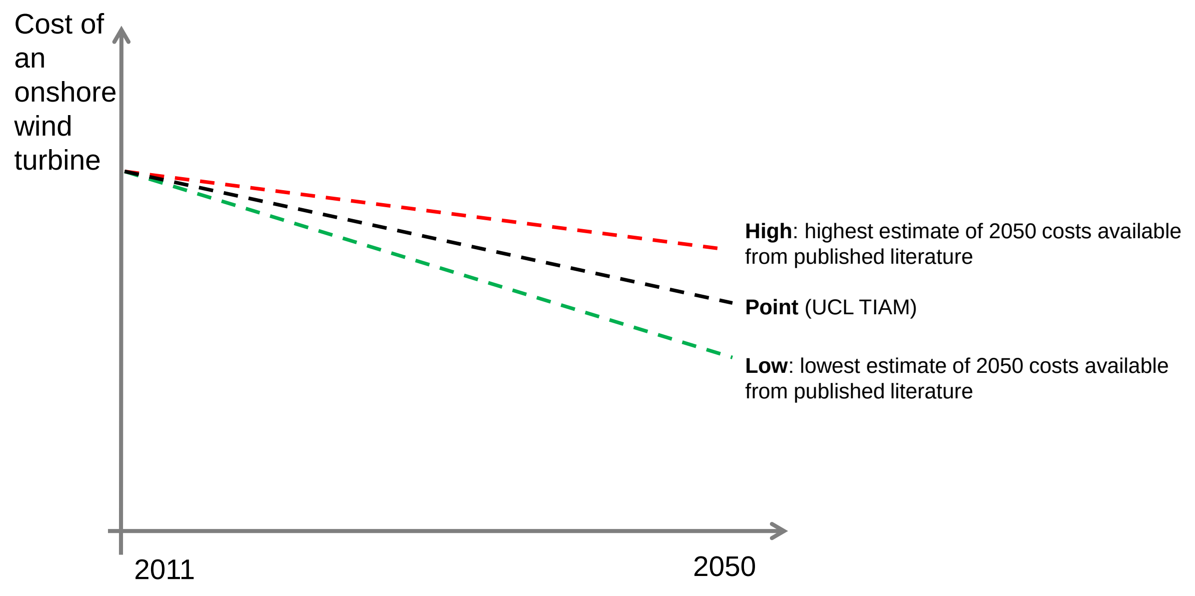
For the most significant technologies, we also include a high/low costs range. The high/low costs range is designed to reflect the **maximum/minimum that costs could be in 2050, based on a range of credible, published studies for 2050**. It will not attempt to place any probability on this range, or say what is most likely. It will simply be a collation of existing evidence. Specifically:

- **Low: this is the lowest cost estimate from a range of sources for 2050.**

- **High: this is the highest cost estimate from a range of sources for 2050.**

The high/low ranges are illustrated in the figure below. Where high or low costs were not available, 2011 costs were inflated or deflated by 20%. The cost data sources and a "red / amber / green" rating are given for all data in the Global Calculator spreadsheet.

Figure 2: high/low costs as defined in the Global Calculator



Fuel costs

Many economic models calculate the resource cost of fuel consumption as the area under the fossil fuel extraction supply curve. This is described in more detail in annex B. However, for the Global Calculator, we use the more simple approach of costing all consumption at the marginal cost of extraction.

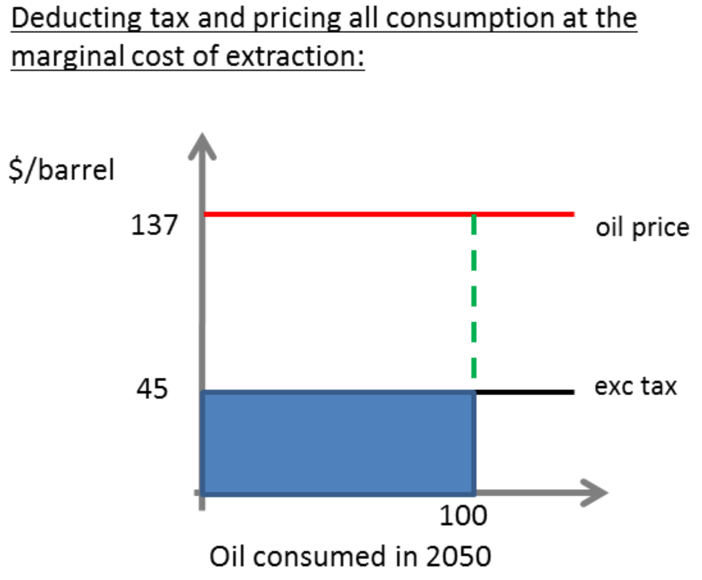
Marginal cost of extraction approach

In the Global Calculator, we will take a simple approach of costing all fossil fuel consumed in 2050 at the marginal extraction cost in that year. This is explained below, using oil as an example:-

Firstly, assume an oil price for 2050. The oil price assumption was arrived at by doing a literature review of oil price projections for 2050 and using the median of the range. This is \$137/barrel in 2050 (2011 prices). There is more detail on this set out below and in annex B. For the intervening years, we assume a straight line trajectory from 2011 to 2050.

Secondly, deduct tax and price all consumption at the marginal cost of extraction. E.g. See figure 4 below. We make the simplifying assumption that there is a single oil price faced by all users in the world in any given year. We then multiply this by quantity consumed in that year, and net off the tax because we are striving to measure resource cost. Currently, approximately 67%[1] of the spot price of crude oil is tax levied by the oil exporting country. The average tax rate levied on oil in 2050 is very uncertain so the best we can do is to assume it is the same as today (67%). So the cost of oil consumed in, say, 2050 will be $137/barrel x 0.33 = $45/barrel. $45 x 100 barrels consumed = $4,500. This is the marginal cost of extraction approach. Of course, this is a simplification: some of the 100 barrels of oil extracted in 2050 will have been extracted at a resource cost of less than $45/barrel. However we do not have data for that. This approach is consistent with other models: for example, the IEA calculate oil consumption cost in 2050 as: marginal extraction cost ($/barrel, excluding tax) x total consumption in 2050.

Figure 4: calculating total resource cost of fuel, net of tax



The "marginal cost of extraction" approach is a good estimate of the true resource cost that the "area under the curve" approach seeks to quantify. As set out in annex B, there is considerable uncertainty about what the true resource cost in 2050 will be, given huge uncertainties about which oil reserves will be extracted and the tax rates that will be levied by oil exporting countries. In this context, the Global Calculator "marginal extraction cost" approach is reasonable method for approximating resource cost. More detail on this is set out in annex B.

Note that the "marginal cost of extraction" approach is similar to the methodology used by the IEA. For example, in the IEA's Energy Technology Perspectives 2014 report, fossil fuel costs in 2050 are calculated by pricing at the margin. (Although the IEA approach differs to ours because they do not deduct taxes levied by oil exporting countries.)

If we had had more time during model development, we would have liked to create functionality in the web tool for the user to be able to assert what the oil price in 2050 should be. There is

[1] Deutsche Bank Markets Research: "Oil and Gas for Beginners", published on 25th January 2013.

considerable uncertainty about future oil prices, so this would have been a good way for the user to sensitivity test costs. Unfortunately we did not have time to do this.

Approach for coal

We apply the same approach to coal as for oil. i.e. Assume a price for coal in 2050, then calculate the resource cost (net of tax) using the marginal cost of extraction approach. The average tax rate paid on coal today is 39%[2]; given massive uncertainty around the future average tax rate, we have kept the fraction constant at 39% to 2050.

Approach for gas

The market for gas is not global in the way that oil, coal and bioenergy are because gas is not as easily transported. The regional markets for gas are generally characterised as: US, Japan, Europe. Therefore we have taken a weighted average of these fuel prices to estimate a "global average" price of gas. We have weighted these region prices according to population estimates for 2050.

We deduct the tax fraction when calculating resource cost. The average tax rate paid on gas today is around 60% (see annex B for how this is calculated). Given massive uncertainty around the future average tax rate, we have kept the fraction constant at 60% in 2050.

Approach for bioenergy

Using a similar approach, we assume prices for solid, liquid and gaseous bioenergy in 2050. We assume there is no tax applied by exporters. Then we calculate the resource cost using the marginal cost of extraction approach.

High, low and central fuel costs

The Global Calculator philosophy is to give the user an insight into the full range of what credible experts believe could be possible by 2050. So for costs, we have defined the high/low range as the highest/lowest price estimates available from the literature.

