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Supplementary Materials: Assessing the Cost of Biomass and Bioenergy Production in Agroindustrial Processes

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1. Economic modelling description

1.1. Netback of Biomass

For any case where you can have savings due to fuel switching to biomass and sale of excess energy, the netback of the biomass is calculated by the following equation:

$$NB = \frac{\text{Energy sales} + \text{Savings} - \text{total costs}}{m} \quad (1)$$

where NB is the netback, m is the biomass flow used. NB is equal to the maximum biomass price that allows for a net economic benefit. To calculate NB in $/GJ, the value of Equation (1) is divided by the lower heating value of biomass.

Energy sales are the result of multiplying the amount of steam or electricity by its price. Net savings are the result of multiplying the amount of steam or electricity by the price of generating steam from fossil fuel and the price of grid electricity, respectively. Thus:

$$\text{Energy sales } = m_{steam} \times \text{steam price} + E_{el} \times \text{electricity price}$$

$$\text{Savings} = m_{steam} \times \text{price of steam using other fuel} + E_{el} \times \text{grid electricity price}$$

Note that the netback is determined without considering the cost of biomass.

1.2. Total Cost of Energy Production

The total cost of energy production (*COP*) is calculated as follows:

$$COP = \mathrm{E}_{imp} \times p_{el} + W \times p_w + m \times p_b + ACC + O \quad (2)$$

where E_{imp} is the amount of electricity imported from the grid (if applicable), p_{el} price paid for such electricity. *W* is the amount of water used for steam generation, p_w is the price paid for water. *m* is the biomass flow and p_b is the reference price of biomass. This reference price may be the price of biomass for alternative use, or the price currently paid, if known. *ACC* is annualised capital expenditure, *O* are other costs, including maintenance and other raw materials.

1.3. Capital Costs

The annual capital cost is derived from the estimate of the total investment. The total investment (*TI*) is determined by:

$$TI = CP + WC + SV + RD + \text{others} \quad (3)$$

where *CP* is the total installed cost of the plant, including equipment purchase, construction, installation, etc. *WC* is working capital, *SV is* the start-up and validation expense, *RD is* the cost of research and development and others may include licensing cost, etc. In the current model version, only the total cost of the plant will be considered, since the other items do not necessarily apply in the case of self-consumption bioenergy production. The total installed cost of the plant is then determined from the cost of the equipment and applying a factor that considers the costs of installation, construction, auxiliary installations, land, instrumentation, etc. This factor is known as Lang's factor:

$$CP = CTE * f_L \quad (4)$$

where *CTE* is the total cost of buying the equipment, and is the Lang factor that varies between approximately 3 and 5. The total cost of purchasing the equipment depends on the size of the equipment, and therefore, how much biomass is processed. The cost of a piece of equipment (*ceq*) is determined by the following equation:

$$ceq = Co\left(\frac{Q}{Qo}\right)^{b} \tag{5}$$

where *Co* is a known base cost to a known Qo base size or capacity, *Q* is the required capacity of the equipment, and b is the scaling exponent. Each base cost can be in reference to a certain year, so the cost is updated to the year of analysis by using the Chemical Process Plant Index *(CEPCI)*, which is an indicator of inflation in the cost of plants accepted for estimation purposes (Chemical Engineering Magazine, 2020). The update is then done as follows:

$$ceq\_a = ceq\_b\left(\frac{CEPCIa}{CEPCIb}\right) \tag{6}$$

where *ceq_a* is the cost updated per year to, while

ceq_b is the cost per reference year b, *CEPCIa* is the index in year a, and *CEPCIb* is the index in year b.

The total cost of purchasing the equipment is then:

$$CTE = \sum_{i=1}^{n} ceq\_a_i \tag{7}$$

where *n* is the total number of computers. Currently, the model considers the following equipment: boiler, backpressure turbine, water pump, and air fan.

Once *CTE* is obtained, you can calculate *CP* (Equation (4)) and then *TI* (Equation (3)). From *TI*, the annual cost of capital is determined. If the investment is financed by a credit:

$$ACC = IT \times arate + Dep \tag{8}$$

where *arate* is the capital cost annualisation factor for a given interest rate. *Dep* is depreciation. When the investment is made by dividends, only depreciation is considered:

$$ACC = Dep \tag{9}$$

The model considers the savage value at the end of the life of the evaluated project. The model then considers linear depreciation over a specified depreciation period:

$$Dep = \frac{IT(1-s)}{tdep} \tag{10}$$

where *s* is the fraction of the initial investment as the life value. *tdep* is the depreciation period.

