Modelling and Life Cycle Sustainability Assessment of Biomass Combined Heat and Power systems (CHP)

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Background

Combined Heat and Power systems (CHP) are a technology for simultaneous electricity and heat generation utilising carbonaceous fuel. Biomass[1] is a non-conflicting (with food or feed production and land use) greenhouse gas efficient fuel, because carbon dioxide released from its combustion is sequestrated or captured during its growth. The simplest configuration to release its energy content or calorific value in the form of steam (heat) and electricity includes biomass boiler followed by back pressure steam turbine. Biomass must contain <25% preferably <10% moisture by mass for efficient combustion in the presence of compressed excess than stoichiometric amount of air in the boiler. The heat released from biomass combustion is utilised to transform (by indirect contact) boiler feed water into high pressure superheated steam in the boiler. High pressure superheated steam at and above 50 atmospheric pressure is expected to be generated. Inside the boiler, the temperature should be restricted to less than 1300°C to avoid NO_x generation by the reaction between molar nitrogen and oxygen present in both air and biomass. The exhaust or flue gas leaving the boiler from the combustion of biomass contains carbon dioxide, nitrogen (primarily from air) and water as main constituents. A certain temperature and pressure of the flue gas is maintained to release the gas to the atmosphere above the stack height. As noted, carbon dioxide released by the combustion of biomass is sequestrated or captured during the growth of the biomass, hence, giving an overall carbon neutral performance. The high pressure superheated steam is a source of heat and power. Electricity can be generated by expanding the steam through a back pressure steam turbine attached to a generator. Steam can be extracted at any pressure (very high, high, medium, low) from the various extraction stages in the turbine according to the quality of the demand for heat. Figure 1 shows CHP schematic. In this configuration, low pressure superheated steam at and above 1 atmospheric pressure is extracted from the back pressure steam turbine. The modelling equations are shown for this configuration.

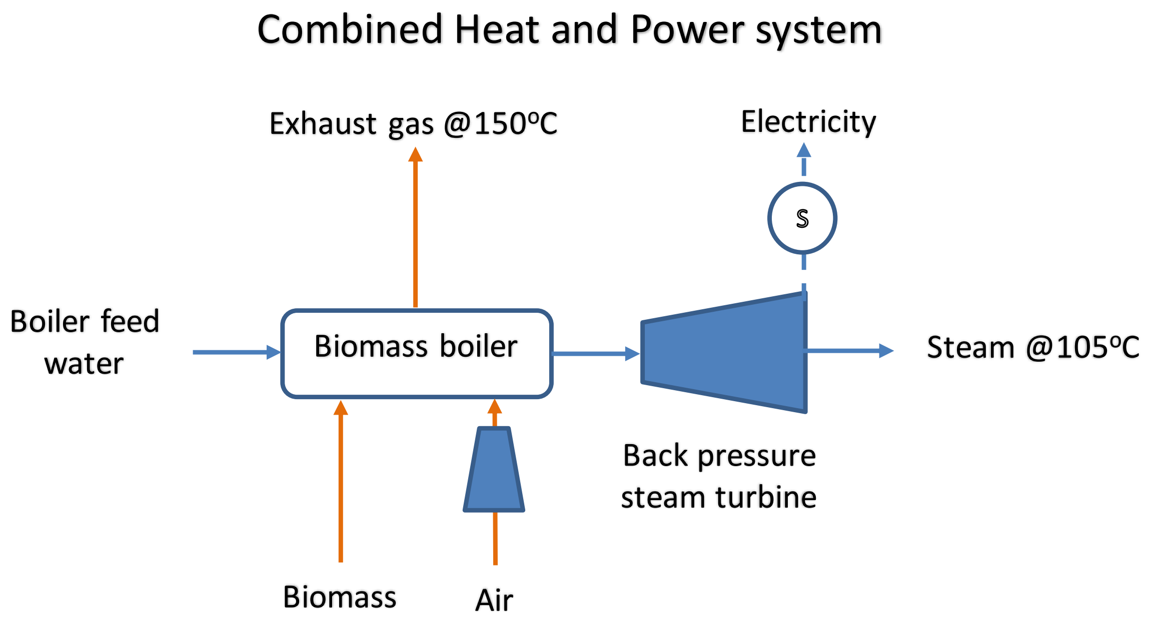

Figure 1. CHP schematic.

