Technology Comparator
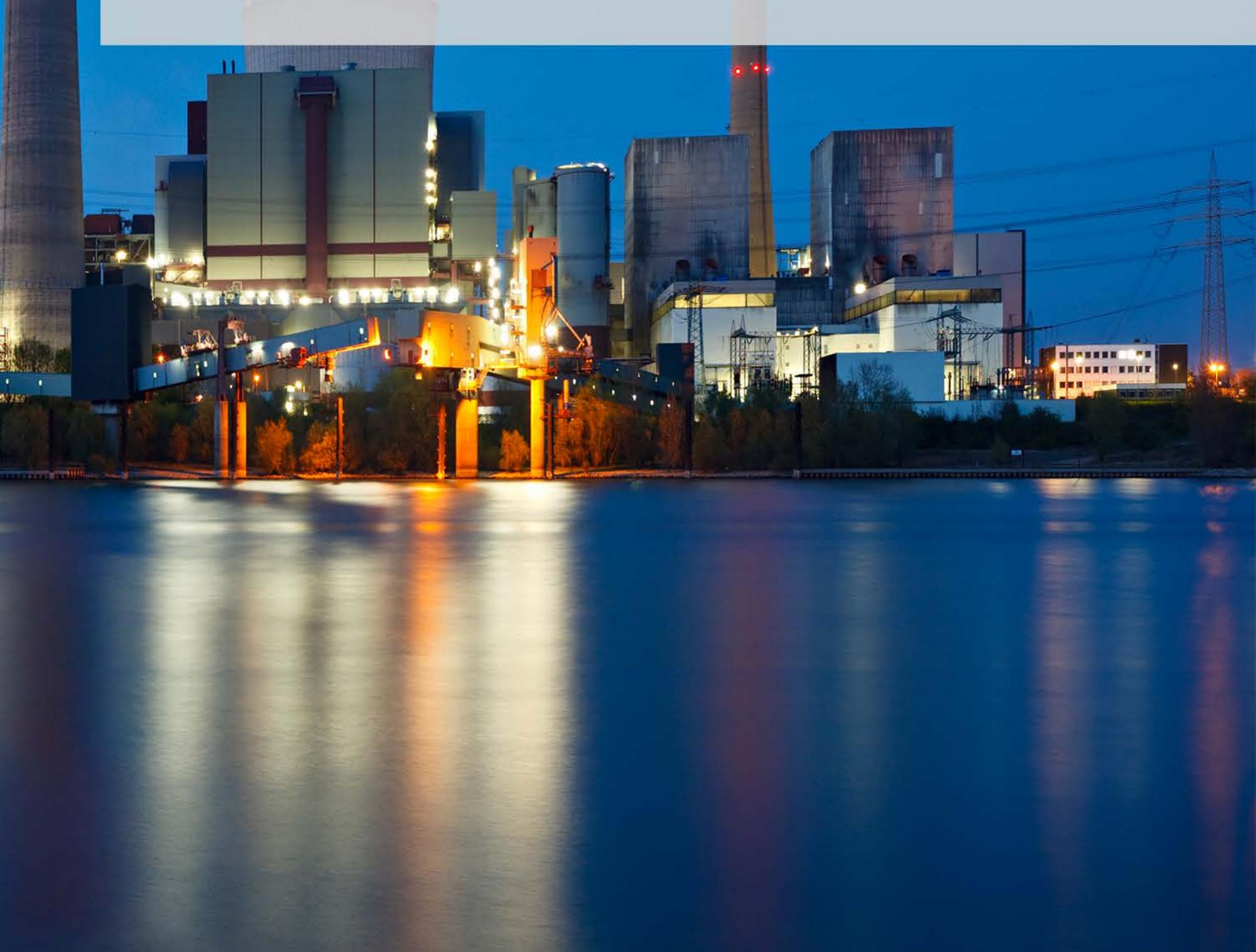# User Guide

Technology Comparator User Guide V1

Table of Contents

Introduction

Purpose of the spreadsheet tool

This tool was developed by ETI in order to supplement the widely used levelised cost of electricity (LCOE). It calculates the cost of accommodating the energy demand in GB[1] by using only a pair of energy technologies; one used as the primary technology under examination, and the other as the back-up. The reasoning is that LCOE does not capture the dispatchability and flexibility features of generating technologies and therefore the kinds of impact they have as part of a mix of different generating technologies, demand management and interconnection.