1.4. Other Costs

For the term O of other costs in Equation (1), this model considers the cost of maintenance, the cost of labour, and others,

$$O = C_m + C_l + C_{otros} \tag{11}$$

The cost of maintenance and others are calculated as a percentage of the total cost of the plant:

$$C_m + C_{otros} = CP(f_m + f_{otros}) \tag{12}$$

where f_m is the percentage of maintenance, and f_{otros} is the percentage for other costs.

The labour cost is calculated by multiplying the total number of hours of operation in one year (per hourly cost of labour). In this current model, this hourly cost is a weighted average of all positions on the plant.

$$C_l = top \times c_{mo} \tag{13}$$

1.5. Economic indicators

For a given reference biomass price, the model also calculates a net present value (VPN), internal rate of return (TIR), and payback period indicators. The equations calculating these indicators are reported elsewhere and are common to all economic evaluations in the models.

2. Upstream Model Description

2.1. Cultivation Cost

The model for cultivation cost consists of the cumulative costs for the establishment, maintenance, harvesting and other cultivation activities. The cost for establishment is divided by the rotation cycle of the crop, so that the total sum of cultivation cost can be written as:

$$CC = \sum_{j}^{J}\sum_{i}^{I} x_{i,j}C_i + \frac{\sum_i^I x_{i,establish}C_i}{T} \tag{14}$$

where CC is cultivation cost, $x_{i,j}$ is the amount of input i in stage j with j={maintenance, harvesting and other}, $x_{i,establish}$ is the amount of input I in the establishment stage and T is the rotation cycle or lifetime of the plantation. Two hydric regimes are considered: rainfed and irrigation. In a simplified model option, the user specifies the total cost for each regime, the percentage of each regime and the total cost is the weighted average using such percentage.

2.2. Transportation Cost

The transportation cost is estimated using a general fixed and variable cost parameter equation as follows:

$$TC = FC + VC(D) \tag{15}$$

where TC is transportation cost, FC is fixed cost and VC is variable cost parameters, while D is the average transportation distance. The parameters depend on the type of vehicle and its transportation capacities. The types of vehicles can be selected, and a percentage for each vehicle is specified by the user for a weighted cost calculation. In addition, the transportation means available are by road and train. The transportation cost by rail is calculated using the same equation with its corresponding parameters. In addition, two other model options are available for transportation by road. One directly uses the cost parameters from Tauro et al., multiplied by the amount transported and transportation distance:

$$TC = B(mD) \tag{16}$$

where B is the base cost, m is the mass transported and D is the distance. The parameter B is different for each type of vehicle available.

2.3. Agroindustrial and Conditioning Costs

In these two stages, an input-output model is used to determine first a mass balance using input factor and yield factors. For each raw material input the input flow is calculated using:

$$F_{input} = x_{input}F_{main\ input} \tag{17}$$

where F_{input} is the amount of raw material input to a process, x_{input} is the mass factor in kg raw material per kg of main input, $F_{main\ input}$ is the amount of main input being processed (the main crop in the agro-industrial processing case, and the raw biomass stream in the conditioning case).

To calculate the amount of output, the equation used is:

$$F_{output} = x_{output}F_{main\ input} \tag{18}$$

where $F_{input}$is the amount of material output from the process, x_{output} is the mass factor in kg of output material per kg of main input. If the total flows are known instead of the factors, they can be specified, but the factor approach is preferred for the case of evaluating various processing capacities.

3. Agro-industrial process simulation results

Table S1. Simulation report as generated by the IMP Bio2Energy software for the tequila production process

Mass balance

Stream	Type	Input flow (ton/y)	Output flow (ton/y)
Agave	Main feed	19500	
Water	Raw material	6054.75	
Yeast	Raw material	23.4	
Bagasse	Biomass product		16408.79
Tequila	Product		2683.2
Methanol	Product		26.82
Vinasse	Emission/waste		5712.23
Tails	Emission/waste		747.123
Total mass balance		25578.15	25578.18

Utility demands

Utility	Annual demand	Price ($/unit)	Subtotal ($/year)
LP steam (ton)	40692.79	14.879	605486.408
Electricity	1,374,945	0.0858	117970.281
Cooling water	9388.58	0.05	469.428

Raw material and product prices, and waste disposal costs

Name	Type	Price/Cost ($/kg)	Subtotal ($/year)
Agave	Main feed	1.1	21450000
Water	Raw material	0.000125	757
Yeast	Raw material	100	2340000
Bagasse	Biomass product	0.005	82
Tequila	Product	15	40248
Methanol	Product	0.05	1
Vinasse	Emission/waste	0.0025	14281
Tails	Emission/waste	0.00125	934