Steady state performance model

This section shows the equations to estimate biomass throughput to achieve a given electricity output and low pressure steam generation in the CHP schematic shown in Figure 1. The biomass boiler-based CHP configuration (Figure 1) has been simulated for three biomass analyses in Aspen Plus 8.8 and equations relating outputs in terms of inputs have been developed from the simulation results suitable for the web-based decision-support platform. The outputs from the model include the amount of steam generation, biomass throughput requirement to meet the electricity demand and electricity and total energy efficiencies. This section also shows the analysis of environmental performance such as global warming potential impact using a life cycle assessment approach. These are estimated from biomass elemental analysis, carbon and hydrogen constituents and site electricity demand. Biomass needed for a given electricity generation is shown in Equation 1.

$$Biomass\ needed\ (including\ moisture)\frac{kg}{hour} = \frac{(1560 \times Electricity\ generation\frac{GWh}{year} - 0.23)}{(Biomass\ carbon\ content\ (dry\ basis)\ wt\% \times 0.375 + Biomass\ hydrogen\ content\ (dry\ basis)\ wt\% \times 1.154)} \times \frac{1}{Boiler\ efficiency} \times \frac{1}{Isentropic\ efficiency\ of\ back\ pressure\ steam\ turbine} \times \frac{1}{Mechanical\ efficiency\ of\ back\ pressure\ steam\ turbine} \times \frac{100}{(Biomass\ carbon\ content\ (dry\ basis)\ wt\% + Biomass\ hydrogen\ content\ (dry\ basis)\ wt\%)} \times \frac{100}{(100 - Biomass\ moisture\ content\ wt\%)} \qquad \text{Equation 1}$$

Carbon and hydrogen contents (dry basis) in wt% constitute the fundamental basis of the equations. These signify energy currency of biomass. Carbon and hydrogen have a calorific value of 37.5 and 115.4 MJ/kg, respectively. $(Biomass\ carbon\ content\ (dry\ basis)\ wt\% \times 0.375 + Biomass\ hydrogen\ content\ (dry\ basis)\ wt\% \times 1.154)$ signifies energy content within carbon and hydrogen in biomass, which is higher than the energy content (or calorific value) of the biomass due to the presence of inert in the biomass. This dependent variable is plotted against electricity generation from back pressure steam turbine using the results of simulation in Aspen Plus 8.8 to obtain the first term on right side in Equation 1. Adjustments were needed due to the efficiencies, such as, of the boiler and (isentropic and mechanical) of the back pressure steam turbine, and to consider the presence of inert in the total biomass throughput (including moisture).

Equation 2 is to estimate the production rate of low pressure superheated steam at and above 1 atmospheric pressure.

$$Steam\ generation\ @105^{o}C\frac{kg}{hour} = \frac{(1560 \times Electricity\ generation\frac{GWh}{year} - 0.23)}{(Biomass\ carbon\ content\ (dry\ basis)\ wt\% \times 0.375 + Biomass\ hydrogen\ content\ (dry\ basis)\ wt\% \times 1.154)} \times \frac{1}{Boiler\ efficiency} \times \frac{1}{Isentropic\ efficiency\ of\ back\ pressure\ steam\ turbine} \times \frac{1}{Mechanical\ efficiency\ of\ back\ pressure\ steam\ turbine} \times (0.2807 \times (Biomass\ carbon\ content\ (dry\ basis)\ wt\% \times 0.375 + Biomass\ hydrogen\ content\ (dry\ basis)\ wt\% \times 1.154) + 0.0463)) \qquad \text{Equation 2}$$

The effect of energy content within carbon and hydrogen in biomass is captured in the final term on right side in Equation 2. The final term on right side in Equation 2 is based on the amount of steam generation in relation to energy content within carbon and hydrogen in biomass using the results of simulation in Aspen Plus 8.8.

