Supplementary Materials: Environmental Assessment of Integrated Food and Cooking Fuel Production for a Village in Ghana

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Emergy table and calculation notes that refer to the table. Calculation notes provide information about input quantities and about UEVs that are calculated in this study. A separate bibliography for table and calculation references is included. For further information, please, contact corresponding author, Hanne Østergård: haqs@kt.dtu.dk.

Table S1. Emergy table.

Note	Item (unit)	Quantity per year				UEV (sej/unit)				Ref. for UEV[a]	Empower (sej/year)[b]				Global Renewability Fraction				Ref. for Global Ren. Fraction[c]
		PP	HH biogas	Village biogas	Agro-forestry	PP	HH biogas	Village biogas	Agro-forestry		PP	HH biogas	Village biogas	Agro-forestry	PP	HH biogas	Village biogas	Agro-forestry	
	Biomass production																		
1	Sun (J)	2.4×10^{15}	2.4×10^{15}	2.4×10^{15}	2.4×10^{15}	1.0×10^{0}				a	2.4×10^{15}	2.4×10^{15}	2.4×10^{15}	2.4×10^{15}	100%				Defined
2	Wind (J)	1.5×10^{11}	1.5×10^{11}	1.5×10^{11}	1.5×10^{11}	2.5×10^{3}				a	3.6×10^{14}	3.6×10^{14}	3.6×10^{14}	3.6×10^{14}	100%				Defined
3	Rain (J)	3.6×10^{12}	3.6×10^{12}	3.6×10^{12}	3.6×10^{12}	3.1×10^{4}				a	1.1×10^{17}	1.1×10^{17}	1.1×10^{17}	1.1×10^{17}	100%				Defined
4	Deep earth heat (J)	6.0×10^{11}	6.0×10^{11}	6.0×10^{11}	6.0×10^{11}	1.2×10^{4}				a	7.2×10^{15}	7.2×10^{15}	7.2×10^{15}	7.2×10^{15}	100%				Defined
5	Soil loss (kg Corg)	1.8×10^{4}	1.4×10^{4}	1.3×10^{4}	2.3×10^{3}	5.0×10^{12}				This work	8.9×10^{16}	6.9×10^{16}	6.3×10^{16}	1.2×10^{16}	0%				Defined
6	Seed (kg)	9.1×10^{2}	9.1×10^{2}	9.1×10^{2}	9.2×10^{2}	4.2×10^{12}			2.7×10^{12}	This work	3.8×10^{15}	3.8×10^{15}	3.8×10^{15}	2.5×10^{15}	42%	42%	42%	58%	This work
7	Pesticide chemicals (kg active ingredient)	1.2×10^{2}	1.2×10^{2}	1.2×10^{2}	1.2×10^{2}	2.5×10^{13}				c,a	3.1×10^{15}	3.1×10^{15}	3.1×10^{15}	3.1×10^{15}	1%				j
8	Synthetic fertiliser (kg)	3.2×10^{3}	2.4×10^{3}	2.1×10^{3}	1.8×10^{3}	3.3×10^{12}				d	1.1×10^{16}	8.0×10^{15}	6.9×10^{15}	5.9×10^{15}	1%				j
9	Machinery (kg)	6.2×10^{0}	6.2×10^{0}	6.2×10^{0}	6.2×10^{0}	1.4×10^{13}				e,a	8.6×10^{13}	8.6×10^{13}	8.6×10^{13}	8.6×10^{13}	5%				j
10	Diesel (L)	8.2×10^{2}	8.2×10^{2}	8.2×10^{2}	8.2×10^{2}	9.1×10^{12}				e	7.5×10^{15}	7.5×10^{15}	7.5×10^{15}	7.5×10^{15}	1%				j
11	Direct labour, low UEV (man-hours)	1.7×10^{4}	1.7×10^{4}	1.7×10^{4}	1.9×10^{4}	3.2×10^{12}				b	5.5×10^{16}	5.5 × 1016	5.5×10^{16}	6.1×10^{16}	10%				k
12	Indirect labour, global UEV (global man-hours)	4.5×10^{2}	4.3×10^{2}	4.2×10^{2}	4.1×10^{2}	1.8×10^{13}				This work	8.4×10^{15}	7.9×10^{15}	7.7×10^{15}	7.5×10^{15}	16%				l

