User Guide

Stochastic (Combined Heat and Power) Anaerobic Digestion Economic Assessment Tool

(SADEAT)

Full Version 1.0.1

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Available to download from here or here or copy either of the following links and paste in your browser;
https://github.com/AbdulSalam2016/SADEAT-Stochastic-Combined-Heat-and-Power-Anaerobic-Digestion-Economic-Assessment-Tool/releases/latest

Summary

Anaerobic digestion (AD) is a process by which micro-organisms break down biodegradable material in the absence of oxygen, leading to the production of biogas and digestate. Combined heat and power (CHP) AD technology converts methane in biogas into electricity and heat. Whilst there is general public support for AD projects, studies have produced mixed results about the economic feasibility of these projects with many findings showing that AD projects are economically unviable. Most studies however adopt a deterministic methodological framework which can lead to non-robust results. A stochastic methodology is inherently robust because it allows a determination of the expected economic outcome of an AD project by probabilistically exploring the realisation of stochastic AD project parameters for multiple simulated cases. However, few economic assessment tools have used a stochastic methodology and to the best of the author's knowledge, no stochastic economic assessment tools are freely available. This user guide presents a free and publicly available stochastic (CHP) AD economic assessment tool (SADEAT). The tool incorporates technical and financial parameters affecting the economics of (CHP) AD projects and allows the user to specify the number of cases of a project to simulate as well as the distribution type (uniform or triangular) of relevant project parameters. The tool can be downloaded here and is compatible for installation on computers operating on a Windows platform.

Contents

1 Introduction

Anaerobic digestion (AD) is a process by which micro-organisms break down biodegradable material such as domestic waste, farmyard manure, energy crops, etc. in the absence of oxygen, leading to a reduction in the mass of the material and the production of biogas and digestate. Combined heat and power (CHP) AD technology converts methane in treated biogas into electricity and heat. The generated electricity and heat can be used to displace on-site electricity and heat demand, or can be sold to a utility. The revenues gained from displaced or sold electricity and heat accrues rents to an AD project. Digestate from AD processes can be rich in soil minerals and can be processed into compost or other value added products that can also be sold to accrue rents to an AD project. The amount of rents from sold or displaced electricity and heat; and the sale of digestate as well as the costs of setting up and running an AD project are the basis of an economic feasibility analysis of the project.

There are mixed results in the literature regarding the economic feasibility of AD projects. Most studies have found AD projects to be economically unviable without some government policy support. Example studies include [1], [2], [3], [4] and [5]. Advocated policies to enhance AD economics include enhanced electricity or heat price tariffs, capital cost grants, favourable depreciation schedules, low taxation, etc. In contrast, studies such as [6] have found AD projects to be economically feasible.

All the above mentioned studies adopt a deterministic methodological framework in their analysis of the economic feasibility of AD projects. However, the realisation of many AD project parameters are inherently uncertain, a fact that is by definition not accommodated in analyses with deterministic approaches. For example, the methane content in biogas can fluctuate in the range 55-80% [7]. In deterministic analyses, a single value in this range is typically assumed as is the case in [8] who assume a value of 60%. In a stochastic approach however, multiple simulated cases of an AD project can be calibrated to realise different values in this range, based on a probability distribution of the realisation of values in the range. In their stochastic approach for example, [9] assume the methane content in biogas to be triangularly distributed with minimum value of 55%, modal value of 60% and maximum value of 80%. The advantage of the stochastic approach is that a distribution of decision support criteria can be drawn from the multiple simulated cases of a single AD project. This gives a robust determination of the expected outcome of the project. Indeed [9] argue that use of a stochastic methodological framework 'provides more robust results relative to previous work' which use deterministic methods.

A number of decision support tools for AD projects are available. Some of these tools are commercial and can only be accessed through fee paid consultancies. Examples include the tools by AMEC Environment and Infrastructure UK Limited, E&J Solutions Ltd, Laurence Gould Partnership and Golder Asscociates (UK) Limited among others [10]. Others are freely available and are typically simple spreadsheets. Examples include the tool presented by [11]. Freely available tools with more advanced user interfaces include the Biomethane Calculator and the Biowatts Beta programme [10]. AgSTAR, a U.S. Environmental Protection Agency (U.S. EPA) program is perhaps the most widely adopted freely available programme for assessing economic feasibility of AD projects. It has been adopted in published studies such as [2].