The set of primary technologies examined in the tool include:

    i.   Onshore Wind
    ii.   Offshore Wind
   iii. Solar PV
   iv. Nuclear
    v.   CCGT with CCS

whereas supplementary technologies are

    i.   CCGT
    ii.   Storage (Li-ion batteries).

Overview

The selected combination of a primary and a supplementary energy technology is used to accommodate the GB energy demand for every single settlement period within a year. The incurred costs of the two technologies combination (capital, O&M, VOM, fuel and CO_{2e} where applicable) are then divided by the total annual energy demand to calculate the £/MWh for the total energy provided and consumed. (Assumption: Single node – No transmission costs or losses are taken into account)

The combination of these two technologies' capacity and availability is derived by optimising (minimising) the cost for accommodating the annual energy demand with the use of Excel's Solver, while always maintaining that the energy demand is served in every single settlement period.

Structure of the document

The document starts by presenting the tool's use, then it describes its structure and operation, finally it presents how and what can be modified i.e. to add a new annual time series or a new technology. The appendix contains the formulae and details regarding data and sources.

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[1] The scope is GB and not the UK, due to the National Grid dataset which is used. Please cf. "Data" section in the Appendix.

1. Use of the tool

Interaction

The interaction between the user and the tool takes place:

1. through the "Main page" worksheet, where the users enter their preferred options for the optimisation setup and

2. through the worksheets "Outputs", "Graphs" and "LCOE" where the users can access selected info on the results.

In order to use the tool for optimisation, the user has to first load the Solver add-in into Excel by following the instructions of the relevant hyperlink[2]. The tool also requires Visual Basic to be installed.

User Inputs

"Main Page" worksheet
This tab contains the User Options on the upper left side of the screen. This is the place where one can choose which technologies will be combined to serve the demand, along with the year which will be used for the time series data.

There are 5 user options, presented through 4 drop-down menus and one manual entry for the CO_{2e} cost. Their structure and contents is as follows:

- **Year:** This list contains the years from 2011 to 2016. The years refer to the relevant time series of total energy demand per settlement period, as well as the capacity factors for renewables technologies per settlement period throughout the whole year ("generation profiles").
- **Generation technology:** This list contains the set of primary technologies used in the tool and it contains three renewables technologies, Onshore Wind, Offshore Wind and Solar PV, and two dispatchable, Nuclear and CCGT with CCS.
- **Supplementary Technology:** The final list contains the back-up technologies supplementing the primary one in accommodating the demand. These comprise CCGT and Storage (Li-ion battery).
- **CO_2 cost:** This cell can be used to insert the carbon price which will be applied to the CO_2-emitting technologies. There are no predetermined values or a defined valid range to allow user's flexibility, except for a validation allowing only positive or zero values.
- **Include "Embedded Carbon":** This is a drop-down list with TRUE and FALSE values indicating whether the embedded carbon of each technology should be taken into account in the carbon cost and carbon emissions calculations.

ELCOE (Extended Levelised Cost of Energy) is the label given to the average annual cost of production using the selected primary and back-up technologies. The tool also calculates the LCOE of the primary technology, which can vary from year to year with the availability of renewables resource. After the user options have been selected, the "Optimise" button should be pressed to launch the optimisation process that minimises the ELCOE result found in cell "E23" of the same tab. The capacity results of the technology pair leading to that ELCOE value are shown in cells "B18-B20", whereas the other items of the "Main Page" tab are presented in greater detail in section 3.

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[2] https://support.office.com/en-us/article/Load-the-Solver-Add-in-in-Excel-612926fc-d53b-46b4-872c-e24772f078ca?ui=en-US&rs=en-US&ad=US

Optimisation results

"Outputs" worksheet
This tab contains a breakdown of the costs for the primary and secondary technology, the costs for the counterfactual case (assumed to be 100% CCGT generation) and information on the selected technologies. This is the place where the users can find a more detailed view of how the costs are structured and acquire a full view of the formulae for achieving the ELCOE.