An obvious criticism of these high/low prices is that the extremes of the range may look unrealistic or unlikely. But our objective in producing these ranges is not to estimate the most likely/realistic future prices. Rather, we are simply attempting to reflect the full range of credible, published estimates of future fuel prices. So we have taken the approach of including any credible experts published estimate of fuel price from the literature. Our central price assumption for 2050 is selected as the median of the range. Our literature review and high, low and central fuel costs are set out in annex B.

Opportunity costs

Different energy models use a variety of different approaches to calculating opportunity costs: there is no single correct methodology. There is also a difference in terminology, reflecting subtle differences between what these models are trying to capture. Terminology includes: finance costs, hurdle rates, discount rates and opportunity costs. For the Global Calculator, we use the

---

[2] This estimate is from a report by Goldman Sachs ("Resource Nationalism Poses a Big Threat to Miners", Goldman Sachs, 23 January 2013) and referenced in submissions made by the Minerals Council of Australia (Development and Operation of the Minerals Resource Rent Tax, the Minerals Council of Australia: Submissions to the Senate Economics References Committee, March 2013).

terminology, "opportunity cost". Following discussion with a range of experts during the build of the Global Calculator, we concluded that any of the following three approaches to opportunity costs could be justified:

1. No opportunity costs
2. Opportunity cost to society
3. Opportunity cost to individual actors

On balance, we concluded that option 2 was most appropriate so this is what have implemented; more detail on this approach is set out below. More details on options 1 and 3 are set out in annex C.

Opportunity cost to society

This approach defines "opportunity costs" as the return that society could have received by investing in capital elsewhere in the economy. i.e. When society invests in a wind turbine / electric car / heat pump, etc, the opportunity cost of this capital expenditure is the return that society could otherwise have achieved by investing in the next best project. The concept of the "next best project" could potentially be interpreted quite widely as investment in man-made capital (such as a coal power plant), human capital (e.g. schools and hospitals) or even social capital (such as the legal and regulatory framework).

Pros of this approach:

- **Consistent with Calculator neutrality on "who pays".** The opportunity cost to society approach is consistent with the Global Calculator method of not specifying who pays for technological roll out. When a user chooses to build lots of wind turbines, insulate many buildings, or increase the number of cars on the road, they are acting like a "benevolent dictator", simply asserting that these changes will take place, but not specifying what policy will be used to deliver them. For example, an increase in the number of wind turbines could be delivered via regulation (whereby the costs would fall on *businesses and householders*) or public subsidy (whereby the costs would be borne by *government / the tax payer*). The Global Calculator is neutral on this question of "who pays" (and in fact it is beyond the capability of the model to even attempt to answer this). By extension, it seems appropriate that when we attempt to calculate opportunity costs, we should be neutral on this question of "who pays" by considering the net cost to society only.
- **Simple**. One of our key principles when building the Global Calculator is to keep the model as simple as possible. This approach involves using the same opportunity cost for technologies across all sectors and all regions of the world. This should make it easier to explain to users.

Cons of this approach:

- **Inconsistent with other models**. Most energy models tend to include opportunity costs in a manner more consistent with option 1. But these are economic models and, as explained in annex C, it is not appropriate to use the hurdle rate approach that they do.

Estimates for the opportunity cost to society

The opportunity cost to society is the return that could have been achieved by investing in the next best project (i.e. the marginal product of capital). Some investments will be very successful and yield returns in excess of the average; but some will fail and yield below average returns. A simple method is to use the rate of overall economic growth, which assumes that capital maintains a constant share in GDP.

The below table sets out some estimates of global GDP growth (historic and projected). Based on this data, we have set the opportunity cost to society at 3% pa for all technologies.

	Growth rate per annum	
	2010-2013 (historic)	2011 to 2050 (projection)
GDP volume (based on PPP exchange rate)	3.3%	2.9%
GDP per capita (based on PPP exchange rate)	2.4%	2.5%

Source: OECD.stat, see: http://stats.oecd.org/Index.aspx?DataSetCode=EO#

Other studies have used similarly low rates as an estimate for social opportunity cost. For example:

- The IEA use a "social discount rate" of 5% in their calculation of levellised costs for the electricity generation sector[3].
- McKinsey use 4% in their "China's Green Revolution" study when they calculate levellised costs for electricity generation.[4]

By setting the **opportunity cost to society at 3%,** we are reflecting the global opportunity cost of capital. This is consistent with the remit of the Global Calculator to focus on the average impact on the globe, rather than specific countries/regions.

Technologies considered

We will impose this opportunity cost on **all capital expenditure** in the Calculator. For example: electricity generation plants; boilers, heat pumps and white goods; cars, bikes, trains, planes; and capital spend on heavy industry. We do not apply opportunity cost to operating costs and fuel costs, because these are one year costs.

How is opportunity cost incurred over time?

Opportunity cost is incurred over the asset's economic life[5] at a compound rate. For example, if we spend $1m capital costs on wind, then in year 1 the opportunity cost will be $0.03m, and in year 2 it will be $0.031m, and in year 3 it will be $0.032m… etc. One reason for compounding opportunity cost is that it ensures it keeps in step with economic growth: for example, when we say that the

---

[3] See IEA(2010): "Projected Costs of Generating Electricity": http://www.iea.org/publications/freepublications/publication/projected_costs.pdf see page 153.
[4] See McKinseys (2009): "China's Green Revolution", file:///C:/Users/Sophie/Downloads/china_green_revolution.pdf
[5] Asset life: period of time an asset could be used for, determined by technical factors. E.g. CCGT gas plan could be used for a maximum of about 30-35 years. Economic life: period of time over which an asset is likely to be economically viable (less than the asset life due to rising maintenance costs or obsolescence). E.g. CCGT plant could be retired after 25 years. Investment horizon is the period over which investors may wish to recoup their costs before the end of the asset's economic life. E.g. For a GGCT plant, this may be 15 years.

economy grows at a rate of 3% pa, this economic growth is compounded. Another reason for compounding opportunity cost is to consider the "project with the next best rate of return" a bond in which interest is paid in and calculated on the compound.

Why is the opportunity cost to society different to the opportunity cost to individual actors?

Private actors face greater risk when undertaking investments than society as a whole. For example, a potential investor in electricity generation has to consider the risk that electricity prices will be lower than expected, which could render the investment unprofitable. Also, they have to consider policy risks (e.g. a change in corporation tax rates or a tightening of safety regulations). And the lender has to consider the credit worthiness of the borrower and will impose a premium on interest rates to reflect this.

But from a societal perspective, the above risks are not relevant. For example, if electricity prices are lower than expected and the nuclear power plant operator makes a loss, this is a cost to the nuclear plant owner, but a benefit to consumers more widely (a transfer payment, assuming the operator is not large enough to cause knock on impacts on the wider economy). Similarly, if corporation tax rates increase, then this will result in a transfer payment from the nuclear plant owner to the public purse.

Of course, there is a risk of cost overruns when building the solar or nuclear power plant but this should be reflected in the assessment of how much they should cost, on average. From a society point of view, the only risk associated with these investments is the risk that they might fail and therefore waste resources – but this is very unlikely. Therefore overall, from a society perspective, the capital investment is virtually risk free.

Discount rate

When costs are presented in the web tool, they are undiscounted – this is in keeping with our philosophy for simplicity. However if the user wishes to see the impact of discounting, they can do so in the spreadsheet. Should the user wish to activate it, the default discount rate in the spreadsheet is the standard UK Government HM Treasury Green Book discount rate of 3.5% (declining to 3% after 30 years) The reasoning for this is set out in annex D.

Limitations

It is important to bear in mind the limitations of the Global Calculator cost analysis. Key caveats are:

- **Costs are extremely uncertain**. Projecting technology costs out thirty five years into the future is extremely uncertain[6]. Users are encouraged to look at the high/low cost ranges generated by the Calculator, rather than focusing on the central estimates.
- Excludes **energy security impacts, costs arising from the damaging impacts of climate change, other welfare costs, land and food, and wider macroeconomic impacts**. The damage costs of climate change could be particularly significant. Costs also exclude any

[6] For example, see the paper by UKERC Technology and Policy Assessment Function (November 2013): "Presenting the Future: an assessment of future costs estimation methodologies in the electricity generation sector" ref UKERC/RR/TPA/2013/001

deployment subsidies or spending on research and development used to help move technologies down their learning curves. Pathways that use land and food choices to reduce emissions may look cheap but there would be costs associated with the actions behind these levers.