To the best of our knowledge, all of the freely available AD decision support tools adopt a deterministic methodological framework. As argued above however, this approach is non-robust, an inherent limitation that is by definition addressed with a stochastic methodological framework. With the growing demand for sustainable renewable energy, robust and freely accessible stochastic decision support tools are needed by farmers, private firms, academics and policy makers to determine investment decisions and/or explore policy options for AD projects. This user guide presents a stochastic (CHP) AD economic assessment tool (SADEAT). SADEAT is freely available to download here and is compatible for installation on computers operating on a Windows platform. The tool was developed by the above author using MATLAB computer software.

SADEAT calculates four criteria of the economic profitability of an AD project. These are (1) net present value (NPV); (2) modified internal rate of return (MIRR); (3) breakeven electricity price; and (4) breakeven heat price. The NPV is the conventional criterion for determining the economic profitability of capital budgeting projects [12]. A positive NPV signifies that a project is economically viable and therefore can be profitably undertaken whilst a negative NPV signifies otherwise. The higher the NPV of a project, the more desirable is the project. The MIRR is a modification of the traditional internal rate of return (IRR) criterion. It resolves some of the problems associated with the traditional IRR calculation mainly that it provides a single rate of return rather than the multiple rates of return often associated with IRR calculations. The MIRR explicitly accounts for the finance rate (for negative project cashflows) and the reinvestment rate (for positive project cashflows) [12]. It is argued that the MIRR is a more realistic and a better measure of project rates of return than the traditional IRR [13] hence its adoption in SADEAT. The breakeven electricity and heat price criteria are further indicators of the economic profitability of an AD project. The higher the electricity or heat breakeven price of a project, the less profitable is the project. Projects with negative breakeven prices are inherently profitable. As SADEAT adopts a stochastic framework, it calculates the above criteria for multiple stochastically simulated cases of an AD project and produces a distribution of the criteria. Users can specify the number of cases of an AD project to simulate and the likely ranges and distributions (uniform or triangular) of relevant project parameters.

2   SADEAT Interface

SADEAT interface has 3 key parts as shown in Figure 1 below. These are (1) the Menu Bar, (2) the Tab Selection Panel and (3) the Input and Result Tabs. Each is described in detail below.
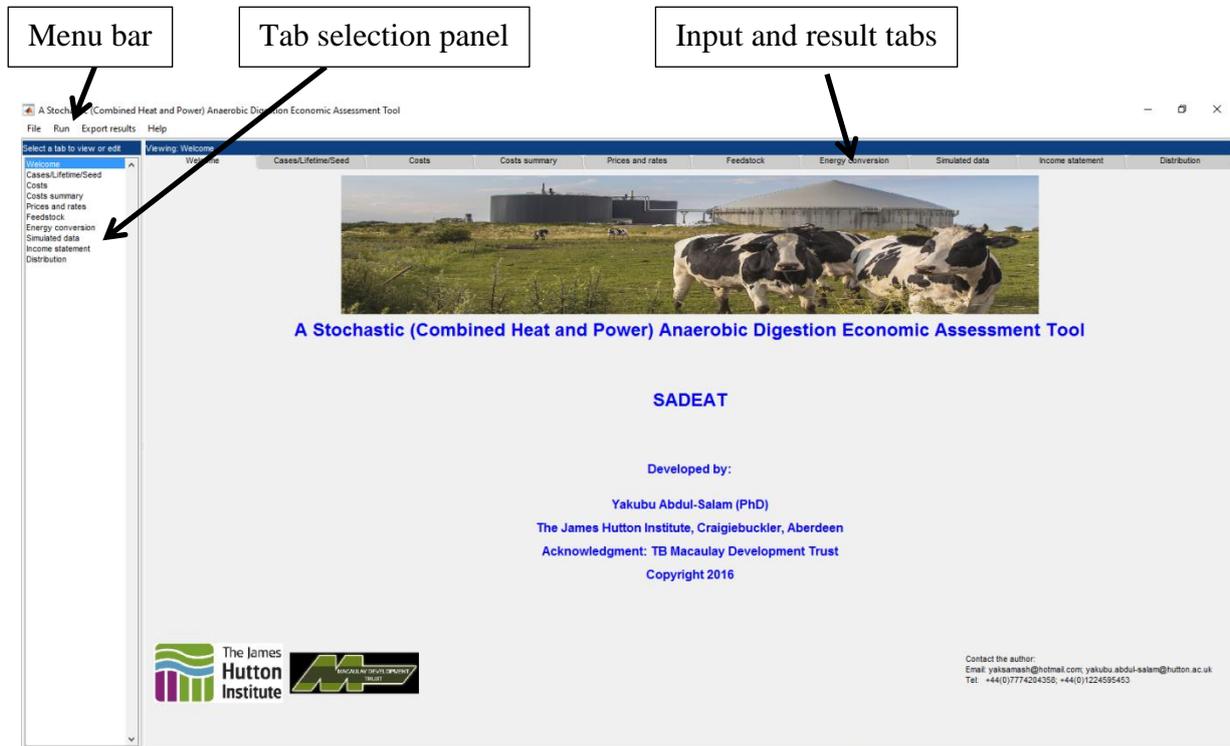
Figure 1: SADEAT interface