"Graphs" worksheet
In this tab the users can find graphs and their respective data. The graphs show: 1. the composition of the total costs split between the various elements of the primary and supplementary technology and 2. the demand, generation and charge/discharge of storage for the months of January and July.

"LCOE" worksheet
The LCOE metric is calculated in this tab for reasons of comparison between the two distinct metrics.

2. Set up and function

Spreadsheet structure and relevant function

The spreadsheet contains a number of tabs each of which is used in a distinct manner. The tabs are listed below according to their use followed by a short description, whereas they are presented in greater detail later in the section.

A feature of the spreadsheet is the extensive application of Named Ranges which are used to facilitate the reading of the formulae and contribute to the consistency and ease of data modification[3].

Tabs overview

General tabs
- Info: Contains general info regarding the spreadsheet tool
- Main page: The main point of interaction; user options are selected here and the main results are shown to the user.

Data tabs
- InputDataGeneral: System-wide data values and technical elements for the technologies such as varying efficiencies, unit sizes.
- InputDataTech: Contains a table with technology specific data such as costs, lifetime, construction time

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[3] Name Ranges are separated in groups defined by their prefix. i.e These starting with "Assumptions" refer to data, "List" to lists of items, "Input" to the values used in the calculations and so forth.

Output tabs
- Outputs: Contains the detailed cost outputs of the optimisation processes and the counterfactual one.
- Graphs: Contains graphs of the cost composition and examples of demand and generation.
- LCOE: Contains the calculation of the LCOE metric for the selected primary technology

Calculations tabs
- CalculationsInterm: Tab holding the calculations for renewables primary technologies
- CalculationsDisp: Tab holding the calculations for dispatchable primary technologies
- CalculationsCounterfactual: Page holding the calculations for the counterfactual, where CCGT is assumed to be the sole technology

Hidden tabs
- Runs: This tab logs information about the runs performed (user options, ELCOE & LCOE, start/end time of optimisation)
- GraphsAuxiliary: Used to concentrate data for the "Carbon Intensity Duration Curve" graphs
- ValidationLists: Contains the validation lists used in the drop-down menus of the "Main Page" user selections, some statistics regarding the energy demand and capacity factors for each year and also a table with conversion factors between units of Power and Energy.
- Raw[year]: These tabs for the year 2011-2016 contain the time-series data used, which were taken from GB System Operator.

Individual tab description

Info

The tab contains i. the title of the tool, ii. its version, iii. the date it was published, iv. the purpose of the tool, v. the list of the tabs, vi. the technologies in the user options and vii. the update notes.

Main Page

The tab contains in the upper left corner the user options (i. Year, ii. Generation Technology, iii. Supplementary Technology, iv. CO2 Cost and v. inclusion of embedded carbon) and right next to them the user options used when the spreadsheet was last time optimised. The latter are used for comparison with the new user options, prompting the user to re-optimise when any of the options has been changed.

Below the user options part, there are the following sections (top to bottom):

- Statistics of the selected year time series (cells "B12-B14"). More specifically i. the total annual demand of electricity, ii. the mean capacity factor for the variable renewable generation (for dispatchable technologies this is set to 100%) and iii. the capacity needed to generate within a year an amount of energy equal to the annual energy demand with the given average capacity factors[4]. The last one is used when storage is selected as a back-up option to ensure that there will always be adequate energy to accommodate the annual demand.

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[4] $Min\ Capacity = \dfrac{Annual\ Energy\ Demand}{Capacity\ Factor * Hours\ in\ Year}$

- Optimisation results data ("B18-B20"), like i. the primary technology capacity, ii. the secondary technology capacity and iii. the storage power rating when it is selected as back-up or the maximum change of power output between two settlement periods for CCGT as back-up.
- Key figures of the counterfactual case ("B24-B27"), namely a system run exclusively on CCGT. More specifically these include the i. the CCGT capacity, ii. the ELCOE of that system iii. the carbon intensity and iv. the share of carbon costs due to carbon price in the total costs.