Equations 3-4 are to calculate the electricity, and heat and electricity generation efficiencies based on target output electricity generation, low pressure superheated steam generation and low heating value (LHV) of biomass.

$$Electricity\ generation\ efficiency = \frac{411 \times Electricity\ generation \frac{GWh}{year}}{Biomass\ needed\ (including\ moisture) \frac{kg}{hour} \times Biomass\ (including\ moisture)\ LHV \frac{MJ}{kg}}$$

Equation 3

$$CHP\ generation\ efficiency = \frac{(411 \times Electricity\ generation \frac{GWh}{year} + 2.77 \times\ Steam\ generation\ @105^{o}C \frac{kg}{hour})}{Biomass\ needed\ (including\ moisture) \frac{kg}{hour} \times Biomass\ (including\ moisture)\ LHV \frac{MJ}{kg}}$$

Equation 4

411 is the factor to convert $Electricity\ generation \frac{GWh}{year}$ into that in MJ/hour: $\frac{1000000 \times 3.6}{24 \times 365}$. The low pressure superheated steam at and above 1 atmospheric pressure and at 105°C has an enthalpy of 2.77 MJ/kg.

The global warming potential to be saved by the CHP is the global warming potential of electricity generation by the service that would be displaced by the CHP. In this case, the factor is determined from the difference in global warming potential impacts between natural gas combined cycle and biomass CHP, i.e. 0.1261 kg CO_2 eq./MJ[2]. The global warming potential saving by the biomass CHP compared to natural gas combined cycle is estimated using Equation 5.

$$Global\ Warming\ Potential\ saving\ compared\ to\ natural\ gas\ combined\ cycle\ \left(\frac{tonne\ CO_2\ eq.}{year}\right) = 454 \times Electricity\ generation \frac{GWh}{year}$$

Equation 5

454 is the factor converting $Electricity\ generation \frac{GWh}{year}$ into $Global\ Warming\ Potential\ saving\ compared\ to\ natural\ gas\ combined\ cycle\ (\frac{tonne\ CO_2\ eq.}{year})$: $0.1261\ \times 3.6\ \times 1000$.

Techno-economic assessment

This section discusses the estimation of capital cost, operating cost, cost of production and product value of CHP and the discounted cash flow analysis over the life cycle of the CHP[1]. The capital cost is estimated using Equation 6. In order to arrive at this equation, first the delivered cost of equipment is estimated by the summation of that of each component in the CHP, i.e. boiler[3] and steam turbine and steam system[1]. Individual delivered costs are adjusted for the present amounts, $Biomass\ needed\ (including\ moisture) \frac{kg}{hour}$ for the boiler and $Electricity\ generation \frac{GWh}{year}$ for the steam turbine and steam system. A Lang factor is then applied to estimate the total capital cost[1].

Capital cost = $(\sum_i DC_i \times (\frac{present\ amount_i}{base\ production\ rate_i})^{scale\ factor_i}) \times Lang\ factor$

Equation 6

DC_i is the delivered cost of each component i in the CHP, $i \in boiler, steam\ turbine\ and\ steam\ system.$ $base\ production\ rate_i$ is the production rate in the same unit as the present amount for the known base size of the component i in the CHP. $scale\ factor_i$ <1 is to capture the effect of economy of scale that the cost effectiveness increases with increasing size of the unit.

The net present value (NPV_y) in a given year y of the CHP operation is calculated using Equation 7[1].

$$NPV_y = NPV_{y-1} + \frac{(Product\ value - Opex - Capex)}{(1+IRR)^y}$$ Equation 7

$$NPV_{y=0} = \text{Capital cost}$$

IRR is the internal rate of return in fraction. $Capex$ is an $Annual\ Capital\ Charge$ (in fraction) applied to the Capital cost (Equation 8). $Opex$ is the operating cost, the summation of the fixed operating cost dependent on the indirect annual capital cost and labour dependent fixed operating cost, applied with a multiplier (Equation 9)[1]. The indirect annual capital cost is dependent on the delivered cost of equipment (Equation 10)[1]. The labour dependent fixed operating cost is a function of $Biomass\ needed\ (including\ moisture)\frac{kg}{hour}$ (Equation 11)[1].