Table S1. *Cont.*

Note	Item (unit)	Quantity per year				UEV (sej/unit)				Ref. for UEV[a]	Empower (sej/year)[b]				Global Renewability Fraction				Ref. for Global Ren. Fraction[c]
		PP	HH biogas	Village biogas	Agro-forestry	PP	HH biogas	Village biogas	Agro-forestry		PP	HH biogas	Village biogas	Agro-forestry	PP	HH biogas	Village biogas	Agro-forestry	
	Biomass conversion																		
13	Firewood (kgdm)	3.5×10^{4}	-	-	-	3.1×10^{11}	-	-	-	This work	1.1×10^{16}	-	-	-	50%	-	-	-	Assumed
14	Charcoal (kg)	2.9×10^{3}	-	-	-	2.1×10^{12}	-	-	-	This work	6.0×10^{15}	-	-	-	50%	-	-	-	Assumed
15	Plastics (kg)	-	1.0×10^{2}	1.8×10^{0}	-	-	9.8×10^{12}		-	f	-	1.0×10^{15}	1.8×10^{13}	-	1%				j
16	Steel (kg)	-	-	8.0×10^{1}	-	-	-	6.9×10^{12}	-	g	-	-	5.5×10^{14}	-	5%				j
17	Timber (kg)	-	7.0×10^{1}	5.8×10^{1}	-	-	1.5×10^{12}		-	g	-	1.0×10^{14}	8.5×10^{13}	-	50%				Assumed
18	Water (L)	-	1.4×10^{4}	1.1×100^{3}	-	-	1.9×10^{9}		-	h	-	2.6×10^{13}	2.1×10^{12}	-	100%				Assumed
19	Manure (kg)	-	8.4×10^{2}	8.3×10^{1}	-	-	1.3×10^{11}		-	i	-	1.1×10^{14}	1.1×10^{13}	-	29%				i
20	Diesel (L)	-	6.8×10^{1}	5.2×10^{1}	1.5×10^{1}	-	9.1×10^{12}			e	-	6.2×10^{14}	4.7×10^{14}	1.3×10^{14}	1%				j
21	Machinery (kg)	-	3.1×10^{0}	3.3×10^{0}	-	-	1.4×10^{13}		-	e,a	-	4.2×10^{13}	4.5×10^{13}	-	5%				j
22	Direct labour, low UEV (man-hours)	7.1×10^{2}	6.2×10^{3}	4.5×10^{3}	4.0×10^{2}	3.2×10^{12}				b	2.3×10^{15}	2.0×10^{16}	1.4×10^{16}	1.3×10^{15}	10%				k
23	Direct labour, middle UEV (man-hours)	-	-	3.8×10^{2}	6.8×10^{0}	9.1×10^{12}				b	-	-	3.4×10^{15}	6.2×10^{13}	10%				k
24	Indirect labour, low UEV (man-hours)	4.7×10^{1}	-	-	-	3.2×10^{12}	-	-	-	b	1.5×10^{14}	-	-	-	10%				k
25	Indirect labour, middle UEV (man-hours)	6.8×10^{0}	-	-	-	9.1×10^{12}	-	-	-	b	6.2×10^{13}	-	-	-	10%				k
26	Indirect labor, global UEV (global man-hours)	1.3×10^{0}	8.0×10^{1}	6.3×10^{1}	1.3×10^{0}	1.8×10^{13}				This work	2.3×10^{13}	1.5×10^{15}	1.2×10^{15}	2.3×10^{13}	16%				1
	Output																		
27	Food and useful energy basket (J), without labour	1.1×10^{12}	1.1×10^{12}	1.1×10^{12}	1.1×10^{12}	2.2×10^{5}	1.9×10^{5}	1.7×10^{5}	1.3×10^{5}		2.5×10^{17}	2.1×10^{17}	2.0×10^{17}	1.5×10^{17}	51%	56%	58%	80%	
28	Food and useful energy basket (J), with labour	1.1×10^{12}	1.1×10^{12}	1.1×10^{12}	1.1×10^{12}	2.8×10^{5}	2.7×10^{5}	2.5×10^{5}	2.0×10^{5}		3.1×10^{17}	2.9×10^{17}	2.8×10^{17}	2.2×10^{17}	43%	43%	45%	58%	

[a] UEVs that are shared among technology scenarios are centered in the columns they belong to. References used are a:[1], b: [2], c:[3], d: [4], e: [5], f: [6], g: [7], h: [8], i:[9],

[b] Sums of empower in lines 27 and 28 exclude inputs 1 and 2 since only the largest of sun, wind and rain inputs are to be accounted for.