Economic Results

Cost item	Value
Total capital investment ($)	2,462,990
Annualised capital cost ($/year)	233,984
Operating costs ($/year)	24,629,897
Total annual costs ($/year)	24,863,881

Allocation results

Product	Flow rate (ton/y)	Economic value ($/y)	Allocated cost ($/ton)
Bagasse	16408.8	82.04	3.08
Tequila	2683.2	40248.00	9247.34
Methanol	26.8	1.34	30.82

Table S2. Simulation report as generated by the IMP Bio2Energy software for the coffee processing

Mass balance

Stream	Type	Input flow (ton/y)	Output flow (ton/y)
Coffee	Main feed	47175	
Coffee pulp	Biomass product		19332.31
Mucilago	Emission/waste		7548
Evaporated water	Emission/waste		9435
Pergamino	Emission/waste		2127.59
Gold coffee	Product		8732.09
Total mass balance		47175	47175

Utility demands

Utility	Annual demand	Price ($/unit)	Subtotal ($/year)
LP steam	32154.95175	14.87945	478448
Electricity	1,400,154	0.0858	120133

Raw material and product prices, and waste disposal costs

Name	Type	Price/Cost ($/kg)	Subtotal ($/year)
Coffee	Main feed	0.35	16511250.00
Coffee pulp	Biomass product	0.01	96.66
Mucilago	Emission/waste	0.01	37740.00
Pergamino	Emission/waste	0.01	10637.96
Gold coffee	Product	2.75	24013.25

Economic Results

Cost item	Value
Total capital investment ($)	1,727,972
Annualised capital cost ($/year)	164,157
Operating costs ($/year)	17,279,721
Total annual costs ($/year)	17,443,879

Allocation results

Product	Flow rate (ton/y)	Economic value ($/y)	Allocated cost ($/ton)
Coffee pulp	19332.3	96.66	3.62
Gold coffee	8732.1	24013.25	1989.67

Table S3. Simulation report as generated by the IMP Bio2Energy software for the orange processing

Mass balance

Stream	Stream type	Input flow (ton/y)	Output flow (ton/y)
Orange	Main feed	633153	
Process water	Raw material	21087.79382	
CaO	Raw material	601.49535	
Orange peels	Biomass product		171426.1748
Concentrated orange juice	Product		105014.8832
Essential oil	Product		1673.6766
Oil extraction wastewater	Emission/waste		178568.9637
Press liquor	Emission/waste		82022.5018
Orange residue	Emission/waste		97141.4990
Other emission/waste	Emission/waste		18994.59
Total mass balance		654842.2892	654842.2892

Utility demands

Utility	Annual demand	Price ($/unit)	Subtotal ($/year)
LP steam	79087.14123	14.87945	1176773
Electricity	12,741,210	0.0858	1093196

Raw material and product prices, and waste disposal costs

Name	Type	Price/Cost ($/kg)	Subtotal ($/year)
Orange	Main feed	0.125	79144125
Process water	Raw material	0.001435	30260.984
CaO	Raw material	0.3	180448.605
Air	Raw material	0	0
Other raw material	Raw material	0	0
Orange peels	Biomass product	0.005	857.130
Concentrated orange juice	Product	2.72	285640.482
Essential oil	Product	12.5	20920.958
D-limonene	Product	12.5	0
Other product	Product	0	0
Oil extraction wastewater	Emission/waste	0.00011	19642.586
Press liquor	Emission/waste	0	0
Orange residue	Emission/waste	0	0
Other emission/waste	Emission/waste	0	0

Economic Results

Cost item	Value
Total capital investment ($)	8,196,944.62
Annualised capital cost ($/year)	778,709.74
Operating costs ($/year)	81,969,446.16
Total annual costs ($/year)	82,748,155.90

Allocation results

Product	Flow rate (ton/y)	Economic value ($/y)	Allocated cost ($/ton)
Orange peels	171426.2	857.13	1.3458
Concentrated orange juice	105014.9	285640.48	732.1450
Essential oil	1673.7	20920.95	3364.6371

Table S4. Simulation report as generated by the IMP Bio2Energy software for the orange peel drying

Mass balance

Stream	Input flow (ton/y)	Output flow (ton/y)
Input biomass	171426	
Dried biomass		48978.8081
Evaporated water		122447.1918
Total mass balance	171426	171426