$$Capex = Annual\ Capital\ Charge \times \text{Capital cost}$$ Equation 8

$$Opex = a \times (\text{fixed operating cost dependent on indirect annual capital cost} \times \text{b} + \text{labour dependent fixed operating cost})$$ Equation 9

$$\text{fixed operating cost dependent on indirect annual capital cost} = \frac{\text{Capital cost}}{Lang\ factor} \times Annual\ Capital\ Charge$$ Equation 10

$$\text{labour dependent fixed operating cost} = \text{c} \times Biomass\ needed\ (including\ moisture)\frac{kg}{hour}$$ Equation 11

$a, b\ and\ c$ are multipliers of the respective cost components to account for a larger set of cost components[1].

$Product\ value$ in Equation 12 is the multiplication between the price and rate of production of individual products (electricity and low pressure superheated steam at and above 1 atmospheric pressure and at 105°C) (Equation 12).

$$Product\ value = Electricity\ price \times Electricity\ generation + Steam\ price \times Steam\ generation\ @105^oC$$ Equation 12

Appropriate factors will be applied to have the cost analysis in a consistent unit.

Equation 13 shows the cost of production of CHP.

$$Cost\ of\ CHP\ production\ (Euro/kWh) = \frac{\left(Capex\ \left(million\frac{Euro}{year}\right) + Opex\ \left(million\frac{Euro}{year}\right)\right) + Biomass\ cost\ \left(million\frac{Euro}{year}\right)}{Electricity\ generation\frac{GWh}{year} \times \frac{CHP\ generation\ efficiency}{Electricity\ generation\ efficiency}}$$

Equation 13

Case study

Table 1 shows the relevant input data for techno-economic and environmental performance analysis of CHP.

Table 1. Input data for techno-economic and environmental performance analysis of CHP.

Input variable	**Example**	**Range**
$Biomass\ moisture\ content\ wt\%$	15	0-25
$Biomass\ carbon\ content\ (dry\ basis)\ wt\%$	52	51.5-53.5
$Biomass\ hydrogen\ content\ (dry\ basis)\ wt\%$	6	5.5-6.5
$Biomass\ (including\ moisture)\ LHV\ \frac{MJ}{kg}$	17.87	17-20
$Boiler\ efficiency$	0.85	0.7-1
$Isentropic\ efficiency\ of\ back\ pressure\ steam\ turbine$	0.85	0.7-1
$Mechanical\ efficiency\ of\ back\ pressure\ steam\ turbine$	0.9	0.7-1
$Electricity\ generation\ \frac{GWh}{year}$	1.6	1-10
$Lang\ factor$	1.5	1-5
$Annual\ Capital\ Charge$	0.13	0.05-0.15
IRR	0.12	0.05-0.15
$Electricity\ price$ (Euro/kWh)	0.07	0.05-0.15
$Steam\ price$ (Euro/tonne)	22	20-25
$Biomass\ cost$ (Euro/tonne)	40	0-100

Equations 1-4 are applied to estimate the biomass throughput, steam generation and efficiencies for the given $Electricity\ generation\ \frac{GWh}{year}$ of 1.6, shown as follows. Figure 2 shows the estimated values of $Biomass\ needed\ (including\ moisture)\ \frac{kg}{hour}$ and $Steam\ generation\ @105^oC\ \frac{kg}{hour}$ using the input variables in Table 1 in Equations 1-2.