- **User driven model, not market based**. The Global Calculator is an engineering based model, not an economic one. This means that the tool will cost whatever combination of technologies and actions the user specifies - it does not take into account price interactions between supply and demand to determine what actions take place.
- **Costs are exogenous**. For most technologies, costs decline over time as they follow a learning curve. However, because the model is user driven, not market based, costs are exogenous: for example, the cost of an electric vehicle in 2030 in the tool is fixed regardless of whether there is a high or low deployment of electric vehicles in that year. However if the user has beliefs about how they would expect the unit costs of particular technologies to change in their pathway, they can sensitivity test the effect of varying these assumptions in the underlying spreadsheet.
- **US cost assumption**. The cost estimates are calculated assuming the whole world faces US technology prices. This simplifying assumption is made because the Global Calculator does not model individual countries. It is not clear whether this will tend to over or underestimate total costs because in countries where capital costs are higher, operating costs are usually correspondingly lower.
- **Fuel costs are particularly uncertain**. Average and marginal fossil fuel extraction costs and average tax rates levied by oil exporting countries in 2050 are extremely uncertain. This could result in actual fuel costs being significantly higher or lower than those estimated here.
- **Some costs are missing**. Unfortunately we could not include some costs. This was either owing to time, uncertainty or the potential negligible nature of costs. It was not possible to estimate costs for insulation, transport efficiency, appliance efficiency, fossil fuel efficiency and the greenhouse gas removal levers. We did not include costs for nuclear decommissioning as it is uncertain whether decommissioning would occur before 2050.
- **It is difficult to estimate the total energy system cost without double counting**. The costs of a car, counted in the transport costs, will include the cost of electricity used in the production of the car. The cost of the electricity is also counted in the power sector costs. Our costs do not try to avoid this double counting as to do so would be highly complex. Therefore we present an index of costs over time to show how the costs could change.

Presentation of costs in the web tool

Costs in the web tool are presented as undiscounted cash flow (i.e. capital costs are overnight, not annualised), including opportunity costs.

This section sets out our thinking behind our choice of cost metrics as presented in the web tool.

Why show index of energy system costs rather than presenting the results in $bn?

The total cost of the energy system in $bn is arguably not a very reliable estimate because the methodology for calculating it double counts some costs but excludes others. For example, energy required to smelt the steel which is ultimately used to make a car is double counted in the sales prices of a vehicle. Examples of costs excluded are building insulation, appliance efficiency and transport efficiency. Economic models such as MARKAL and TIMES also experience the problem of double counting some costs and excluding others. In an ideal world, these models would calculate energy system cost in a way consistent with GDP accountancy (e.g. using the value added method). But models do not do this because it is too conceptually complex and there would be significant data challenges. Therefore we decided against showing the total energy system cost of pathways in $bn. However, it is very insightful to look at how the energy system cost of a pathway changes over time. We wanted users to appreciate that such costs could more than double between now and 2050. The best way of presenting this information to users is therefore using an index.

Why allow users to view the cost of a counterfactual pathway?

When the user is considering the cost of their pathway, it is important that they appreciate that the counterfactual is not "spend nothing". Even in a world that does not tackle climate change, we still need to invest in our energy infrastructure. Therefore we encourage users to select a counterfactual pathway and view their pathway costs alongside this.

Why show users the high/low cost range?

There is massive uncertainty in costs between now and 2050, so we felt it was very important that the user should see not just the central cost of their pathway, but the high/low range around it. Significantly, if the uncertainty ranges for two pathways overlap, then it means that depending on the circumstances either one of them could be more expensive.

Why show users the % of GDP?

The tool calculates whether the user's pathway is cheaper or more expensive than the counterfactual and expresses this as a % of GDP. This is calculated as: (average annual cost of the energy system in the user's pathway over period 2011-2050 – average annual cost of the energy system in the counterfactual pathway over 2011-2050) / average annual global GDP over the period 2011-2050 x 100. This helps the user contextualise the relative cost of their pathway.

Annex A: TIAM-UCL model as the source for most of our cost point estimates

Why have we used TIAM-UCL model for most of our point estimates?

We have used University College London (UCL)'s TIAM-UCL[7] model for the point estimates in the Global Calculator. TIAM = TIMES Integrated Assessment Model. The mitigation part of the model (TIMES) is an economic model (i.e. a cost optimiser). We have used it because:

- **Costs data for US today and 2050**. The US is one of 16 regions in the TIAM-UCL model, and they have costs data for today (2011) and 2050, which meets our needs.
- **Open source and from a credible, widely used source**. The costs data in TIAM-UCL is published and from various credible sources. Most of the costs estimates are from the IEA ETP 2010 and 2012 publicly available reports, the EIA (Energy Information Agency), and the EPRI Program on Technology Innovation. This is important because we are incorporating the data into the Global Calculator spreadsheet and publishing it under the Open Government Licence[8]. If the data is from a credible, widely used, published source, it will be easier to defend and explain the use of that data to our stakeholders.
- **Costs in appropriate format.** The TIAM-UCL costs are in the appropriate format for our use, i.e. capital costs are overnight costs (as opposed to levellised costs). Their costs can also be stripped free from discounting and financial costs. In the Global Calculator model, we will build the functionality to add finance costs and do discounting separately.
- **Recently updated.** The TIAM-UCL cost data was peer review recently (early 2014).
- **Coverage of the whole energy sector**. The TIAM-UCL model has costs for the whole energy sector. This is important because it is better for our purposes if our point estimates come from a single data source because:
  - <u>Easier to defend</u>. Our experience with the UK Calculator is that the choice of point estimate is very contentious among stakeholders. In the UK Calculator, we resolved this controversy by taking our cost data from the UK MARKAL model, which was the single, most comprehensive and openly available data source the UK had available. Crucially, UK MARKAL covered the whole of the energy system (electricity, buildings, transport, industry) and so could supply us with technology costs for over three quarters of the technologies in the UK Calculator. This meant that we avoided getting into a detailed debate justifying and explaining our individual technology assumptions. UK MARKAL supplies the point estimate costs for about three quarters of the UK Calculator.
  - <u>Cost comparisons are likely to be fairer</u>. By drawing all cost estimates from a single source, it is more likely that costs will have been calculated in a consistent way, or have been subject to a similar level of scrutiny. This will be harder to say for costs from different sources.

---

[7] TIAM = TIMES Integrated Assessment Model. TIMES is a more advanced version of MARKAL. TIMES = The Integrated MARKAL-EFOM System. MARKAL = MARKet ALlocation model. UCL TIAM documentation: www.ukerc.ac.uk/support/ES_TIAM-UCL_Documentation_2010

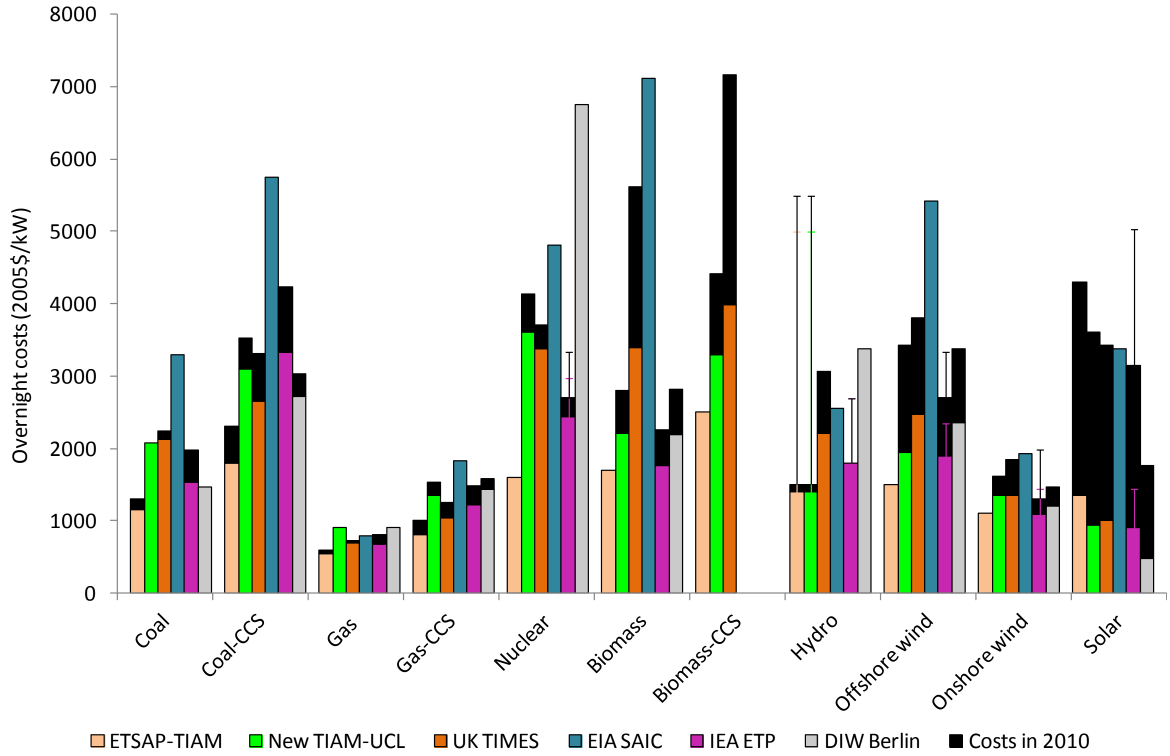
[8] www.nationalarchives.gov.uk/doc/open-government-licence/version/2/

However, there were some occasional instances where TIAM-UCL did not have a cost we needed. For example, the costs for the manufacturing sector of bringing about process improvements. In this case, we have used other sources. The Global Calculator spreadsheet includes details of all data sources, with a red/amber/green rating.