On the top middle of the screen is the optimisation button launching the macros and below it are key outputs of the optimisation results:

- the shares of the demand accommodated by the primary technology or the secondary technology ("E12-E13")
- the total generation of the primary technology as a share of the annual demand, the overspill and the storage losses where applicable ("E17-E19")
- the ELCOE of the optimisation ("E23")
- the average carbon intensity of the solution ("E24")
- the LCOE of the primary technology ("E26")

To the right of the results' figures are the relevant graphs showing:

- how the demand is satisfied by the 2 technologies, as well as the amount of overspill
- the carbon intensity duration curve for the year[5]

InputDataGeneral
This tab contains figures used system-wide, such as but not limited to: Cost of Capital, NPV discount rate, tCO_2 cost, Storage Efficiency and so forth. It also contains short tables with the efficiency rates for dispatchable technologies and assumptions over unit sizes for the Gas turbines power plants.

The data sources are described in the relevant section of the Appendix.

InputDataTech
This tab contains a table with technology specific data related to costs and time used in cost calculation, where each column represents a technology and each row a feature. All the data have values inserted directly, with the exception of the last 3 lines containing Annualised, IDC and NPV factors. For the Nuclear and Gas technologies i. the Fuel & VOM costs[6] and ii. the CO_2-emissions cost are also calculated by using the efficiency rates, the fuel costs and the carbon costs respectively.

The data sources are described in the relevant section of the Appendix.

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[5] The graph is blank whenever a combination of non-CO2 emitting technologies is selected (namely, renewables or Nuclear as primary + Storage as supplementary).
[6] These are the sum of VOM costs with the addition of fuel costs per MWh of output, where applicable.

Outputs

The outputs tab is the place where a more detailed breakdown of the total costs can be found, together with the technology specific costs for facilitation of the user[7]. The costs are calculated over the whole period of a primary generation technology's life with the use of factors (annualised capital costs, IDC and NPV[8]).

The top section of the page is split in 3 parts which show (from left to right) the cost breakdown for i. the counterfactual case, ii. the optimisation with intermittent technologies as primary options and iii. the optimisation with dispatchable cases[9]. The total costs components are:

- Capacity costs (Volume and Power Rating for the case of Storage)
- Fixed costs
- Fuel & VOM costs
- Emissions costs

The components presented above are summed up for the primary and complementary technology individually and then both are added together to extract the total costs over the lifetime of the primary technology. The ELCOE is calculated by dividing the costs' sum with the annual demand.

In addition to costs, there is a number of few other metrics shown in the Outputs tab:

- Carbon Intensity
- CO_2 cost share
- Total energy generated by the primary technology (as share of the demand)
- Share of the demand accommodated by the primary technology
- Share of the demand accommodated by the supplementary technology
- Overspill, losses from storage (if applicable) as well as other metrics for the timeseries

Note: Conditional formatting is used in this tab, so that the dispatchable results will be visible when a dispatchable technology is selected as primary and vice versa for the intermittent renewables.

CalculationsInterm

This is the tab where the calculations for the combinations containing VRE technologies take place. The exact steps and formulae are presented in detail in the Appendix.

CalculationsDisp

Similarly to the tab above, this tab contains the calculations for the dispatchable technologies and is presented in detail in the Appendix.

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[7] The cells with light grey font are used during the optimisation process and also indicate the last time the optimisation was launched.

[8] In the cases where the lifetime differs between the primary and the supplementary technology, the NPV factor of the primary one is applied to both.

[9] The results are split in 3 parts due to the use of different tabs for the results' calculations. The calculations were kept separate between dispatchable and VRE, due to the different way their calculations are structured.

CalculationsCounterfactual

This final calculations tab contains the calculations for the counterfactual case. It is presented in detail in the Appendix.

Hidden tabs

GraphsAuxiliary

This tab contains the calculations and values – arranged in centiles – used for the plotting of the carbon intensity duration curves per each calculations tab described above.

ValidationLists

This is the place where the lists for the drop-down menus can be found, with some statistics for the data series used to the right and also a table with unit conversions.

- The lists contain i. the years, ii. the primary generation technologies, iii. a field indicating whether the generation technologies are intermittent and iv. the supplementary technologies.
- The statistics contain i. the total annual demand and ii. the average capacity factors of the VRE technologies.
- The conversion table contains the numbers used for conversion of power and energy units with the use of Named Ranges to facilitate the reading of the formulae.