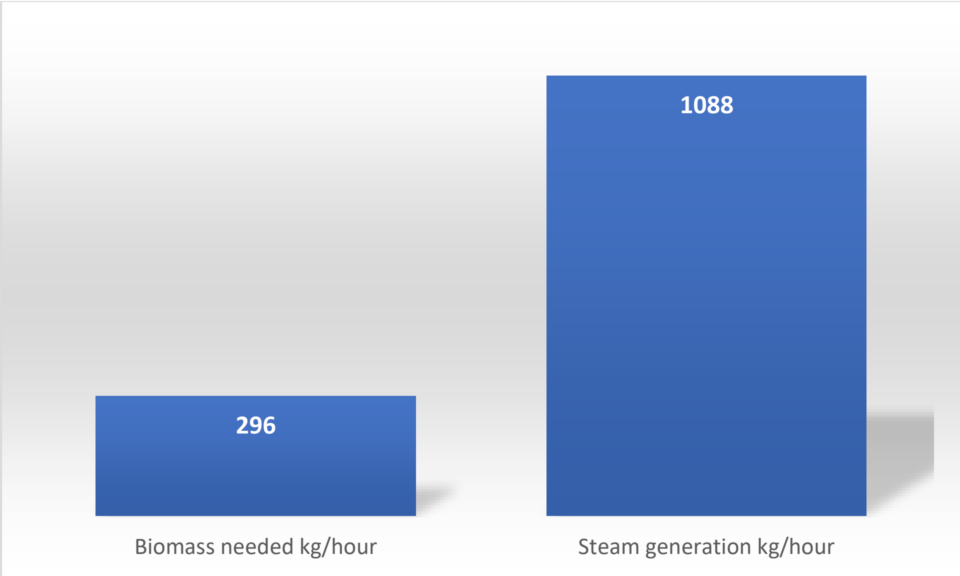

Figure 2. Estimated values of $Biomass\ needed\ (including\ moisture)\,\frac{kg}{hour}$ and $Steam\ generation\ @105^{o}C\,\frac{kg}{hour}$ using the input variables in Table 1.

Figure 3 shows the estimations of $Electricity\ generation\ efficiency$ and $CHP\ generation\ efficiency$ using Equations 3-4 based on the example values of the input variables in Table 1.

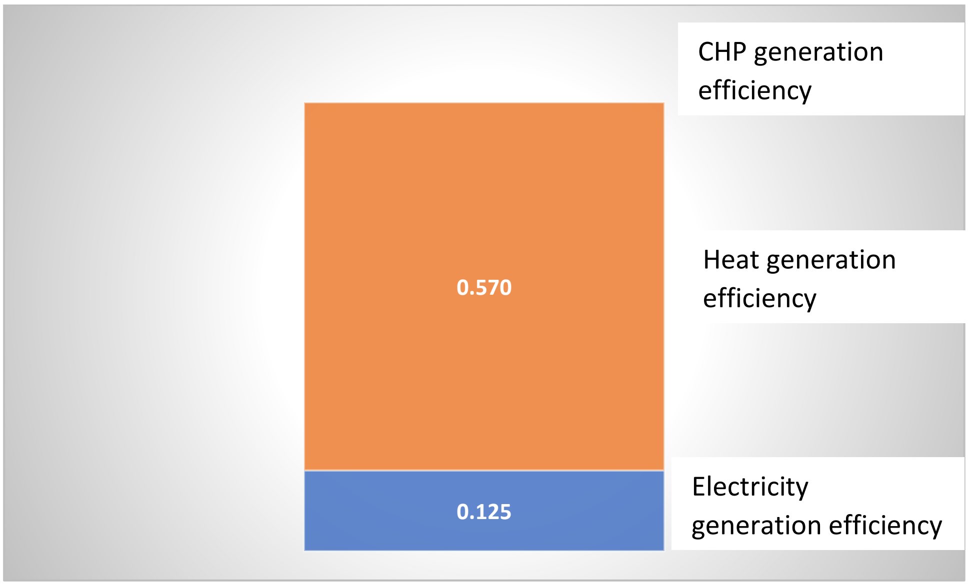

Figure 3. $Electricity\ generation\ efficiency = 0.125$ and $CHP\ generation\ efficiency = 0.695$.

In case of $Global\ Warming\ Potential\ saving\ compared\ to\ natural\ gas\ combined\ cycle\ (\frac{tonne\ CO_2\ eq.}{year})$, the cases of biomass, solar and pumped hydro are compared, as the latter two are reported to have higher global warming impacts than biomass but lower global warming impacts than natural gas based energy systems[2]. $Global\ Warming\ Potential\ saving\ compared\ to\ natural\ gas\ combined\ cycle\ (\frac{tonne\ CO_2\ eq.}{year})$ is shown for biomass, solar and pumped hydro energy systems in Figure 4. Thus, biomass, followed by solar and pumped hydro gives the highest to the lowest $Global\ Warming\ Potential\ saving\ compared\ to\ natural\ gas\ combined\ cycle\ (\frac{tonne\ CO_2\ eq.}{year})$.