Costs within the US could be more uncertain than costs between regions

For example, see below graph showing 2050 cost estimates used by various different models. As can be seen, in extreme cases (such as offshore wind), the highest cost estimate is more than a 200% increase on the lowest cost estimate. This cost difference is much greater than the difference between region factors: the TIAM-UCL region factors are typically +/- 20% of US costs and in extreme cases they are +/- 40%.

Figure 1: comparison of costs used in different 2050 global energy models



Source: TIAM-UCL team

Annex B: fuel costs

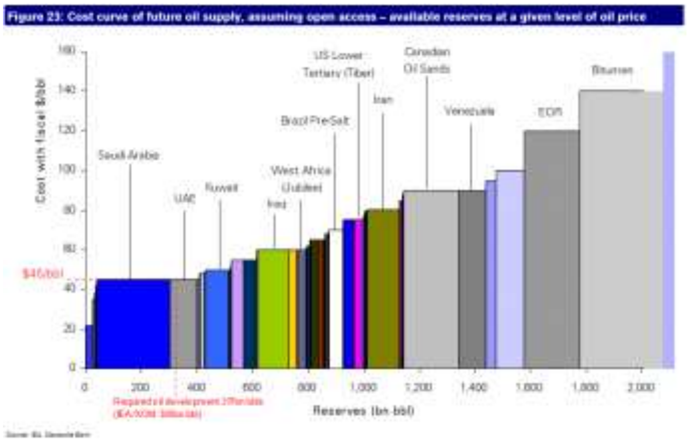
This annex includes:

- Explanation of the "area under the curve" approach to calculating the resource cost of fossil fuel extraction, used by some economic models
- Comparison of resource cost as calculated by the "area under the curve" and "marginal cost of extraction" approaches
- Discussion of average tax rate for gas assumption.
- Discussion of bioenergy prices.
- Results of literature review for oil, gas and coal prices in 2050.

Area under the curve approach

Some economic models calculate the total cost of fuel consumption using a fossil fuel extraction cost curve. For example, see below oil extraction cost curve from Deutsche Bank[9]. This graph shows total reserve availability over the long term – it is not specific to a particular year. The simple approach would be to calculate cumulative consumption of oil and take the relevant area under the curve as an estimate of resource cost. But this approach will underestimate resource costs because in reality fossil fuel is not extracted strictly in order of cheapest first, owing to the fact that different oil exporting countries may/not want to exploit their reserves.

<u>Figure i: cost of extracting oil, assuming open access</u>

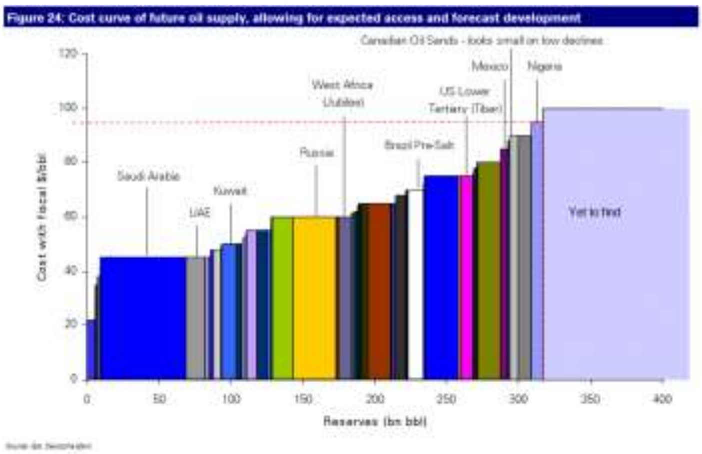


Some studies attempt to account for this by trying to predict which sources will be extracted in that time period. For example, the Deutsche Bank study[10] has attempted to identify the sources of oil most likely to be extracted first. Notice that the marginal extraction cost in figure i is $45/barrel, compared to almost $100/b as calculated in figure ii. This helps to explain why future oil prices are so uncertain.

---

[9] Deutsche Bank: "The Peak Oil Market: Price Dynamics at the end of the Oil Age", 4th October 2009.
[10] Deutsche Bank: "The Peak Oil Market: Price Dynamics at the end of the Oil Age", 4th October 2009.

<u>Figure ii: cost of extracting oil, based on forecast development</u>

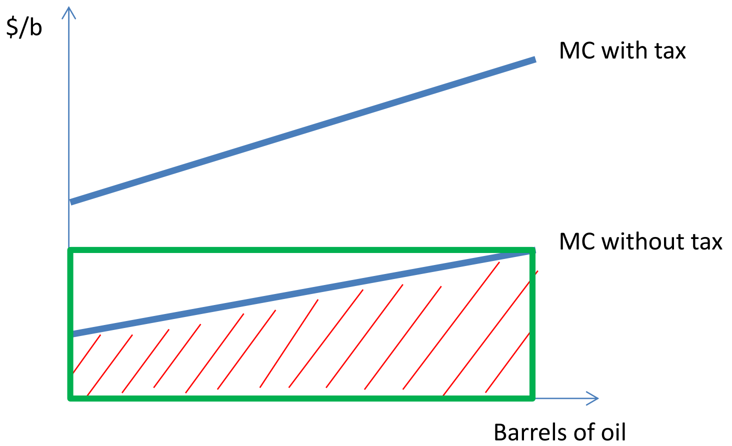


Comparison of resource cost as calculated by the "area under the curve" and "marginal cost of extraction" approaches

In a theoretical world where oil is extracted strictly cheapest first and all oil is taxed at the same rate, the marginal cost of extraction approach would overestimate resource costs

Figure a below illustrates the simplest, theoretical case where oil is extracted strictly in order of cheapest first and all oil has the same fuel tax applied. The "true" resource cost in figure a is the red shaded area under the curve. However the Global Calculator would estimate the resource cost as the green rectangle (i.e. pricing all oil at the marginal extraction cost). This would be an overestimate.

<u>Figure a: Global Calculator would overestimate resource cost if all oil was extracted cheapest first and faced the same tax rate</u>

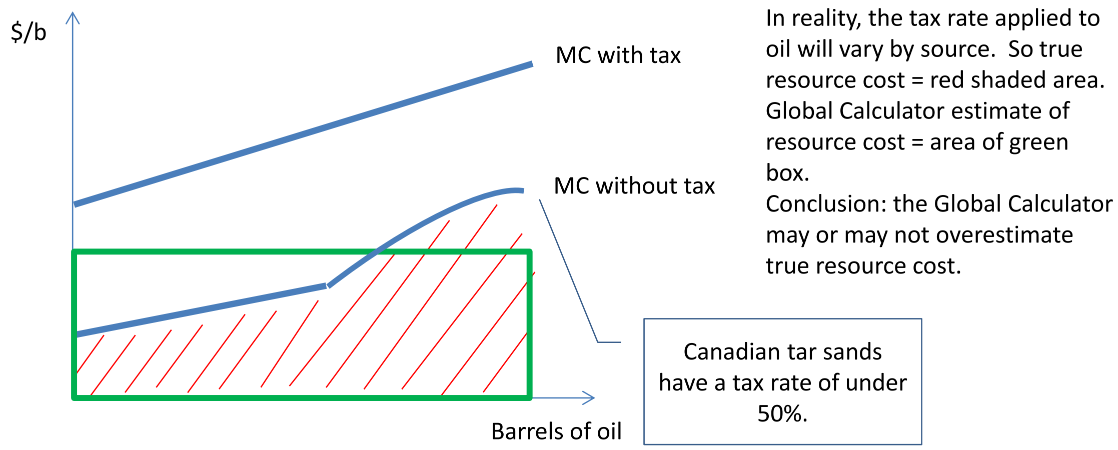


If all oil was extracted cheapest first and faced the same tax rate, then true resource cost = red shaded area.
Global Calculator estimate of resource cost = area of green box.
Conclusion: in these circumstances, the Global Calculator would overestimate true resource cost.