Raw Data tabs

The tabs named "Raw[year]" contain the annual time series used in the calculations. The fields contain the following timeseries in that order:

- Date
- Settlement period (half-hourly)
- GB demand per settlement period
- Onshore wind capacity factor per settlement period
- Solar PV capacity factor per settlement period
- Offshore wind capacity factor per settlement period[10]

VBA routines

The VBA routines are arranged in two modules named "DataRoutines" and "OptimisationRoutines" respectively.

The "OptimisationRoutines" module contains the following subroutines:

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[10] Offshore Wind capacity factors data were not available, therefore the timeseries were constructed by applying a multiplying factor to the onshore wind capacity factors timeseries based on the assumption that i. both are affected by the same weather patterns approximately, ii. but offshore has higher wind potential. Therefore, the offshore wind capacity factor is the result of a formula, which upscales the concurrent onshore wind capacity factor by applying a multiplier, while capping it at 100%.

- "SolveIntermittent" and "SolveDispatchable" which set up the optimisation by i. assigning starting values for the decision variables and ii. defining the constraints and then call the solver for the intermittent and the dispatchable technologies respectively[11].
- The "Optimise" subroutine is launched by the Optimise button form control and is calling the one of the two subroutines above depending on the kind of primary technology that has been selected. It performs also additional actions like saving the user options and logging them in the "Runs" hidden worksheet.
- The "BatchRuns" routine can be used to launch groups of optimisations. It can be run only through VBA and in order to be used by advanced users to facilitate their analyses.

The "DataRoutines" module contains the following subroutines and functions:

- The "AssignRawValues" subroutine copies the date, settlement period, demand and capacity factors timeseries values from the selected user option data worksheets into the calculations tabs
- The "CostCompostionData" and "CostCompositionChart" gather the individual cost components data and create the chart of the ELCOE cost composition respectively in the "Graphs" tab
- The "MonthlyData" subroutine gathers the data of demand, generation, storage charge/discharge and copies them into the "Graphs" tab in order to be used in the relevant charts for January and July

3. Modifications and additions

Cost and technical assumptions

The values found in the tables of "InputDataGeneral" and "InputDataTech" can be changed to reflect different cost or technical assumptions. The values which are results of a formula in the "InputDataTech" – Fuel & VOM costs and CO_2 emissions – is preferable to be modified by changing the primary values. The rest can be modified directly on the cells with the exception of "CO_2 cost" which is part of the user options.

Inserting a new year

The users have the option to add their own time series of half-hourly periods, as long as they comply with a few conventions mentioned below. The new or modified annual time series can be inserted by adding:

- A new tab with a name starting with the prefix "Raw" plus the year (or an alternative identifier) having the same data-field structure and the same locally defined named ranges[12]. The

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[11] The optimisation algorithm used is the "GRG Nonlinear", therefore the starting values are essential to maintain consistent results. The starting values for capacity is $\frac{Annual\ Energy\ Demand}{Average\ Capacity\ Factor * Hours\ in\ a\ Year}$, which is the capacity needed to deliver the exact amount of energy demand and is in theory a plausible outcome. For the case of intermittent technologies, the 2nd decision variable – amount of empty storage at the beginning of the year – is set to 0.

[12] Named ranges with a worksheet scope defined as follows: Dates – "A2:A17569", SettlPeriods – "B2:B17569", TotalDemand – "C2:C17569", OnshoreWindCapFactor – "D2:D17569", SolarPVCapFactor – "E2:E17569" and OffshoreWindCapFactor – "F2:F17569" to include 17568 cells that correspond to the half-

simplest way to maintain the structure and named ranges would be to copy the whole tab of another "Raw Data" tab as an object and alter its name. The time series values could then be inserted on the tab as values on the existing named ranges.

- The year (or the alternative identifier) at the "Year" list in "ValidationLists" worksheet

Inserting a new technology

It is a more complex process to insert a new primary technology and the steps depend on whether the technology is dispatchable or intermittent.