2.1   Menu Bar

The menu bar is on top of the interface and has 4 components. These are File, Run, Export results and Help.

2.1.1   File

To exit SADEAT, users may select 'File' on the menu bar, then select the option 'Exit'. Alternatively, users may exit by selecting the Windows exit symbol (i.e. the red-cross) on the far top right of the interface.

2.1.2   Run

This component of the menu bar allows users to run SADEAT and produce results. Upon a change in inputs, users must re-run SADEAT for new and updated results. There are 4 options under the 'Run' component. These are (1) 'Net Present Value (NPV)'; (2) 'Modified Internal Rate of Return (MIRR)'; (3) 'Breakeven electricity prices'; and (4) 'Breakeven heat prices'. To calculate NPV distributions of an AD project for example, users must select the

option 'Net Present Value (NPV)'. Upon selection of any of the 4 options, SADEAT interface is disabled as calculations are run in the background. The cursor symbol also changes from a 'pointer' to a 'busy watch' to signal to the user that SADEAT is processing calculations. Users would not be able to edit and/or change inputs whilst SADEAT is running. When processing of calculations is complete, the user interface is enabled again and the cursor changes to a pointer. This allows examination of results and/or entry of new inputs for new calculations.

2.1.3 Export results

This component of the menu bar allows the user to export results. There are three options under this component. These are 'Export data in tab Simulated data', 'Export data in tab Distribution' and 'Export graphs'. 'Export data in tab Simulated data' allows the user to export the tabular data in tab 'Simulated data' into an excel sheet. 'Export data in tab Distribution' allows the user to export the data underlying the graph in tab 'Distribution' into an excel sheet. 'Export graphs' is currently disabled. When enabled, it would allow users to export the graphs in tab 'Income statement' and tab 'Distribution'. Users can however reproduce these graph in excel by exporting data to excel using the 'Export data in tab Simulated data' and 'Export data in tab Distribution' options.

2.1.4 Help

To open this user guide from within SADEAT for help, select 'Help' on the menu bar and select the option 'Open user guide'.

2.2 Tab Selection Panel

This part of SADEAT interface provides the user with an alternative means of selecting input and result tabs (see Section 2.3 below). These tabs allow the user to input the AD project parameters (i.e. costs, biophysical data, etc.) and also view results. Rather than selecting these tabs directly from the Input and Result Tabs section, the user may select the tabs from the Tab Selection Panel instead.

2.3 Input and Result Tabs

The Input and Result Tabs are the tabs that allow the user to input the AD project parameters and also view the results of SADEAT calculations. There are 10 of these tabs, of which 1 is the face of SADEAT (i.e. the 'Welcome' tab), 6 tabs are input tabs and 3 tabs are results tabs. Each tab is described below.

2.3.1 Welcome

This is the face of SADEAT and contains the contact details of the author.

2.3.2 Cases/Lifetime/Seed

This is an input tab. The tab allows the user to specify the 3 parameters implied in the tab title. These are the number of cases of an AD project the user wishes to simulate, the lifetime of the project and the seed number that controls stochastic simulation of project parameters. Users may specify between 10 and 10,000 cases to simulate. The larger the number of cases simulated, the longer it takes for SADEAT to complete calculations. The minimum and maximum lifetimes of an AD project are also restricted to 5 and 20 years respectively. The maximum restriction of 20 years is imposed because Feed-in-tariff (FIT) and renewable heat incentive (RHI) payments are typically awarded for up to a maximum of 20 years only. The seed number controls the stochastic behaviour of SADEAT. Results are reproducible if the seed number is unchanged. For a different set of results to be simulated, users have to change the seed number which then re-sets SADEAT stochastic behaviour. The seed number can be any positive integer.