In reality, it is unclear whether the "marginal cost of extraction" approach will over or under-estimate resource cost

In reality, the simple assumptions used above do not apply. In reality oil is not extracted strictly in order of cheapest first and oil does face different tax rates depending on the country it is exported from. In these circumstances, the marginal extraction cost curve might look more like figure b, below. Here, the true resource cost is red shaded area and the Global Calculator estimate of resource cost is the green rectangle. So it is not clear whether the Global Calculator will over or under-estimate true resource costs.

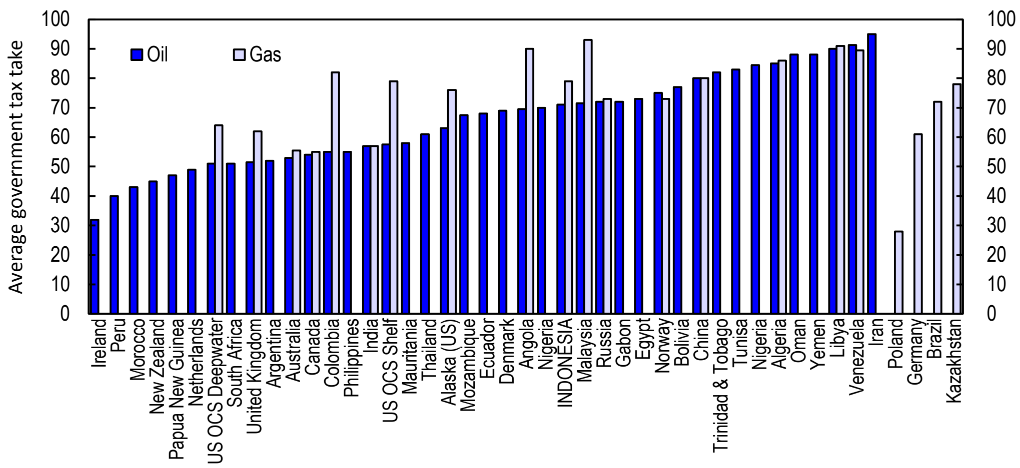
Figure b: Global Calculator might under or overestimate resource cost



Conclusion: given the significant uncertainty around which oil reserves will be extracted and the tax rates that will be applied in 2050, it is not possible to say whether the Global Calculator will over or underestimate true resource cost. In the tool, we will always present incremental costs (i.e. cost of one pathway relative to another) so this will make results more reliable.

Average tax rate for gas

The current average tax rate for gas levied by gas exporting countries is similar but not identical in many countries, see graph below. Tax rate varies from around 30% to 90%, with the average appearing to be around 60%. Note that 60% is an "eyeball" estimate of the average. It is reasonable to take such an approximate estimate because it's intended to reflect the tax rate in 2050, which is extremely uncertain.



Source: *OECD Economic Surveys: Indonesia 2012*, and based on Agalliu, I. (2011), "Comparative Assessment of the Federal Oil and Gas Fiscal Systems", U.S. Department of the Interior, Bureau of Ocean Energy Management, Herndon, VA, for oil, and Johnston, D. (2008), "Changing Fiscal Landscape", Journal of World Energy Law & Business, Vol. 1, pp. 31‑54, for gas.

Bioenergy prices

Most of the literature presents bioenergy costs appropriate to specific production processes. However, our bioenergy costs should be in terms of solid, liquid and gaseous bioenergy because this is how we model it in the tool. The only estimates of solid, liquid and gaseous bioenergy for 2050 that we have been able to find are set out in the table below. These estimates are used as central prices in the Global Calculator. The high/low range is calculated by applying +/- 20%.

Bioenergy	$/GJ in 2050	Comment	Source
Solid	7.2	E.g., pellets, wood chips, firewood.	Based on Shah et al (2013) Imperial College London https://workspace.imperial.ac.uk/climatechange/Public/pdfs/Collaborative%20publications/Halving_CO2_emissions_ANNEX_September_2013.pdf
Liquid	11.8	Weighted average for ethanol and biodiesel (costs after the industrial process, i.e., at the mill gate)	
Gaseous	5	E.g., landfill gas, biodigestion of animal slurry (always assuming no cost for the used residue)	

Results of fossil fuel price literature review

The results of the oil, coal and gas literature review and our high, low and central prices are set out on the next page.

Oil

Oil price projections for 2050 ($/barrel, 2011 prices)			
Source	Estimate	$/boe (2011 prices)	Comment
Grantham Institute for Climate Change	High	153	Taken from: Energy Futures Lab and Grantham Institute for Climate Change (2013): Halving Global CO2 by 2050: Technologies and Costs. http://www3.imperial.ac.uk/climatechange/publications/collaborative/halving-global-co2-by-2050
	Low	102	
Energy Policy	95th percentile	272	Figures are for 2030 and not clear what price year is used (assume 2011). Taken from: "An expert elicitation of climate, energy and economic uncertainties", Energy Policy, October 2013, vol 61, p811-821. See: http://www.sciencedirect.com/science/article/pii/S030142
	upper quartile	161	
	median	120	
	lower quartile	88	
	5th percentile	52	
US Energy Information Agency	High	201	Figures are for 2040. Taken from: http://www.eia.gov/forecasts/aeo/er/early_prices.cfm
	Reference	139	
	Low	74	
International Energy Agency, Energy Technology Perspectives	2DS prices	90	These are the oil prices for 2050 assumed by the IEA in their 2, 4 and 6C scenarios. Source: IEA Energy Technology Perspectives 2014 (www.iea.org/etp2014).
	4DS prices	137	
	6DS prices	160	
UCL TIAM model	High	145	These oil prices assume a 67% tax rate. They are the oil prices generated by the UCL TIAM model when it produces a 2C and 5C pathway. i.e. These oil prices are endogenously calculated by TIAM.
	Low	133	
UK Department of Energy and Climate Change	High	188	Prices are for 2030, and assumed constant to 2050. https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/212521/130718_decc-fossil-fuel-price-projections.pdf
	Mid	130	
	Low	72	
Global Calculator oil price range	**High**	**272**	**High:** because this is the highest estimate from our literature review. This is the 5th percentile estimate from the Energy Policy study.
	Default	**137**	**Default:** because this is the median fuel cost from our literature review. This is the estimate from the IEA 4DS.
	Low	**52**	**Low:** because this is the lowest estimate from our literature review for 2050. This is the 95 percentile estimate from the Energy Policy study.

Coal

Coal price projections for 2050 ($/tonne, 2011 prices)			
Source	Estimate	$/tonne	Comment
Grantham Institute for Climate Change	High	153	Taken from: Energy Futures Lab and Grantham Institute for Climate Change (2013): Halving Global CO2 by 2050: Technologies and Costs. http://www3.imperial.ac.uk/climatechange/publications/c
	Low	102	
US Energy Information Agency	Average US coal price	169	Figure is for 2040. Taken from: http://www.eia.gov/forecasts/aeo/er/early_prices.cfm
UK Department of Energy and Climate Change	High	160	Prices are for 2030, and assumed constant to 2050. https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/212521/130718_decc-fossil-fuel-price-projections.pdf
	Mid	119	
	Low	90	
International Energy Agency, Energy Technology Perspectives 2014	2DS prices	55	These are the coal prices for 2050 assumed by the IEA in their 2, 4 and 6C scenarios. Source: IEA Energy Technology Perspectives 2014 (www.iea.org/etp2014).
	4DS prices	108	
	6DS prices	124	
UCL TIAM model	4DS	136	UCL TIAM include fuel prices excluding tax in their model, so we have inflated these prices by 39% to include tax.
	2DS	76	
Global Calculator coal price range	**High**	**169**	**High:** this is the highest estimate from our literature review. It refers to the US EIA's coal price estimate.
	Default	**119**	**Default:** this is the median estimate from our literature review. It refers to the DECC mid point coal price projection for 2030.
	Low	**55**	**Low:** this is the lowest estimate from our literature review. It refers to the IEA ETP14 2DS coal price.