- For both technologies the users have to insert a new field in the "InputDataTech" table and populate it with the relevant data.
- Then the name of the technology needs to be inserted in the Generation technologies list in the "ValidationLists" tab with TRUE or FALSE to the right in order to indicate whether the technology is intermittent.
- Finally:
  - For renewable technologies (intermittent) i. the time series with the capacity factors for each year have to be inserted in the data tabs and ii. the relevant range[13] in each "Raw[year]" tab should be defined with local scope and the following name "[technology name]CapFactor", similar to what applies for the existing renewables technologies.
  - For dispatchable technologies the modifications should be performed in the formulae of the "CalculationsDisp" and depend on a case by case basis. Due to its complexity, it is preferable to test new technologies (i.e. other Nuclear) by altering the existing ones and modifying the relevant elements under consideration in the data tabs.

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hourly settlement periods of a leap year. It is necessary to maintain the structure of the whole ranges (rows 2:17569) in order to produce correct results.

[13] The named ranges should extend from row 2 to 17569, i.e. "G2:G17569".

I. Cost formulae

Capacity Costs[14]:

$$Total\ Cap\ Costs$$
$$= Optimised\ Capacity * Cap\ Cost\ per\ Unit * Annualised\ factor * IDC\ factor$$
$$* NPV\ factor^{15}$$

Fixed Costs:

$$Total\ Fixed\ Costs = Optimised\ Capacity * Fixed\ Cost\ per\ Unit * NPV\ factor$$

Fuel and VOM costs for Nuclear and CCGT with CCS (primary technologies)

$$Fuel\ \&\ VOM\ Costs = Annual\ Energy\ Output * Cost\ per\ Unit\ of\ Energy\ Output * NPV\ factor$$

Fuel and VOM costs for CCGT (complementary technology)

$$Fuel\ \&\ VOM\ Costs = Annual\ Fuel\ Input * Gas\ Cost\ per\ Unit * NPV\ factor$$

Emission costs[16]

$$Emission\ Costs$$
$$= \left(CO_2\ Emissions + \sum_{tech} \frac{CO_2\ per\ CapUnit_{tech} * CapUnit_{tech}}{Lifetime_{tech}} \right.$$
$$\left. + \sum_{tech} CO_2\ per\ Gen.Energy_{tech} * Gen.Energy_{tech} \right) * CO2\ Cost * NPV\ factor$$

ELCOE

$$ELCOE = \frac{Total\ costs\ over\ lifetime}{Annual\ Energy\ Demand * NPV\ factor\ of\ Primary\ technology}$$

Carbon Intensity

$$CO_2\ Intensity$$
$$= \frac{CO_2\ Emis. + \sum_{tech} \frac{CO_2\ per\ CapUnit_{tech} * CapUnit_{tech}}{Lifetime_{tech}} + \sum_{tech} CO_2\ per\ Gen.Energy_{tech} * Gen.Energy_{tech}}{Annual\ Energy\ Demand}$$

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[14] For Storage, Volume Costs and Power Rating Costs are calculated separately using the same formula.

[15] The NPV Factor used in all cases comes from the primary technology.

[16] Direct CO_2 emissions are calculated a bit differently between supplementary CCGT and CCGT with CCS. For CCGT the amount of fuel consumed over a year is multiplied with the emissions factor of Gas, whereas for CCGT with CCS emissions are calculated directly on the tab and added over a year.

CO2 cost share

$$CO_2(\%) = \frac{Emissions\ Costs}{Total\ Costs}$$

II.   Calculations tabs formulae

Counterfactual

In the counterfactual case, the assumption is that the energy demand is fully accommodated by CCGT units exclusively. The fields in the tab are structured as follows:

- Columns A and B contain the dates and settlement periods of the selected year respectively, whereas column C contains the total demand per settlement period measured in GW. These 3 fields have hard-coded values which are assigned by the "AssignValues" routine when the optimisation process is launched.
- Columns D to H are used to calculate the number of units which are on per settlement period. The logic applied in the calculations is that the ON units are either used to deliver energy for their synchronous settlement period, or that they have been turned on to generate energy for settlement periods in the near future. The latter option is applied to represent the time needed to achieve full load after a hot or cold start. More specifically:
  - o Column D is calculating the number of CCGT units needed to accommodate the demand
  - o Column E is calculating the number of CCGT units that are inside the hot start window, which is assumed to be 2 days (96 settlement periods)[17]
  - o Columns F & G calculate the number of units turned on that are inside the hot start and cold start window respectively[18]
  - o Column H adds the previous 2 together to identify the total CCGT units committed and also considers the minimum amount of spinning reserve needed (in case no CCGT energy is used to accommodate the demand)
- Columns I to L are used to perform the calculations related to fuel consumption and carbon intensity
  - o Column I calculates the load factor of the units (assumed uniformly distributed) with the application of a minimum value at 40%[19]
  - o Column J calculates the efficiency of the units under the calculated load factor[20]
  - o Column K the respective fuel consumption for the settlement period
  - o Column L the carbon intensity for the settlement period

Intermittent

The calculation logic for the intermittent primary technologies is to use the capacity factor profiles from years 2011 to 2016 and identify the optimal capacities for the primary and complementary

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[17] For the 1st and 2nd of January, the last days of the same year are used to represent/complement the Hot Start window

[18] Assumption: 1 hr to full load from Hot Start, 3.5 hr to full load from Cold Start, and <30' for shut down

[19] Excel formula: MAX(Energy Demand/(Number of Units * Unit Capacity), 40%)

[20] Interpolation between the 2 extreme points of 40% and 100% load factor

technology which can accommodate the demand for every single settlement period. The fields in the tab are structured as follows:

- Columns A and B contain the dates and settlement periods of the selected year respectively, whereas column C contains the total demand per settlement period measured in GW and column D the capacity factors of the selected VRE technology per settlement period. These 4 fields have hard-coded values which are assigned by the "AssignValues" routine when the optimisation process is launched.
- Columns E to H contain formulae for the calculation of the energy delivered by the primary and the supplementary technology. More specifically:
    - Column calculates the output (in power units – GW) of the primary technology per settlement period for the given capacity factor and optimal primary capacity[21]
    - Column F calculates the respective surplus (+) or deficit (-) of energy output (in power units – GW) compared to the demand
    - Column G is used when the CCGT is selected as supplementary technology and it calculates the power needed by the CCGT units so that the energy demand in the settlement period will be served[22]
    - Columns H is used to calculate the potential injection or withdrawals of energy (in power units – GW) from the batteries by applying the roundtrip efficiency losses and subsequently the energy storage levels (in energy)[23]
- Columns I to L contain formulae for the calculation of energy and losses from storage. More specifically:
    - Column I calculates the storage levels (energy units – GWh) and is used for the estimation of power rating and storage volume values for the batteries[24] (Assumptions: no energy losses over time and point 0 represents the starting point of storage levels[25])
    - Column J calculates the actual injection or withdrawals of energy (in power units – GW)
    - Column K calculates the losses and column L calculates the overspill of the primary technologies either for storage or for CCGT as a supplementary technology.
- Columns M to Q and R to U contain the same calculations and formulae that are found in columns D to H and I to L of the "CalculationsCounterfactual" worksheet respectively.

Dispatchable

The calculations logic for the dispatchable tab depends on whether Nuclear or CCGT with CCS have been chosen as primary technology. The columns and their respective calculations have certain similarities with the previously presented calculations sheets. The fields in this tab are structured as follows:

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[21] $Primary\ Technology\ Output\ (power)_t = Optimal\ Capacity * Capacity\ factor_t$

[22] Excel formula: MAX (-Deficit,0)

[23] $Injection = Surplus * \sqrt{Roundtrip\ Efficiency}$, whereas $Withdrawal = \dfrac{Deficit}{\sqrt{Roundtrip\ Efficiency}}$

[24] Power Rating is defined as the maximum Charge/Discharge which is calculated by the change in storage levels between two settlement periods and Storage Volume is the difference between the maximum and the minimum storage levels over a year.