2.3.3 Costs

This is an input tab. The tab allows the user to input building and machinery capital costs as well as the initial overhead costs of an AD project. There are 3 panels in this tab. The first panel is labelled 'Building and infrastructure capital costs, £'. This panel allows the user to input capital costs for building and infrastructure units. As the user inputs these capital costs, the total building and infrastructure capital cost is updated and outputted in the last row of the panel. The second panel is labelled 'Machinery capital costs, £'. This panel allows the user to input the capital costs for machinery. Again as the user inputs these capital costs, the total machinery capital cost is updated and outputted in the panel's last row. Users must note that the entry 'Grant assistance' is a capital income, not a capital cost; and so it is subtracted from the total capital cost of building and/or machinery capital. When inputting building and machinery capital costs, users must include replacement costs of the various building and machinery units. This means that total building and machinery capital costs include replacement costs of building and machinery components over the life of an AD project. The last panel of the Costs tab allows the user to input overhead costs. The resulting total overhead cost is that of the initial project period only. The total overhead cost for subsequent project periods increases at the rate of inflation as set by the user (see tab 'Prices and Rates'). For example let *totalOverheadCost* represent the initial period overhead cost and let *inflationRate* represent the inflation rate. For any period t, the total overhead cost is calculated as follows;

$$totalOverheadCost(t) = totalOverheadCost \times (1 + inflationRate)^t \tag{1}$$

where $totalOverheadCost(t)$ is overhead cost in period t and $t \in \{0,1,...,T-1\}$ years where T is the lifetime of the project.

Note that building, machinery and overhead costs are not stochastic parameters hence all simulated cases of an AD project assume the same values for these costs.

2.3.4 Costs Summary

This is an input tab. The tab allows the user to input further information related to the cost of an AD project. These include the duration for depreciating the building and machinery capital costs. It also allows the user to input information about the percentage of total capital cost that is funded with debt as well as the duration for repaying the debt. The tab also summarises information regarding the cost of the project. These include textual as well as graphical summaries which are automatically updated if the user changes information about project costs.

2.3.5 Prices and Rates

This is an input tab. The tab allows the user to input various prices and money/finance related rates. These include FIT for electricity, export price of electricity, RHI for heat, and the export price of heat. The tab also allows the user to input rates including the interest rate for debt, the inflation rate for costs and prices, the discount rate for discounting cashflows and the tax rate, all expressed in 0-100 percent. It also allows the user to input the MIRR finance rate and the MIRR reinvestment rate, also expressed in 0-100 percent. Note that prices and rates are not stochastic parameters hence all simulated cases of an AD project assume the same values for prices and rates.

2.3.6 Feedstock

This is an input tab. The tab allows the user to input information about the types of feedstock of an AD project, the feedstock amounts and the feedstock biogas yields. Feedstock amount and biogas yields are stochastic parameters and their realisations for each simulated case of an AD project depends on their user entered ranges and user selected distributions. The user is presented with an option to select either of two distributions for these parameters. These are uniform and triangular distributions. When triangular distribution is selected, the user inputs the minimum, modal and maximum values for the parameters. The modal value of a parameter is the value with the highest probability of being realised by the project. Most of the simulated cases therefore stochastically realise parameter values that are close or equal to the modal value. When uniform distribution is selected, the modal entry is disabled. The user is allowed to input only minimum and maximum values and all realisable values in the specified ranges of the parameters have equal chances of being realised.

2.3.7 Energy Conversion

This is an input tab. The tab allows the user to input information related to an AD unit's conversion of biogas from feedstock to electricity and heat energy. Most of the parameters regard the efficiency of an AD unit. The parameters in this tab are stochastic and the user has the option to choose either a uniform or triangular distribution. When triangular distribution is selected, the user inputs the minimum, modal and maximum values of the parameters. The modal value of a parameter is the value with the highest probability of being realised by the simulated cases. When uniform distribution is selected, the modal entries are disabled and the user inputs the minimum and maximum values of the parameters only; with all values within the minimum and maximum ranges equally realisable.

2.3.8 Simulated Data

This is a result tab. The tab allows the user a detailed tabular view of the income statement of each simulated case for each year. Annual revenues, costs, cashflows, etc. are shown.

2.3.9 Income Statement

This is a result tab. The tab allows the user a graphical view of summaries of annual income statements across all simulated cases. Mean, minimum, maximum and 95% confidence intervals for annual revenues, costs, cashflows, etc. over all simulated cases are graphically shown.