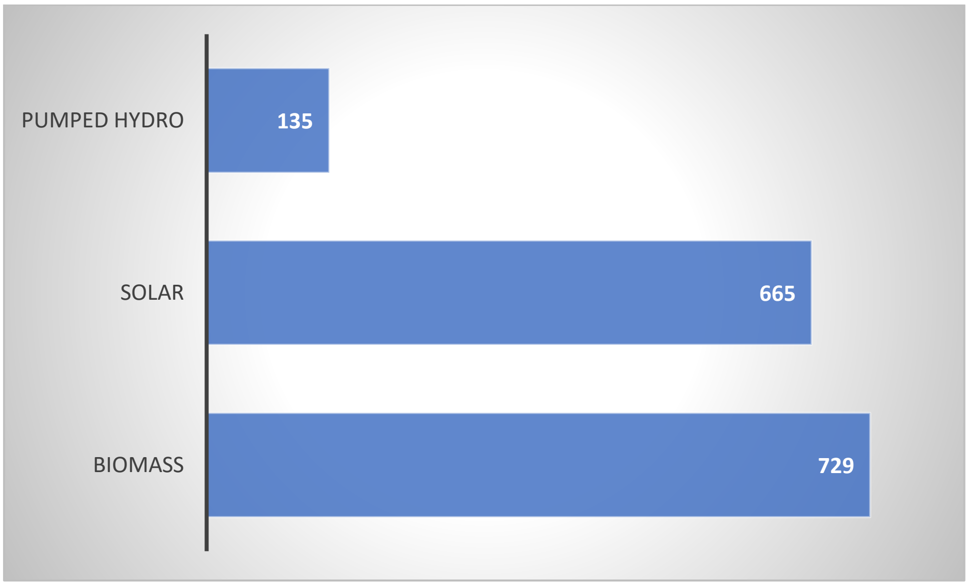

Figure 4.

$Global\ Warming\ Potential\ saving\ compared\ to\ natural\ gas\ combined\ cycle\ (\frac{tonne\ CO_2\ eq.}{year})$ of biomass, solar and pumped hydro systems.

The delivered cost of equipment (DC_i) is shown in Equations 14-15 for the boiler, and steam turbine and steam system, respectively.

$$Delivered\ cost\ of\ boiler\ (million\ Euro)\ =\ 0.00174 \times (Biomass\ needed\ (including\ moisture)\frac{kg}{hour})^{0.7}$$ Equation 14

$$Delivered\ cost\ of\ steam\ turbine\ and\ steam\ system\ (million\ Euro)\ =\ 0.1942 \times (Electricity\ generation\frac{GWh}{year})^{0.7}$$ Equation 15

The factor 0.00174 in Equation 14 is estimated based on 0.385 million Euro (or 0.4323 million \$) capital investment of a boiler processing 0.62 kg/s times 3600 for hourly biomass throughput using a scaling factor of 0.7. The basis thus defined is given in[3].

The factor 0.1942 in Equation 15 is estimated based on 5.1 million \$ capital investment of steam turbine and steam system generating 10.3 MWe using a scaling factor of 0.7. The basis thus defined is from[1].

These factors are adjusted for the given units in Table 1.

After applying a $Lang\ factor$ of 1.5 to the total delivered cost of the boiler, and steam turbine and steam system, the capital cost estimated is 0.55 million Euro using Equation 6. $Capex$ is calculated as 0.071 million Euro/year after applying an $Annual\ Capital\ Charge$ of 0.13 in Table 1.

In Equations 9-11, $a, b\ and\ c$ multiplier values are: 1.3, 0.19 and 0.09 (when the biomass flowrate is in g/h), respectively[1]. See Appendix A for the derivation of the dimensionless $a, b\ and\ c$ multiplier values. $Opex$ using Equation 9 is estimated as 0.046 million Euro/year.