[c] References used are j: [10], k: [11], l: [12].

Calculation Notes

Note	*Biomass production*
1	**Sun (J)** 1.20×10^{21} J/year for country [11] divided by 2.30×10^{7} ha and multiplied with 45 ha.
2	**Wind (J)** 7.50×10^{16} J/year for country [11] divided by 2.30×10^{7} ha and multiplied with 45 ha.
3	**Rain (J)** 1.80×10^{18} J/year for country [13] divided by 2.30×10^{7} ha and multiplied with 45 ha.
4	**Deep earth heat (J)** 42 mW/m^2 [14] converted to 1.32×10^{10} J/ha/year and multiplied with 45 ha.
5	**Soil loss (kg Corg)** 700 kg/ha/year soil organic matter (assuming 1 mm/year as [15]) of which 56% is considered soil organic carbon [16] Multiplied with 45 ha. HH biogas: reduced by net addition 3900 kg of recycled C. Village biogas: reduced by net addition of 5200 kg recycled C. Agro-forestry: reduced by 87% [17]. UEV: Based on 1.91×10^{5} sej/J of soil organic matter [18] with 56% soil organic carbon and an energy content of 3.5 kcal/g [18] UEV of SOC = UEV of SOM / 56% × (3.5 kcal/g × 4186 J/kcal) × 10^{0} g/kg = 5.0×10^{12} sej/kg.
6	**Seed (kg)** Interview data. Includes only purchased seed. Most seed is from own production. Agro-forestry: 3 kg/ha of leucaena seeds [19] every 20 years was added, equal to 6 kg/year/40 ha. UEV: Found by iterating the food output UEV of PP found in this study and assuming that it is applicable for purchased seed in the two biogas technology options. For Agro-forestry, the UEV is iterated based on inputs to the modelled agro-forestry production system. Global Renewability Fraction: Found by iterating the food output renewability fraction found in this study.
7	**Pesticide chemicals (kg active ingredient)** Interview data.
8	**Synthetic fertiliser (kg)** Interview data. HH biogas: reduced by 156 kg elemental N that is recycled, equal to 782 kg of NPK mixture (20-3-10). Village biogas: reduced by 1336 kg of NPK mixture. N is considered the limiting nutrient. Agro-forestry: reduced by 50% on maize and beans fields (40 ha out of 45 ha).
9	**Machinery (kg)** Based on interview data. For tractor wear and tear we assume an estimated 0.089 kg/hour of use for ploughing, de-husking or transport.
10	**Diesel (L)** Based on interview data. Fuel use is estimated to approximately 9 L/ha.
11	**Direct labour, low UEV (man-hours)** Interview data.
12	**Indirect labour, global UEV (global man-hours)**

Based on interview data. Purchased inputs in PP are tractor hire incl. diesel (4,206 GHS/year), pesticides (3,058 GHS), fertiliser (2,332 GHS), seed (1,559 GHS) for a total of 11,155 GHS/year. This is approximately 4,800 USD/year using the conversion rate of 0.43 US Dollars per Ghanaian Cedi. Reduced synthetic fertiliser inputs results in 4,600 USD/year (HH biogas), 4,400 USD/year (Village biogas), and 4,300 USD/year (incl. leucaena seed). USD values are converted to global man-hours with the conversion rate of 10.6 USD/man-hour, calculated as: Gross World Product/laboured hours in a year = GWP / (labour force×avg. work year) = 6.1×10^{13} USD/year / (3.1×10^{9} persons × 40 hours/week/person × (52-6) weeks/year) = 6.1×10^{13} USD/year / (3.1×10^{9} persons × 1840 hours/year) = 10.6 USD/hour. GWP (year 2008) from [12] and labour force data (year 2008) from the [20].

UEV: Global emergy flow (year 2008)/total labour estimate (year 2008) = 1.1×10^{26} sej/year / (3.1×10^{9} persons × 1840 hours/person) = 1.8×10^{13} sej/global man-hours.

Bioenergy production

13 **Firewood (kgdm)**

Interview data. The stated value is equivalent to approximately 45 tons of dead wood with 22% moisture content.

UEV: Based on Table 13 in [21], multiplied with 1.68 for emergy baseline adjustment:

9963 sej/J × 1.68 × 18.3MJ/kgdm × 1 × 1006 J/MJ = 3.06 × 1011 sej/kgdm.

Global Renewability Fraction: Assumed, see sensitivity analysis.