2.3.10 Distribution

This is a result tab. The tab allows the user to view the distribution of any of the four decision support criteria simulated. There are also notes to summarise the information shown in the distribution.

3   Error Warning Prompts in SADEAT

There are copious prompts in SADEAT to warn the user of errors in inputs. The main prompts are occasioned by the following events or conditions;

3.1   Leaving user-input boxes blank

SADEAT does not allow blank user inputs. If the user leaves a user-input box blank, SADEAT triggers a message to warn the user that blank inputs are not allowed and that the previous value in the input box had been restored.

3.2   Entering non-numbers

SADEAT does not allow input of non-numbers. If the user inputs a non-number in a user-input box, SADEAT triggers a message to warn the user that non-numbers are not allowed and that the previous number in the box had been restored.

3.3   Entering negative numbers

SADEAT does not allow input of negative numbers. If the user inputs a negative number, SADEAT triggers a message to warn the user that negative numbers are not allowed and that the previous positive number in the box had been restored.

3.4 Parameters requiring input of integer numbers only

A number of parameters require input of integer numbers only. These include the project lifetime (years), number of AD cases to simulate, seed number for controlling stochastic behaviour, the building and machinery depreciation durations (years) and the debt repayment term (years). If the user inputs a non-integer number for these parameters, the number inputted would be rounded up to the nearest integer. A warning message is also triggered to inform the user of this correction.

3.5 Parameters with limits on the range of numbers

Some parameters have restrictions on the range of numbers they intake. Some of these restrictions are natural. For example percentages are restricted to 0-100% only. Others are in recognition of AD regulation. For example, project lifetime has been restricted to a maximum of 20 years since FIT and RHI payments are typically made for up to 20 years only. Some restrictions are arbitrary. For example the maximum number of cases the user can simulate is 10,000. This limit is only imposed to reduce computational burden on SADEAT.

3.6 Parameters with logical controls

Some parameters have logical controls on the values they can intake. For example, the building and machinery depreciation periods (years) cannot be greater than the project lifetime (years). Likewise, the debt repayment term (years) cannot be greater than the project lifetime (years). Also maximum values of project parameters cannot be less than modal or minimum values; modal values cannot be less than minimum values. If a user input occasions a violation of these restrictions, SADEAT triggers a message to warn the user that a violation has occurred and that the previous value in the box had been restored.

3.7 Non-generation of electricity and/or heat

A scenario may arise such that electricity and/or heat generation is zero for all simulated cases. If such a scenario arises, SADEAT does not calculate the breakeven price of electricity (i.e. when electricity generation is zero) and/or heat (i.e. when heat generation is zero) as this would be mathematically spurious and logically incoherent. A number of conditions may give rise to non-generation of electricity and/or heat. These include;

   i. All feedstock quantities have been inputted as 0.00 tonnes; or their associated feedstock biogas yields have been inputted as 0.00 m^3/tonne
  ii. All feedstock biogas yields have been inputted as 0.00 m^3/tonnes; or their associated feedstock quantities have been inputted as 0.00 tonnes
 iii. All inputs for the parameter 'Energy in methane' are 0.00 kWh/m^3
  iv. All inputs for the parameter 'Amount of methane in biogas' are 0.00%
   v. All inputs for the parameter 'CHP plant electricity efficiency' are 0.00%
  vi. All inputs for the parameter 'Overall plant inefficiency' are 100.00%
 vii. All inputs for the parameter 'Parasitic load electricity' are 100.00%

viii.   All inputs for the parameter 'Parasitic load heat' are 100.00%

ix.   All inputs for the parameter 'Downtime' are 100.00%

When non-generation of electricity and/or heat occurs, SADEAT triggers a message to warn the user that breakeven electricity prices cannot be calculated (i.e. when there is non-generation of electricity) and/or breakeven heat prices cannot be calculated (i.e. when there is non- generation of heat).