Using Equation 12 and the price data in Table 1, the product value is estimated to be 0.32 million Euro/year.

The total cost ($Capex + Opex + Biomass\ cost$) (in million Euro/year) divided by the CHP generation (in GWh/year) gives the minimum selling price of energy (Equation 13), 0.025 Euro/kWh, lower than the price of electricity (Table 1), thus, making the CHP profitable.

Life cycle sustainability assessment: Social and other environmental indicators

In environmental impact assessment categories, acidification, urban smog, eutrophication and fossil resource depletion potentials are also estimated using life cycle assessment approach. Their units and life cycle impact assessment methodologies applied[1] are shown as follows.

Acidification potential: mass unit of SO_2 equivalent per year or per unit CHP generated using the CML method.

Urban smog potential: mass unit of NMVOC (non-methane volatile organic compound) equivalent per year or per unit CHP generated using the ILCD or ReCiPe method.

Eutrophication potential: mass unit of Phosphate equivalent per year or per unit CHP generated using the CML method.

Fossil resource depletion potential: GJ per year or per unit CHP generated using any life cycle impact assessment method.

Biomass CHP shows performance improvement in GWP compared to solar, pumped hydro and natural gas. Hence, for biomass, solar, pumped hydro and natural gas based energy systems, acidification, urban smog, eutrophication and fossil resource depletion potentials are analysed in the TESARREC platform. Table 2 shows the life cycle impact per unit electricity generation from the various systems in the various categories.

Table 2. Life cycle impact per unit electricity generation (per GWh) from the various systems in the various categories.

Life cycle impact category	Unit	Biomass	Solar	Pumped hydro	Gas
Acidification potential	tonne SO_2 equivalent	0.876595	0.428700	1.962646	0.204136
Urban smog potential	tonne NMVOC equivalent	0.848932	0.302699	1.005260	0.298885
Eutrophication potential	tonne Phosphate equivalent	0.360017	0.202860	0.600598	0.044935
Fossil resource depletion potential	GJ	1347.577596	837.835200	4781.759404	6484.063680

Social life cycle assessment (SLCA) estimates five main governing social categories, labour rights & decent work, health & safety, human rights, governance and community infrastructure[1]. Among the different SLCA databases developed so far, the Social Hotspot Database (SHDB) is the most significant. Over a 5-years project, the New Earth involved stakeholders worldwide to assign importance and risk to each theme under each category in a sector of goods in a country. The supply chain interactions are considered in the computation of total index of a theme for a given sector in a given country. In constructing the SHDB, the team combined the Global Trade Analysis Project (GTAP) data on import-export of goods between countries and social risk characterisation data (from stakeholders) to calculate social attributional risks of products in two ways, countries of origin and life cycle approaches.

The unit of risks is medium-risk hour (mrh) for a given functional unit, e.g. rate of product formation in case of a production system, in terms of its monetary value worth. The social issues, themes and categories have thus a common unit of mrh and thus, the weighted sum can be applied to present social scores at the various levels.

The UK imports approximately 10% of their electricity supply from France, Netherlands, Belgium, Ireland and Denmark. Within the 10% import to the UK, the percentage distributions of the import from these various countries are 49%, 24%, 20%, 6% and 1%, respectively. The trade import data have been collected from the UN Commodity Trade Statistics (UNCOMTRADE, 2019). The individual social theme risks are factored by the netted fractional imports considering the entire supply chain and these factored individual social theme risks are added to give a total social theme risk for given sector in given country. Equation 16 shows the individual total social theme risk calculation.

$$Risk_{T,p} = \sum_{c} R_{T,p,c} \times Frac_{p,c}$$

$$\sum_{c} Frac_{p,c} = 1 \qquad \text{Equation 16}$$

$Risk_{T,p}$ is the individual total social theme risk for a given product p in a given country. $R_{T,p,c}$ is the risk of a theme in the country of origin as well the countries (c) exporting to the given country (the countries of origin approach) or in the entire supply chain influencing the exports to the given country (the life cycle approach), the product p. $Frac_{p,c}$ is the fraction of the product p produced in country or imported externally using the countries of origin or the life cycle approach.