Biomass product moisture (%)	30

Utility demands

Utility	Units	Annual demand
Electricity	kWh	191,197
Direct heat	MJ	113000000

4. Sensitivity to electricity prices

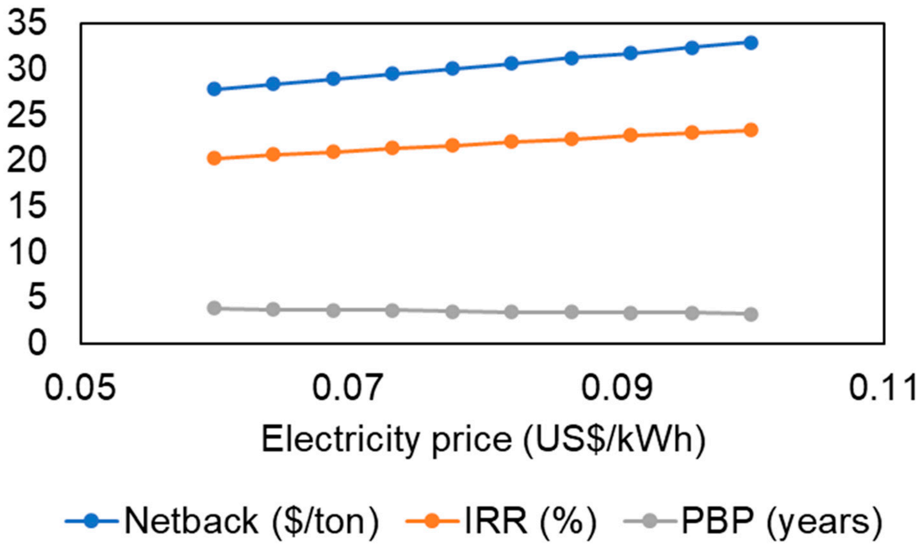

Figure S1. Sensitivity of electricity prices of agave bagasse case.

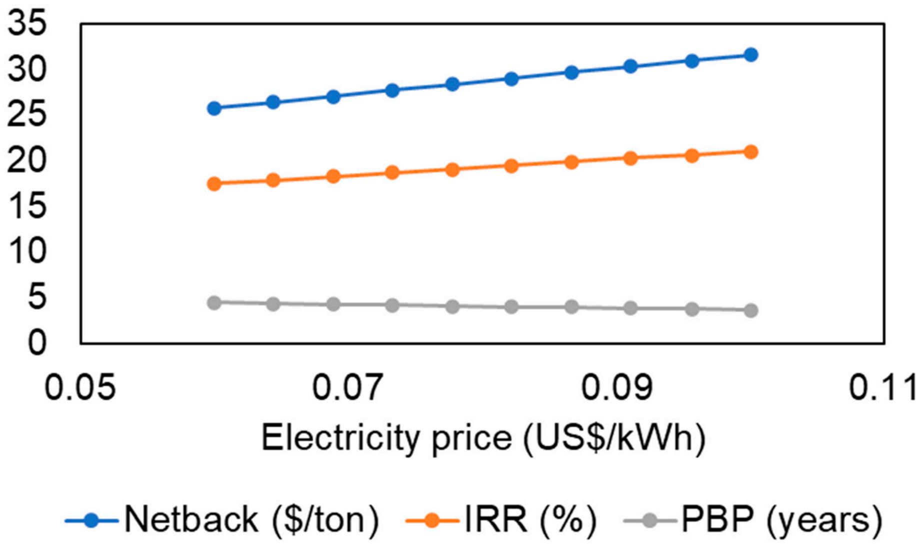

Figure S2. Sensitivity of electricity prices of coffe pulp case.

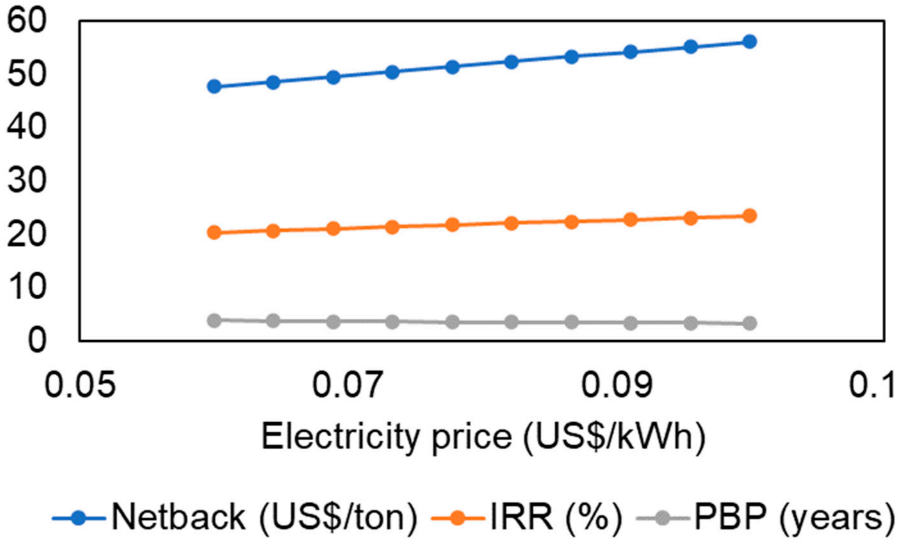

Figure S3. Sensitivity of electricity prices of orange peels case.