4   Models underlying SADEAT

4.1   Calculating NPVs, £

Consider that a user wishes to simulate N stochastic cases of an AD project which has a project horizon of T years. Let i represent the set of the N stochastically simulated cases of this project and t represent the set of T years of the project lifetime. Also let *elecPriceGenFIT* and *elecPriceExport* represent the initial year FIT for AD electricity and the initial year export price of electricity respectively. The export price of electricity could be chosen as the export FIT of AD electricity or the market rate for sale of electricity. Now let *heatPriceRHI* represent the initial year RHI tariff for heat generated by AD and *heatPriceExport* represent the initial year export price of heat. Given these parameters, the NPV of each of the N simulated cases of the project can be calculated as follows;

$$\underset{NPV(i)}{solve} \quad NPV(i) = -totalCapitalCost(i) + \sum_{t=0}^{T-1} \frac{cashFlow(i,t)}{(1+discountRate)^{t-1}} \tag{2}$$

where

$$cashFlow(i,t) = postTaxProfit(i,t) + machineryDepreciationCost(i,t)$$
$$+ buildingDepreciationCost(i,t) \tag{3}$$

$$postTaxProfit(i,t) = preTaxProfit(i,t) - tax(i,t) \tag{4}$$

$$tax(i,t) = taxRate \times preTaxProfit(i,t) \ \forall \ preTaxProfit(i,t) > 0 \tag{5}$$

$$preTaxProfit(i,t) = annualRevenue(i,t)$$
$$- overheadCost(i,t) - loanRepaymentCost(i,t)$$
$$- machineryDeprecicationCost(i,t) \tag{6}$$
$$- buildingDepreciationCost(i,t)$$

$$annualRevenues(i,t) = electricityRevenue(i,t) + heatRevenue(i,t) \tag{7}$$

$$electricityRevenue(i,t) = \big(\big(elecPriceGenFIT + elecPriceExport\big)/100\big)$$
$$\times\big(1 + inflationRate\big)^{t-1} \tag{8}$$
$$\times annualElectricityGeneration(i,t)$$

$$heatRevenue(i,t) = \big(\big(heatPriceRHI + heatPriceExport\big)/100\big)$$
$$\times\big(1 + inflationRate\big)^{t-1} \tag{9}$$
$$\times annualHeatGeneration(i,t)$$

$i \in \{1,...,N\}$ simulated cases, $t \in \{0,1,...,T-1\}$ years

where

$NPV(i)$, £	NPV of simulated case i
$totalCapitalCost(i)$, £	Total capital cost of simulated case i. All simulated cases have the same total capital cost (see Tab 'Costs'). The total capital cost includes the initial capital cost and the capital cost of all replaced capital items during the project life.
$cashflow(i,t)$, £	Cashflow of simulated case i in period t
$discountRate$, %	Discount rate for discounting cashflows
$postTaxProfit(i,t)$, £	Post tax profit of simulated case i in period t
$machinerDepreciationCost(i,t)$, £	Machinery depreciation cost of simulated case i in period t
$buildingDepreciationCost(i,t)$, £	Building depreciation cost of simulated case i in period t
$tax(i,t)$, £	Tax cost of simulated case i in period t
$taxRate$, %	Tax rate
$preTaxProfit(i,t)$, £	Pre-tax profit of simulated case i in period t
$annualRevenue(i,t)$, £	Revenues from sale of electricity and heat for simulated case i in period t
$overheadCost(i,t)$, £	Overhead cost of simulated case i in period t.
$loanRepaymentCost(i,t)$	Loan repayment cost of simulated case i in period t
$electricityRevenue(i,t)$, £	Revenue from sale of electricity for simulated case i in period t
$heatRevenue(i,t)$, £	Revenue from sale of heat for simulated case i in period t
$annualElectricityGeneration(i,t)$, kWh	Total saleable AD electricity output (see Section 4.5 for how this is calculated)
$annualHeatGeneration(i,t)$, £	Total saleable AD heat output (see Section 4.5 for how this is calculated)
$inflationRate$, %	Inflation rate
$elecPriceGenFIT$, p/kWh	Initial year FIT for AD electricity generation
$elecPriceExport$, p/kWh	Initial year FIT for AD electricity export, or market rate for sale of electricity
$heatPriceRHI$, p/kWh	Initial year RHI for AD heat generation
$heatPriceExport$, p/kWh	Initial year market rate for sale of heat

Note that SADEAT allows user input of initial year electricity and heat prices only. These initial year prices are then annually inflated over the project lifetime based on the inflation rate specified by the user in tab 'Prices and rates' (see equation (8) and equation (9); divisions by 100 in these equations convert p/kWh to £/kWh). Note also that in capital budgeting analyses, depreciation costs are added to the post-tax cashflow because depreciation costs do not represent cash outflows (i.e. see equation(3)). They do however determine the project tax bill hence are first subtracted from the pre-tax profit (i.e. see equation (6)). The feedstock and bio-physical properties of each simulated case is stochastically simulated hence revenues for each simulated case would be different, leading to N different NPVs. The distribution of these NPVs provides a better understanding of the expected NPV of the simulated AD project.