[25] The storage levels can take negative and positive values per settlement period representing the relative charging compared to the starting point. The maximum storage level is capped by the 2nd decision variable which defines the amount of empty storage capacity at the beginning of the year.
Excel formula: MIN(Storage Levels(t-1)+0.5*Potential Injection/Withdrawal(t) ,Optimisation_EmptyStorage)

- Columns A and B contain the dates and settlement periods of the selected year respectively, whereas column C contains the total demand per settlement period measured in GW. These 3 fields have hard-coded values which are assigned by the "AssignValues" routine when the optimisation process is launched.
- Columns D to G, H to K, L to P and Q to T contain the same calculations and formulae that are found in columns E to H, I to L, M to Q and R to U of the "CalculationsIntermittent" worksheet respectively. The formula in column D follows a different approach depending on the option of primary generation technology:
  - o It moves freely[26] for the capacity delivered by CCGT with CCS up to the amount found by the solver's optimisation
  - o For Nuclear – which is treated as a single unit – a lower limit is applied to represent its flexibility limitations (assumption: 50% of the optimal capacity). However, ramping rates were considered steep enough to ramp-up from 50% to 100% in less than 30' and vice versa for the ramp-down
- Columns U to Z contain formulae to perform calculations related to the CCGT with CCS option. More specifically:
  - o Column U calculates the number of units that need to be on in order to deliver the power calculated in column D[27]
  - o Column V calculates the load factor assuming that the load is uniformly distributed among the units
  - o Column W calculates the efficiency by interpolating between the 2 load factor points defined in "InputDataGeneral" tab for CCGT with CCS
  - o Column X calculates the fuel used per settlement period[28]
  - o Column Y calculates the CO_2 emitted per settlement period by interpolating the capture rates between the 2 load factor points defined in "InputDataGeneral" tab
  - o Column Z calculates the carbon intensity per MWh of energy demand

III. Data

The data for energy demand and capacity factors per settlement periods (tabs "Raw[year]") are compiled from the publically available data of National Grid[29] which refer to the GB values, excluding therefore Northern Ireland[30]. As mentioned previously in the document, the capacity factors for offshore wind are constructed by applying to the onshore wind ones a modifiable multiplying factor.

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[26] Excel formula: MIN(Optimisation Capacity, Energy Demand)

[27] For CCGT with CCS no distinction was made between cold and hot starts, whereas the time from starting to full load was assumed to be 2 hrs. The load factor is calculated uniformly and the CO2 contribution is calculated separately based on the assumptions written in tab "InputDataGeneral".

[28] $Fuel = \dfrac{number\ of\ Units\ ON * Unit\ size * Load\ factor}{Efficiency\ rate}$

[29] http://www2.nationalgrid.com/UK/Industry-information/Electricity-transmission-operational-data/Data-Explorer/

[30] The demand is the summation of energy demand excluding the embedded generation (field I014_ND of the National Grid file) and of solar and wind embedded generation (fields EMBEDDED_WIND_GENERATION and EMBEDDED_SOLAR_GENERATION). The capacity factors are calculated by dividing the embedded generation with the embedded capacity (fields EMBEDDED_WIND_GENERATION with EMBEDDED_WIND_CAPACITY and EMBEDDED_SOLAR_GENERATION with EMBEDDED_SOLAR_CAPACITY).

The data found in tab "InputDataTech" and "InputDataGeneral" are based on ETI best judgement of likely 2030 costs etc at the date of development (in 2017). Users can alter the data to insert the values of their preference if they wish to test different set of assumptions. Users are strongly encouraged to do this!

The hot/cold start window for CCGT and the ramping rates are based on the "Technical Assessment of the Operation of Coal & Gas Fired Plants" document[31] published by DECC and the Nuclear flexibility on the "Nuclear Energy and Renewables"[32] published by OECD-NEA.

IV. Acronyms

Average Cost of Energy	ACOE
Combined Cycle Gas Turbine	CCGT
Carbon Capture and Storage	CCS
Extended Levelised Cost of Electricity	ELCOE
Interest During Construction	IDC
Levelised Cost of Electricity	LCOE
Net Present Value	NPV
Operation and Maintenance	O&M
Variable Operations and Maintenance	VOM
Variable Renewable Energy	VRE

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[31]
https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/387566/Technical_Assessment_of_the_Operation_of_Coal_and_Gas_Plant_PB_Power_FIN....pdf
[32] http://www.oecd-nea.org/ndd/reports/2012/system-effects-exec-sum.pdf