Gas

Gas price projections for 2050 ($/Mbtu, 2011 prices)

Source	Estimate	$/Mbtu	Comment
Grantham Institute for Climate Change	High	13.26	Taken from: Energy Futures Lab and Grantham Institute for Climate Change (2013): Halving Global CO2 by 2050: Technologies and Costs. http://www3.imperial.ac.uk/climatechange/publications/collaborative/halving-global-co2-by-2050
	Low	10.20	
Knoema	2020 estimate	9.00	Knoema presents gas prices for 2020 for US (Henry Hub), Europe (UK NBP) and Japan. We have weighted these according the GDP in these countries in 2011 to calculate a global average cost. See: http://knoema.com/ncszerf/natural-gas-prices-long-term-forecast-to-2020-data-and-charts
International Energy Agency, Energy Technology Perspectives 2014	6DS prices	12.32	The IEA publishes gas prices for US, Europe and Japan. We have calculated a global average gas price as an average of these three prices, weighted according to GDP in those countries in 2011. Source: IEA Energy Technology Perspectives 2014 (www.iea.org/etp2014).
	4DS prices	11.06	
	2DS prices	7.41	
Global Calculator gas price range	**High**	**13.26**	**High:** because this is the highest gas price from our review (from the Grantham Institute "high" estimate).
	Default	**11.06**	**Default:** because this is the median of our literature review, from the IEA 4DS.
	Low	**7.41**	**Low:** because this is the lowest gas price from our review from the IEA 2DS.

Annex C: opportunity costs: alternative approaches

As set out in the main paper, the approach to estimating opportunity costs varies considerably depending on what study or model you consider. We concluded that there was no single "correct" approach and in fact it was possible to justify any three of the following approaches for use in the Global Calculator:

1. No opportunity costs
2. Opportunity cost to society
3. Opportunity cost to individual actors

We decided to go for option 2 – more details on this are set out in the main paper. This annex provides more detail on option 1 and 3.

Option 1: no opportunity cost

We could simple exclude opportunity costs from the Global Calculator.

Pros of this approach:

- **Consistent with the engineering approach of the Calculator**. The Global Calculator focuses on measuring physical, tangible aspects of the energy system and it could be argued that our costs methodology should mirror this. The Calculator is an engineering-based model, not an economic one. Economic, optimisation models seek to replicate the behaviour that individual businesses, motorists or householders might make, based on historical observed relationships. They do this using hurdle rates (for more discussion, see option 3 below). But the Global Calculator is not attempting to do this – the user simply asserts what the level of technology roll out should be. So it is arguably not appropriate for us to include opportunity costs.
- **Consistent with view that enterprise is not a factor of production**. The Classical Economics school of thought argues that there are only three factors of production: labour, capital and land. This approach would consider the rewards to enterprise as a transfer payment, rather than a resource cost. Given that we are attempting to capture the resource cost, this suggests we should not include opportunity costs.

Cons of this approach:

- **Prudent to err on the side of inclusion**. Opportunity costs are significant and in real life they have a real impact on investment decisions, so it is prudent to include them.
- **Bias towards capital intensive projects**. If we excluded opportunity costs, the Calculator would be bias towards capital intensive projects: they would appear cheaper than they really are.
- **Consistent with other models**. TIAM-UCL (and most other energy models) include opportunity costs.
- **Consistent with view that enterprise is a factor of production**. In contrast to the Classical school of thought, the Neo-Classical Economics approach argues that enterprise is a factor of production. So given that we are seeking to calculate resource costs, we should include opportunity costs (as the reward to enterprise).

Option 3: opportunity cost to individual actors

This approach considers the opportunity cost to the individual actor. i.e. What return could a business / householder / motorist have achieved by investing in the next best project? The table below sets out what these opportunity costs to individual actors might look like, for the US region.

Opportunity costs to individual actors: rates we considered for the Global Calculator

Sector	Central/ high/ low	Real interest rate	Loan lifetime	Comment
Electricity generation	Central	8%	15 years	Ernst & Young have advised that, based on their expertise on the electricity sector, the US real interest rate for this sector would be 4 to 12%. The mid point of this is 8%. This looks about right, as the UK MARKAL model uses 10% for power/industry. Also, research for the UK Calculator indicated that the equivalent rate paid by UK electricity generators would be 10% but since then interest rates have fallen. The IEA use an 8% required rate of return for their electricity and district heat network technologies. The lifetime loan could be 15 years as this reflects the amount of time that these loans are, in reality, paid off over.
	Low	0	15 years	Zero is appropriate because some users will wish to calculate costs excluding opportunity. (See discussion under option 1: no opportunity cost).
	High	18%	15 years	18% is a 10% uplift to the central. This large uplift reflects the fact that the US (and may other countries) are currently experiencing historically low interest rates. The Federal Reserve base rate is currently low compared to its sixty year average of 6.8% and its all time high of around 20% in 1981. As a comparator, the UK base rate is currently 0.5%, compared to high of nearly 15% in 1989.[11]
Heavy industry	Central	8%	15 years	We presume that industry will face similar interest rates as the electricity generation sector, so the interest rate is the same.
	Low	0	15 years	Same reason for setting the electricity low interest rate at 0%, see above.
	High	18%	15 years	This is a 10% uplift on the central, based on the same rationale as for electricity, above.

[11] https://www.usbank.com/home-equity/ , https://www.bankofamerica.com/home-loans/home-equity-loans/overview.go

Sector	Central/ high/ low	Real interest rate	Loan lifetime	Comment
Transport	Central	2%	6 years	A high street interest rate for car loans in the US is around 2.4 to 4.9%[12]. Take a mid point of 4%. For those who take out a loan to pay for the car, there is an opportunity cost of 4% to reflect interest repayments they must make. Some people will not take out a loan and will buy the car upfront – in this case, 4% reflects the foregone interest they could have received by investing the money in, say, a bank. (Note that the interest rate individuals can get from a bank is less than 4%, so this is an overestimate. But the required rate of return for businesses purchasing vehicles will be higher, so these two effects could balance out to 4%.) Planes and trains will probably be subject to higher interest rates, but passenger vehicles will be the vast majority of capital expenditure in transport so it is most important that the rate is relevant to that.[13] An appropriate loan lifetime would be 6 years, as this is the average length of time that a US citizen owns a new car, before selling it on[14].
	Low	0	6 years	Same reason for setting the electricity low interest rate at 0%, see above.
	High	12%	6 years	This is a 10% uplift on the central, based on the same rationale as for electricity.
Buildings	Central	2%	10 years	A high street interest rate for home improvement loans in the US is around 4%[15]. But not everyone will take a loan to finance this, and some people will have access to cheaper rates. Making the simple assumption that half of these improvements are purchased through these loans, this brings the central interest rate down to 2%. 10 year loan period seems reasonable (e.g. it's the typical length of a Green Deal improvement).
	Low	0	10 years	Same reason for setting the electricity low interest rate at 0%.
	High	12%	10 years	This is a 10% uplift on the central, based on the same rationale as for electricity.

[12] http://www.path2usa.com/car-loan , https://www.bankofamerica.com/auto-loans/auto-loans-financing.go
[13] In the UK Calculator, passenger vehicles accounted for at least three quarters of transport costs.
[14] https://www.polk.com/company/news/u.s._consumers_hold_on_to_new_vehicles_nearly_six_years_an_all_time_high

[15] https://www.bankofamerica.com/home-loans/home-equity-loans/overview.go , https://www.usbank.com/home-equity/ Note these rates are higher than those levied by the Green Deal in the UK (the base rate that a Green Deal customer will pay is 6.96%, or around 5.5% real rate. But the Green Deal team emphasised that some UK residents would access cheaper finance than this through, for example, their mortgages.

Interest rate for other regions

Under option 3, we would need to apply an adjustment factor to these US interest rates in order to calculate the appropriate rates in the other six regions. Here are some possible ways we could do this:

- Revise rates in proportion to the central bank rates in these regions today. We could either do this as an absolute or relative adjustment (e.g. if the US had a base rate of 0.25%; if the Western Europe base rate was 0.5%, then we could double the opportunity cost or add 0.25% to it). But this approach would not work well when converting US to, say, Africa region prices because there would be a higher risk associated with investment in Africa due the region's different political and regulatory frameworks. But this risk would not be fully reflected in the base rate differential.
- Alternatively, the adjustment factor could be based on the different region rates used by TIAM-UCL.