14 **Charcoal (kg)**

Interview data. Charcoal is made primarily from live trees (88% in [22]) with approximately 15% conversion efficiency, based on mass. This makes an average ton of charcoal equivalent to 5.9 tons of live trees and 0.8 tons of dead wood. For the 2.9 tons in PP and Agro-forestry, this is equivalent to 17 tons of live trees and 5.2 tons of dead wood.

UEV based on interview data concerning 1500 kg of charcoal: 10 t of wood for 40 bags with 37.5 kg charcoal in each (i.e. 15% weight efficiency). Estimate of four days of labour (½ day for sawing, ½ day for mounding, a total of 1 day for monitoring, 2 days for bagging and transporting to village) with 1/8 semiskilled and 7/8 farmhand labour. Fuel use 7.6 L. UEV = emergy flow / 1500 kg charcoal = (wood emergy + fuel emergy + semiskilled labour emergy + farmhand labour emergy)/1500 kg = (10,000 kg × 3.06×10^{11} + 7.6 L × 9.14×10^{12} sej/L + 4 man-hours × 9.1 × 1012 sej/man-hour + 28 man-hours × 3.2×10^{12} sej/man-hour)/1500 kg = 2.17×10^{12}.

Global Renewability Fraction: Assumed, see sensitivity analysis.

15 **Plastics (kg)**

HH biogas [23]: For each of 7 plants: 6 digester and 2 effluent storage 240 L PVC barrels, each weighing 10 kg and 2 gas storage 1000L plastic tanks of 35 kg each. Life span 10 years. Village biogas: 10 kg of plastic in fittings and pump and two 240 L tanks of 10 kg each for one container. It is assumed that a village-scale biogas plant will use three containers to match village supply, and that the plant produces approximately five times the output required by the seven households. The inputs are adjusted for this.

16 **Steel (kg)**

Village biogas: 2400 kg shipping container and 200 kg storage tank, life span 20 years (based on [24]). Adjusted to biogas requirement of seven households (see Calculation note 15).

17 **Timber (kg)**

Interview data. HH biogas and Village biogas: Estimated 700 kg for a barn. Life span 10 years.
Global Renewability Fraction: Assumed, see sensitivity analysis.

18 **Water (L)**
HH biogas [23]: At startup, each digester barrel is filled with 160 L of water. Re-start of subsequent batches involve re-using 140 L of effluent and adding 20 L of fresh water. For 7 plants, 6 digesters per plant and 8.7 batches/year:
(6 × 160+6 × 8.7 × 20) L/year = 14,000 L/year. Village biogas: From [24], adjusted to biogas requirement of seven households (see Calculation note 15).

19 **Manure (kg)**
HH biogas: 20 kg manure per digester per year assumed. Village biogas: From [24], converted to kg of dry matter and adjusted to biogas requirement of seven households (see Calculation note 15).

20 **Diesel (L)**
HH biogas and Village biogas: Estimated fuel use in transport of crop residues and digestate from and to fields.

21 **Machinery (kg)**
PP and Agroforestry, interview data: Chainsaw use is negligible. HH biogas and Village biogas: Estimated tractor wear and tear in transport of crop residues and digestate from and to fields is 0.05 kg/t. Village biogas: Includes an average 1.0 kg of generator and compressor use per year.

22 **Direct labour, low UEV (man-hours)**
PP: Interview data for firewood collection. HH and Village biogas: For harvesting/collecting residues we assume half of the labour requirements to harvest, transport locally and bag food parts. Labour to transport digestate back to fields is estimated to 5.6 man-hours/ton. Spreading green manure on fields is estimated to 8 man-hours/ton. HH biogas plant establishment is estimated to 25 man-hours apiece multiplied with seven plants, divided over a 10-year life span. HH biogas plant management is estimated to 400 man-hours/year in total, approximately ½ hour/refill/plant. Village biogas plant establishment and operation is estimated to 380 middle UEV man-hours/year (accounted for in line 23) and 1800 low UEV man-hours/year based on [24]. Agro-forestry: 50 hours/ha is added for cultivation, pruning and mulching of leucaena trees, equal to approximately 40% of direct labour use in pre-harvest activities in maize farming (following [25]). This equals 2,000 hours/year/relevant area.

23 **Direct labour, middle UEV (man-hours)**
Village biogas: Construction manager and craftsman inputs, allocated over 20-year life span, and operation manager inputs, based on [24]. Agro-forestry: Chainsaw operator, based on interview data.

24 **Indirect labor, low UEV (man-hours)**
PP: Farmhand labour in charcoal production, based on interview data.