Using the UNCOMTRADE (2019) data and the SHDB, a 2019 base case scenario and a scenario with 100% self-generation case (or no import) in the UK are compared in terms of weighted aggregated risks in social categories using the country of origin approach, in the TESARREC platform. The SLCA plot illustrates that the self-generation by in-country biomass CHP gives greater incentives in all SLCA categories compared to import scenarios.

References

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3. Wan, Y.K., Sadhukhan, J., and Ng, D.K.S. (2016) Techno-economic evaluations for feasibility of sago biorefineries, Part 2: Integrated bioethanol production and energy systems. *Chemical Engineering Research & Design*, Special Issue on Biorefinery Value Chain Creation, 107, 102-116.
4. Sadhukhan, J., Martinez-Hernandez, E., Amezcua-Allieri, M.A. and Aburto, J., 2019. Economic and environmental impact evaluation of various biomass feedstock for bioethanol production and correlations to lignocellulosic composition. *Bioresource Technology Reports*, *7*, p.100230.

Appendix A (Please Refer to Chapter 2 of Reference 1. Sadhukhan, J. Ng, K.S. and Martinez-Hernandez, E., 2014. *Biorefineries and Chemical Processes: Design, Integration and Sustainability Analysis*. Wiley, Chichester, UK. for economic analysis calculations.)

The operating costs can be classified into two main categories: fixed and variable operating costs. Fixed operating costs are independent of the production rate and quantity, in contrast to variable operating costs. This includes the costs of maintenance, labour, taxation, insurance, royalties etc. Fixed operating costs are estimated using factors, normally based on indirect capital cost and labour cost. Other costs such as the costs of research and development, sales expenses and general overheads are added as % to obtain the total operating cost. Thus, the value of a in Equation 9 is 1.3. The accounting of these cost items is shown in Equation A1.

$$costs\ of\ research\ and\ development\ +\ costs\ of\ sales\ expenses\ +$$
$$costs\ of\ general\ overheads\ =\ 30\%\ of\ Direct\ Production\ Cost \qquad \text{Equation A1}$$

The indirect capital cost is 1.26 times the delivered cost of equipment for solid-fluid processing system. The indirect capital cost includes the following cost items: engineering and supervision, construction expenses, legal expenses, contractor's fee and contingency. Furthermore, the fixed operating cost dependent on the indirect capital cost is 0.15 times the indirect capital cost. The fixed operating cost dependent on the indirect capital cost includes the following cost items: maintenance, capital charges, insurance, local taxes and royalties. Thus, the value of b in Equation 9 is $1.26 \times 0.15 = 0.19$.

The fixed operating cost dependent on the personnel cost is 1.9 times the personnel cost. The fixed operating cost dependent on the personnel cost includes the following cost items: labour, laboratory, supervision and plant overheads. The personnel cost is \$52033 per t/h throughput[4]. 1 EURO is assumed to be 0.9 times \$1. Thus, the value of c in Equation 13 is $1.9 \times 0.9 \times 52033/1000000 = 0.09$.

Conclusions

https://tesarrec.web.app/sustainability/chp allows modelling of techno-economic, environmental and social life cycle performance analyses of biomass based Combined Heat and Power systems (CHP). This is a new addition to the TESARREC platform directly generated from the Newton Fund Impact Scheme. Combined Heat and Power systems (CHP) are a technology for simultaneous electricity and heat generation utilising carbonaceous fuel. Biomass is a non-conflicting (with food or feed production and land use) greenhouse gas efficient fuel, because carbon dioxide released from its combustion is sequestrated or captured during its growth. It allows estimation of biomass throughput to achieve a given electricity output and low pressure steam generation in the CHP schematic. The outputs from the model include the amount of steam generation, biomass throughput requirement to meet the electricity demand and electricity and total energy efficiencies. It also shows the analysis of environmental and social performances using a rigorous holistic 'whole-system' life cycle sustainability assessment approach. The novel platform allows businesses, industries, SMEs and investors in evaluation of their local or (sub)country level system for sustainability. Policymakers can evaluate climate impact savings against other contemporary systems to set out carbon targets, such as net zero carbon target.