5. Two-way analysis of Variance (ANOVA) of sensitivity results

Table S5. ANOVA results for dependent variable Netback and independent variables biomass input and biomass type.

Independent variable	DF	Sum of squares	Mean square	F value	P value
Biomass input (ton/day)	17	658.48	38.73	9,63 *	4.45e-4
Biomass type	2	213.36	106.68	26.51 *	1.01e-4
Model	19	2757.75	145.14	36.07	8.96e-7
Error	10	40.24	4.02	--	--
Corrected total	29	2797.99	--	--	--

Table S6. ANOVA results for dependent variable Netback and independent variables fossil fuel price and biomass type.

Independent variable	DF	Sum of squares	Mean square	F value	P value
Fossil fuel price (US$/GJ)	9	3921.53	435.73	24.99 *	2.14e-8
Biomass type	2	3479.24	1739.62	99.80 *	1.81e-10
Model	11	7400.77	672.80	38.60	3.13e-10
Error	18	313.76	17.43	--	--
Corrected total	29	7714.52	--	--	--

Table S7. ANOVA results for dependent variable Netback and independent variables boiler steam pressure and biomass type.

Independent variable	DF	Sum of squares	Mean square	F value	P value
Boiler steam pressure (Bar)	17	110.45	6.50	8.00 *	9.88e-4
Biomass type	2	2822.48	1411.24	1737.71 *	1.94e-13
Model	19	3850.14	202.64	249.52	6.57e-11
Error	10	8.12	0.81	--	--
Corrected total	29	3858.26	--	--	--

Table S8. ANOVA results for dependent variable Unit cost and independent variables biomass input and biomass type.

Independent variable	DF	Sum of squares	Mean square	F value	P value
Biomass input (ton/day)	17	13.03	0.77	28.38 *	3.09e-6
Biomass type	2	3.22	1.61	59,71 *	2.75e-6
Model	19	17.41	0.92	33.94	1.20e-6
Error	10	0.27	0.027	--	--

Corrected total	29	17.68	--	--	--

Table S9. ANOVA results for dependent variable Unit cost and independent variables boiler steam pressure and biomass type.

Independent variable	DF	Sum of squares	Mean square	F value	P value
Boiler steam pressure (Bar)	17	0.03	1.48e-3	1.77	0.18
Biomass type	2	0.04	0.02	23.28 *	1.73e-4
Model	19	0.12	6.50e-3	7.74	1.06e-3
Error	10	8.40e-3	8.40e-4	--	--
Corrected total	29	0.13	--	--	--

Table S10. ANOVA results for dependent variable Payback period and independent variables biomass input and biomass.

Independent variable	DF	Sum of squares	Mean square	F value	P value
Biomass input (ton/day)	17	49.15	2.89	16.65 *	3.78e-5
Biomass type	2	14.27	7.14	41.09 *	1.50e-5
Model	19	62.18	3.27	18.85	1.96e-5
Error	10	1.74	0.17	--	--
Corrected total	29	63.92	--	--	--

Table S11. ANOVA results for dependent variable Payback period and independent variables fossil fuel price and biomass type.

Dependent variable: PBP (years)	DF	Sum of squares	Mean square	F value	P value
Fossil fuel price (US$/GJ)	9	45.09	5.01	1264.31 *	0

Biomass type	2	1.77	0.88	223.15 *	1.98e-13
Model	11	46.86	4.26	1075.01	0
Error	18	0.07	0.01	--	--
Corrected total	29	46.93	--	--	--

Table S12. ANOVA results for dependent variable Payback period and independent variables boiler steam pressure and biomass type.

Dependent variable: PBP (years)	**DF**	**Sum of squares**	**Mean square**	**F value**	**P value**
Boiler steam pressure (Bar)	17	0.28	0.02	4.29 *	1.12e-3
Biomass type	2	0.14	0.08	20 *	3.20e-4
Model	19	0.88	0.05	13.08	1.06e-4
Error	10	0.04	0.35e-3	--	--
Corrected total	29	0.91	--	--	--