4.2   Calculating MIRRs, %

Given the cashflows in equation (3) and the finance and reinvestment rate of an AD project, one is able to calculate the MIRR of all simulated cases of the project. The finance and reinvestment rates are inputted by the user in tab 'Prices and rates'.

4.3   Calculating breakeven electricity prices, p/kWh

All parameters are as previously defined in Section 4.1. Let $elecPriceBreakeven(i)$ represent the breakeven electricity price for simulated case i. Then given the definitions above, $elecPriceBreakeven(i)$ for each of N simulated cases can be calculated as follows;

$$\underset{elecPriceBreakeven(i)}{solve} \quad -totalCapitalCost(i) + \sum_{t=0}^{T-1} \frac{cashFlow(i,t)}{(1+discountRate)^{t-1}} = 0 \tag{10}$$

where

$$cashFlow(i,t) = postTaxProfit(i,t) + machineryDepreciationCost(i,t) \\ +buildingDepreciationCost(i,t) \tag{11}$$

$$postTaxProfit(i,t) = preTaxProfit(i,t) - tax(i,t) \tag{12}$$

$$tax(i,t) = taxRate \times preTaxProfit(i,t) \ \forall \ preTaxProfit(i,t) > 0 \tag{13}$$

$$preTaxProfit(i,t) = annualRevenue(i,t) \\ -overheadCost(i,t) - loanRepaymentCost(i,t) \\ -machineryDepreciationCost(i,t) \\ -buildingDepreciationCost(i,t) \tag{14}$$

$$annualRevenues(i,t) = electricityRevenue(i,t) + heatRevenue(i,t) \tag{15}$$

$$electricityRevenue(i,t) = \big(elecPriceBreakeven(i)/100\big)$$
$$\times (1+inflationRate)^{t-1} \tag{16}$$
$$\times annualElectricityGeneration(i,t)$$

$$heatRevenue(i,t) = \big((heatPriceRHI + heatPriceExport)/100\big)$$
$$\times (1+inflationRate)^{t-1} \tag{17}$$
$$\times annualHeatGeneration(i,t)$$

$i \in \{1,...,N\}$ simulated cases, $t \in \{0,1,...,T-1\}$ years

Note that the breakeven electricity price calculated for each simulated case is the initial year breakeven electricity price only. These initial year prices are then inflated over the lifetime of the project (see equation (16)) based on the inflation rate specified by the user in tab 'Prices and rates'.

4.4   Calculating breakeven heat prices, p/kWh

All parameters are as previously defined in Section 4.1. Let $heatPriceBreakeven(i)$ represent the breakeven heat price for simulated case i. Then given the definitions above, $heatPriceBreakeven(i)$ for each of N cases can be calculated as follows;

$$\underset{heatPriceBreakeven(i)}{solve} \quad -totalCapitalCost(i) + \sum_{t=0}^{T-1} \frac{cashFlow(i,t)}{(1+discountRate)^{t-1}} = 0 \tag{18}$$

where
$$cashFlow(i,t) = postTaxProfit(i,t) + machineryDepreciationCost(i,t)$$
$$+ buildingDepreciationCost(i,t) \tag{19}$$

$$postTaxProfit(i,t) = preTaxProfit(i,t) - tax(i,t) \tag{20}$$

$$tax(i,t) = taxRate \times preTaxProfit(i,t)$$
$$\forall \, preTaxProfit(i,t) > 0 \tag{21}$$

$$preTaxProfit(i,t) = annualRevenue(i,t)$$
$$-overheadCost(i,t) - loanRepaymentCost(i,t)$$
$$-machineryDepreciationCost(i,t) \tag{22}$$
$$-buildingDepreciationCost(i,t)$$

$$annualRevenues(i,t) = electricityRevenue(i,t) + heatRevenue(i,t) \tag{23}$$

$$electricityRevenue(i,t) = \big((elecPriceGenFIT + elecPriceExport)\big)/100$$
$$\times (1+inflationRate)^{t-1} \tag{24}$$
$$\times annualElectricityGeneration(i,t)$$

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$$heatRevenue(i,t) = \left(heatPriceBreakeven(i)/100\right)$$
$$\times \left(1+inflationRate\right)^{t-1} \tag{25}$$
$$\times annualHeatGeneration(i,t)$$

$i \in \{1,...,N\}$ simulated cases, $t \in \{0,1,...,T-1\}$ years

Note that the breakeven heat price calculated for each simulated case is the initial year breakeven electricity price only. These initial year prices are then inflated over the lifetime of the project (see equation (25)) based on the inflation rate specified by the user in tab 'Prices and rates'.