Are "hurdle rates" a good estimate for the opportunity costs we should use in the Global Calculator?

Economic optimisation models (such as UCL-TIAM) use "hurdle rates" to help the model to replicate investment behaviour exhibited by businesses, motorists, etc. For example, the UK MARKAL model uses a hurdle rate of 10% for electricity generation and industry and 7.5% for transport and buildings. But the Global Calculator does not work like this: in the Global Calculator, the user simply asserts how much technology will be rolled out in each sector.

So are hurdle rates helpful for informing our choice of opportunity rates for use in the Global Calculator? We should consider this separately for businesses (electricity generators and industry) and individuals (motorists/householders).

- **Businesses (electricity generators and industry)**. In economic optimisation models, hurdle rates are necessary because we know from observing the behaviour of, say, electricity generators, that they will only invest in a new power plant if the rate of return on their investment is greater than or equal to, say, 10%. Therefore, when economic optimisation models calculate the least cost pathway to 2050, they should account for the fact that electricity generators will require at least 10% return before investing. i.e. For an electricity generator, the "next best project" has a rate of return of 10%. They require 10% to: compensate them for the cost of taking out a loan and making interest payments on it; reward them for taking on the riskiness of the project; and to provide them with a profit to their investment. In conclusion, it would be fair to say that a hurdle rate of, say, 10% is an accurate estimate of the opportunity cost faced by businesses, so they <u>could be used</u> to inform our estimates for opportunity costs in the Global Calculator.
- **Individuals (motorists/households).** Motorists also behave as if they have a high hurdle rate (e.g. 7.5%). i.e. A motorist will only buy a more expensive, fuel efficient vehicle, if the return from their capital investment exceeds 7.5% rate of return. To some extent, this hurdle rate reflects the cost of taking out a loan and making interest payments on it. But this high hurdle rate is mostly due to the fact that motorists have a high rate of time preference (i.e. they do not like spending more money on the upfront purchase price of the vehicle). So it is not appropriate to interpret the full, say 7.5%, as an opportunity cost faced

by motorists/householders, therefore it would not be appropriate to use this as an estimate for opportunity costs in the Global Calculator.

Pros of this approach:

- **Consistency with other models**. The opportunity costs set out in the above table would be more comparable with the assumptions used in other economic models. However these are economic models and, as discussed above, it is not necessarily appropriate to use the approach they do.

Cons of this approach:

- **Costs by sector could be misleading**. By applying a higher opportunity cost to electricity generators/manufacturing, capital expenditure in these sectors will appear more expensive than capital expenditure in the transport/buildings sectors. This is true from the perspective of the individual actor. But the user might incorrectly infer that, from a *societal* point of view, it was optimal to invest relatively more capital expenditure in transport/buildings and relatively less in electricity/manufacturing. But this would be incorrect. From a societal point of view, opportunity costs should be considered equal across all sectors. (For more detail, see discussion in the main paper.)
- **Complex**. This approach would be complex to implement in the Global Calculator because it would require us to set opportunity costs that would vary by sector and region.

Annex D: discount rate

When costs are presented in the web tool they are undiscounted, in keeping with our principle to keep the model methodology simple.

However if users wish to see the impact of discounting, they can do so in the spreadsheet and we would recommend that they discount at the standard UK Government HM Treasury Green Book discount rate (3.5% for the first thirty years, 3% thereafter). This annex explains why we recommend this approach over the Stern-adjusted lower discount rate (of 3% and declining).

HM Treasury Green Book discount rate

The Treasury's Green Book[16] sets out the definition and de-construction of the Social Time Preference Rate (STPR). The STPR is the rate used for discounting future benefits and costs in order to trade-off the value society attaches to present, as opposed to future, consumption. The STPR, represented by r, is the sum of these two components, i.e.:

$r = \rho + \mu.g$

There are two components to the STPR:

- ρ: rate at which individuals discount future consumption over present consumption, on the assumption that no change in per capita consumption is expected
- $\mu.g$: per capita consumption is expected to grow over time and therefore future consumption will be plentiful relative to the current position and thus have lower marginal utility. This effect is represented by the product of the annual growth in per capita consumption (g) and the elasticity of marginal utility of consumption (μ).

The term ρ comprises two elements:

- L: catastrophe risk: the likelihood that there will be some event so devastating that all returns from policies, programmes or projects are eliminated, or at least radically and unpredictably altered. Examples are technological advancements that lead to premature obsolescence, or natural disasters, major wars etc.
- δ: pure time preference: reflects individuals' preference for consumption now, rather than later, with an unchanging level of consumption per capita over time.

The values of these factors are as follows: $r = \rho + \mu.g$ $3.5 = 1.5 + (1*2)$

However over the longer term (beyond 30 years), uncertainty over the future suggests the discount rate should decline. So the discount rate becomes:

<u>Table 1 – Standard Green Book discount rate</u>

16 https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/220541/green_book_complete.pdf

Period of years	0–30	31-75	76–125	126–200	201–300	301+
Discount rate	3.5%	3.0%	2.5%	2.0%	1.5%	1.0%

Stern-adjusted lower discount rate

The Stern Review concluded that in the context of climate change we should use a lower discount rate. The Stern Review argues that in the case of climate change, ρ should be lower because:

- L: catastrophe risk: this is lower when considering economy-wide action to cut emissions than when looking at individual projects because the risk of the world ending is less than the risk of an individual project becoming obsolete.
- δ: pure time preference: Stern reflected an ethical judgement that it was not appropriate to discount on the basis of birth date.

On this basis supplementary guidance from HMT provides an adjusted profile of discount rates, set out below.

Table 2 – Stern-adjusted discount rates

Period of years	0–30	31–75	76–125	126–200	201–300	301+
Discount rate	3.0%	2.57%	2.14%	1.71%	1.29%	0.86%

Which discount rate should we use in the Global Calculator?

The HMT supplementary guidance suggests using both discount rates as a sensitivity test of the results. However we need to decide which rate we use as a default; unfortunately the guidance is not very clear on this. However there are three arguments which tend to support the idea of using the standard 3.5% as the default discount rate:-

Issue	Supports the use of the following discount rate
Precedent. The Impact Assessment for the UK's 2050 target to reduce greenhouse gas emissions by 80% on 1990 levels used the standard Green Book discount rate.	**3.5%**

Time horizon. The supplementary guidance suggests that this lower discount rate should be used where "the effects under examination are very long term (in excess of 50 years)". However the Global Calculator looks out just 35 years ahead.	**3.5%**
Net benefits. The guidance and verbal advice from the Treasury indicates that the Stern adjusted discount rate should be applied to net cost-benefits. But the Global Calculator only considers costs.	**3.5%**

Therefore we will use the Green Book discount rate of 3.5%, declining to 3% after 30 years, as our default choice (as set out in table 1). But users will be able to sensitivity test this in the spreadsheet.

Annex E: Technologies in the Global Calculator

Urban bicycle
Urban motorbike with internal combustion engine
Urban motorbike with electric engine
Urban four wheeled car with internal combustion engine based on liquid fossil fuels
Urban four wheeled car with internal combustion engine based on gas
Urban four wheeled car with plug-in hybrid technology (electric and internal combustion)
Urban four wheeled car with electric engine
Urban four wheeled car with hydrogen engine
Urban bus with internal combustion engine based on liquid fossil fuels
Urban bus with internal combustion engine based on gas
Urban bus with plug-in hybrid technology (electric and internal combustion)
Urban bus with electric engine
Urban bus with hydrogen engine
Urban train with non-electric power
Urban train with electric power
Rural walking
Rural bicycle
Rural motorbike with internal combustion engine
Rural motorbike with electric engine
rural four wheeled car with internal combustion engine based on liquid fossil fuels
rural four wheeled car with internal combustion engine based on gas
Rural four wheeled car with plug-in hybrid technology (electric and internal combustion)
Rural four wheeled car with electric engine
Rural four wheeled car with hydrogen engine
rural bus with internal combustion engine based on liquid fossil fuels
rural bus with internal combustion engine based on gas
Rural bus with plug-in hybrid technology (electric and internal combustion)
Rural bus with electric engine
Rural bus with hydrogen engine
Rural train with non-electric power
Rural train with electric power
International passenger plane short haul with traditional engine
International passenger plane short haul with hydrogen power
International passenger plane long haul with traditional engine
International passenger plane long haul with hydrogen power
International passenger train with non electric power
International passenger train with electric power
Domestic light freight truck with internal combustion engine based on liquid fossil fuels
Domestic light freight truck with internal combustion engine based on gas
Domestic light freight truck with plug-in hybrid technology (internal combustion engine and electric)
Domestic light freight truck with electric engine
Domestic light freight truck with hydrogen engine
Domestic heavy freight truck with internal combustion engine based on liquid fossil fuels
Domestic heavy freight truck with internal combustion engine based on gas
Domestic heavy freight truck with plug-in hybrid technology (internal combustion engine and electric)
Domestic heavy freight truck with electric engine
Domestic heavy freight truck with hydrogen engine
Domestic freight train with non-electric power

Domestic freight train with electric power
Domestic freight ship with traditional engine
Domestic freight ship with hydrogen engine
international heavy freight truck with internal combustion engine based on liquid fossil fuels
international heavy freight truck with internal combustion engine based on gas
International heavy freight truck with plug-in hybrid technology (internal combustion engine and electric)
International heavy freight truck with electric engine
International heavy freight truck with hydrogen engine
International freight train with non electric power
International freight train with electric power
International freight ship with traditional engine
International freight ship with hydrogen power
International freight plane with traditional engine
International freight plane with hydrogen engine
Urban solid boiler used by people with access to electricity for space heating
urban liquid boiler used by people with access to electricity for space heating
urban gas boiler used by people with access to electricity for space heating
urban heat pump used by people with access to electricity for space heating
urban electricity heater used by people with access to electricity for space heating
urban solar heater used by people with access to electricity for space heating
urban chp used by people with access to electricity for space heating
urban district heating used by people with access to electricity for space heating
rural solid boiler used by people with access to electricity for space heating
rural liquid boiler used by people with access to electricity for space heating
rural gas boiler used by people with access to electricity for space heating
rural heat pump used by people with access to electricity for space heating
rural electricity heater used by people with access to electricity for space heating
rural solar heater used by people with access to electricity for space heating
rural chp used by people with access to electricity for space heating
rural district heating used by people with access to electricity for space heating
non residential solid boiler used by people with access to electricity for space heating
non residential liquid boiler used by people with access to electricity for space heating
non residential gas boiler used by people with access to electricity for space heating
non residential heat pump used by people with access to electricity for space heating
non residential electricity heater used by people with access to electricity for space heating
non residential solar heater used by people with access to electricity for space heating
non residential chp used by people with access to electricity for space heating
non residential district heating used by people with access to electricity for space heating
Urban solid boiler used by people with access to electricity for water heating
urban liquid boiler used by people with access to electricity for water heating
urban gas boiler used by people with access to electricity for water heating
urban heat pump used by people with access to electricity for water heating
urban electricity heater used by people with access to electricity for water heating
urban solar heater used by people with access to electricity for water heating
urban chp used by people with access to electricity for water heating
urban district heating used by people with access to electricity for water heating
rural solid boiler used by people with access to electricity for water heating
rural liquid boiler used by people with access to electricity for water heating
rural gas boiler used by people with access to electricity for water heating
rural heat pump used by people with access to electricity for water heating
rural electricity heater used by people with access to electricity for water heating

rural solar heater used by people with access to electricity for water heating
rural chp used by people with access to electricity for water heating
rural district heating used by people with access to electricity for water heating
urban compression air conditioner used by people with access to electricity
urban chillers systems used by people with access to electricity
urban solar cooling used by people with access to electricity
rural compression air conditioner used by people with access to electricity
rural chillers cooling used by people with access to electricity
rural solar cooling used by people with access to electricity
non residential compression air conditioner used by people with access to electricity
non residential chillers cooling used by people with access to electricity
non residential solar cooling used by people with access to electricity
urban solid stoves used by people with access to electricity
urban liquid stoves used by people with access to electricity
urban gas stoves used by people with access to electricity
urban electricity stoves used by people with access to electricity
urban traditional biomass boiler used by people with access to electricity
rural solid stoves used by people with access to electricity
rural liquid stoves used by people with access to electricity
rural gas stoves used by people with access to electricity
rural electricity stoves used by people with access to electricity
rural traditional biomass boiler used by people with access to electricity
urban incandescent light bulb
urban halogens light bulb
urban compact fluorescent lamp
urban LEDs bulb
rural incandescent light bulb
rural halogens light bulb
rural compact fluorescent lamp
rural LEDs bulb
non residential incandescent light bulb
non residential halogens light bulb
non residential compact fluorescent lamp
non residential LEDs bulb
urban refrigerator used by people with access to electricity
urban dishwashers used by people with access to electricity
urban clothwasher used by people with access to electricity
urban clothdryers used by people with access to electricity
urban TV used by people with access to electricity
urban miscellaneous used by people with access to electricity
rural refrigerator used by people with access to electricity
rural dishwashers used by people with access to electricity
rural clothwasher used by people with access to electricity
rural clothdryers used by people with access to electricity
rural TV used by people with access to electricity
rural miscellaneous used by people with access to electricity
Urban solid boiler used by people without access to electricity
urban traditional biomass boiler used by people without access to electricity
Rural solid boiler used by people without access to electricity
Rural traditional biomass boiler used by people without access to electricity

Urban traditional biomass stoves used by people without access to electricity
Rural traditional biomass stoves used by people without access to electricity
Urban buildings
Rural buildings
Global non residential equipment
Other energy consumption of non residential sector (except lighting, appliances, heating, cooling)
Non residential buildings
Oxygen steel technology
Hisarna Oxygen steel technology
Electric steel technology
DRI Electric steel technology
Alumina Aluminium technology
Primary Aluminium technology
Secondary Aluminium technology
Chemicals: High Value Chemicals technology
Chemicals: Ammonia technology
Chemicals: Methanol technology
Chemicals: Others technology
Pulp & paper: Pulp technology
Pulp & paper: Virgin technology
Pulp & paper: Recycled technology
Cement technology
Timber technology
Other industries technology
Unabated solid-fuel ultrasupercritical power plant
Unabated solid-fuel supercritical power plant
Unabated solid-fuel subcritical power plant
Unabated liquid-fuel efficient power plant
Unabated liquid-fuel inefficient power plant
Unabated open-cycle gas turbine power plant
Unabated combined cycle gas turbine power plant
Carbon capture solid-fuel ultrasupercritical power plant
Carbon capture solid-fuel supercritical power plant
Carbon capture solid-fuel subcritical power plant
Carbon capture liquid-fuel efficient power plant
Carbon capture liquid-fuel inefficient power plant
Carbon capture open-cycle gas turbine power plant
Carbon capture combined cycle gas turbine power plant
Nuclear power stations
On shore wind farms
Off shore wind farms
Hydroelectric dam
Tidal
Wave
Solar photovoltaic farms
Concentrated solar farms
Geothermal
Storage unit

Annex F: Region factors

The Global Calculator uses costs for just one world region, the US. However, in reality, capital and operating costs may vary between different countries. Therefore, we have also populated the model with "region factors". These factors are used to generate costs for world regions, e.g. the region factor for ICE cars in India is 0.8. TIAM-UCL has region factors for 16 regions which it uses to convert US costs into the appropriate country equivalent. In the TIAM-UCL model, these region factors are constant over time[17]. TIAM-UCL have provided us with five/six sets of region factors, so we now have the following costs in the Global Calculator for all energy technologies:

Region
US
India
China
Central & South America (same as Former Soviet Union)
Western Europe
Africa

We chose these regions because they represent a good spread of cost variation. Also, these regions combined currently represent 70% of global population[18] and 75% of global GDP[19].

In the Global Calculator spreadsheet, the user will be able to toggle between different region choices to view the cost results as if the whole world faced Indian/Chinese/African, etc prices. Typically region factors are +/- 20% of US costs, but in extreme cases they can be +/- 40%.

[17] This is probably an unrealistic assumption: we would expect emerging economy costs to converge to developed country levels over time. We have used this assumption because it was simplest to implement what was available from the UCL TIAM model.
[18] In 2012 the world's population was: ~310m US, ~400m Western Europe, ~1,240m India, ~1,350m China, ~40m Central America, ~390m South America, ~~300m Former Soviet Union (1990) and ~1,030m Africa. This sums to ~5,060m. The world population in 2014 is ~7,050.
[19] In 2012 the GDP of these regions are: ~$16tn US, ~$17tn total EU, ~$2tn India, ~$8tn China, ~$5tn total Latin America, ~$2n Russia (i.e. excludes other former Soviet states) and ~$2tn Africa. The global GDP in 2012 was around $70tn.