4.5 Calculating electricity and heat output of CHP AD
4.5.1 Feedstock amount, feedstock biogas yield and volume of biogas

Let f represent the set of all feedstock types used by a CHP AD project and let $feedstockAmount(f)$ and $feedstockYield(f)$ represent the amount (in tonnes) and biogas yield (in m^3/tonne) of the feedstocks respectively. The total annual volume of biogas produced by the CHP AD unit from its feedstock can be calculated as follows;

$$annualBiogasProduction(m^3) = \sum_f \left(feedstockAmount(f) \times feedstockYield(f)\right) \tag{26}$$

where $annualBiogasProduction$ volume is given in m^3.

4.5.2 Efficiency and energy production

Let $energyInMethane$, measured in kWh/m^3, represent the amount of energy in a m^3 of methane, and let $proportionMethaneInBiogas$, measured as a percentage (%), represent the proportion of methane in a m^3 of biogas. Then the energy content in a m^3 of biogas can be calculated as follows;

$$energyContentInBiogas(kWh/m^3) =$$
$$proportionMethaneInBiogas(\%) \tag{27}$$
$$\times energyInMethane(kWh/m^3)$$

where $energyContentBiogas$ is given in kWh/m^3.

Inefficiencies in the conversion of biogas to electricity and heat energy mean a CHP AD unit realises less than the full potential of energy in the biogas it converts. Hence, let $lossInefficiency$ represent the inefficiency of a CHP AD plant arising from loss of energy to

the environment. Also let *electricityConversionEfficiency* represent the efficiency realised in converting methane to electricity and *heatConversionEfficiency* represent the efficiency realised in converting methane to heat, both measured as percentages (%). Additionally, in order for CHP AD plants to function, some of the electricity and/or heat produced are internally consumed by the plant. This is known as parasitic load. Hence let *parasiticLoadElectricity* and *parasiticLoadHeat*, both measured in percentages (%), represent the proportion of generated electricity and heat that is internally consumed by the plant. Also, CHP AD plants are unlikely to achieve the maximal operation time in a year due to project downtimes. The frequency and duration of downtimes have implications for annual electricity and heat output. Hence let *downtime*, measured as percentage (%), represent the proportion of the 8700 hours a year that a CHP AD plant is non-operational due to downtimes for machine repairs and replacements, etc. Given these parameters, the total annual electricity and heat energy generated by a CHP AD unit can be calculated as follows;

$$
\begin{aligned}
annualElectricityGeneration\left(kWh\right) = \\
electricityConversionEfficiency\left(\%\right) \\
\times\left(1 - lossInefficiency\left(\%\right)\right) \\
\times\left(1 - parasiticLoadElectricity\left(\%\right)\right) \\
\times energyContentInBiogas\left(kWh/m^3\right) \\
\times annualBiogasProduction\left(m^3\right) \\
\times\left(1 - downtime\left(\%\right)\right)
\end{aligned}
\tag{28}
$$

$$
\begin{aligned}
annualHeatGeneration\left(kWh\right) = \\
heatConversionEfficiency\left(\%\right) \\
\times\left(1 - lossInefficiency\left(\%\right)\right) \\
\times\left(1 - parasiticLoadHeat\left(\%\right)\right) \\
\times energyContentInBiogas\left(kWh/m^3\right) \\
\times annualBiogasProduction\left(m^3\right) \\
\times\left(1 - downtime\left(\%\right)\right)
\end{aligned}
\tag{29}
$$

where *annualElectricityGeneration* and *annualHeatGeneration* are given in kWh. The amount of electricity produced and sold determines project NPVs and breakeven electricity prices.

5   Future versions, improvements, bugs, etc.

Inclusion of rents from digestate and greenhouse gas credits in the economics of AD projects are the subject of current work for incorporation in future versions of SADEAT. Every effort has been made to ensure that SADEAT is user-friendly and free of errors. However, if you

have suggestions about how SADEAT may be improved, or if you have found a bug, then the author would like to request that you contact him (email: yaksamash@hotmail.com; yakubu.abdul-salam@hutton.ac.uk).

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Source of image on SADEAT welcome page; http://www.leavesley.com/ (last accessed; June 2016)

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