25 **Indirect labor, middle UEV (man-hours)**
PP: Chainsaw operator in charcoal production, based on interview data.

26 **Indirect labor, global UEV (global man-hours)**
Sum of purchased inputs: PP and Agro-forestry: chainsaw fuel in charcoal production is 13 USD. HH biogas production: Cost of digester and storage tanks, fittings and pipes, barn materials and additional tractor hire and diesel amount to 850 USD/avg.year. Village biogas production:

666 USD for the parts: 146 USD/year for materials (based on [24]) plus an estimated 46 USD/year for storage tank, generator and compressor, 427 USD/year for additional diesel and tractor requirements and 47 USD/year for barn. Conversion to man-hours: see Calculation note 12.
UEV: See Calculation note 12.

Output

27 **Food and useful energy basket (J)**
Food output from interview data is approximately 64 t with an assumed moisture content of 85% equal to 55 tdm/year. Energy content is based on 18.8 MJ/kgdm, the energy content of maize grain [26]. Energy output: 55 tdm/year × 18.8 MJ/kgdm = 1034 GJ/year.
UEV: Calculated by summing emergy inputs (lines 3–10 and 13–21) and dividing with energy content (line 27).

28 **Food and useful energy basket (J), with labour**
Energy output: see Calculation note 27.
UEV: Calculated by summing emergy inputs (lines 3–26) and dividing with energy content (line 27).

References

1. Odum, H.T.; Brown, M.T.; Williams, S.B. Handbook of emergy evaluation: A compendium of data for emergy computation issued in a series of folios. Folio #1—Introduction and global budget. University of Florida: Gainesville, FL, USA, 2000.
2. Kamp, A.; Morandi, F.; Østergård, H. Development of concepts for human labour accounting in Emergy Assessment and other Environmental Sustainability Assessment methods. *Ecol. Indic*. **2016**, *60*, 884–892.
3. Brown, M.T.; Arding, J. *Transformities Working Paper*; Center for Wetlands, University of Florida: Gainesville, FL, USA, 1991.
4. Brandt-Williams, S. Handbook of emergy evaluation: A compendium of data for emergy computation issued in a series of folios. Folio #4—Emergy of Florida Agriculture. University of Florida: Gainesville, FL, USA, 2002.
5. Kamp, A.; Østergård, H.; Gylling, M. Sustainability assessment of growing and using willow for CHP production. In Proceedings of the 19th European Biomass Conference and Exhibition, Berlin, Germany, 2011.
6. Brown, M.T.; Buranarkan, V. Emergy indices and ratios for sustainable material cycles and recycle options. *Resour. Conserv. Recycl*. **2003**, *38*, 1–22.
7. Buranakarn, V. Evaluation of recycling and reuse of building materials using the emergy analysis method. Ph.D. Thesis, Department of Architecture, University of Florida, Gainesville, 1998.
8. Buenfil, A.A. Emergy evaluation of water. Ph.D. Thesis. Department of Environmental Engineering Sciences, University of Florida, Gainesville, 2001.
9. Bastianoni, S.; Marchettini, N.; Panzieri, M.; Tiezzi, E. Sustainability assessment of a farm in the Chianti area (Italy). *J. Clean. Prod*. **2001**, *9*, 365–73.
10. Ortega, E.; Cavalett, O.; Bonifacio, R.; Watanabe, M. Brazilian soybean production: Emergy Analysis with an expanded scope. *Bull. Sci. Technol. Soc*. **2005**, *25*, 323–34.
11. NEAD (National Environmental Accounting Database). Update 2012. Center for Environmental Policy, University of Florida, Gainesville, FL, USA. Available online: www.cep.ees.ufl.edu/nead/ (accessed on 15 April 2016).
12. Brown, M.T.; Ulgiati, S. Understanding the global economic crisis: A biophysical perspective. *Ecol. Model*. **2011**, *223*, 4–13.
13. NEAD (National Environmental Accounting Database). Update 2009. Center for Environmental Policy, University of Florida, Gainesville, FL. The old version of the database, with detailed information about rainfall, is no longer available online. The website http://sahel.ees.ufl.edu/database_resources.php was accessed on 25 September 2014.
14. Beck, A.E.; Mustonen, E. Preliminary heat flow data for Ghana. *Nat. Phys. Sci*. **1972**, *235*, 172–174.

15. Lefroy, E.; Rydberg, T. Emergy evaluation of three cropping systems in southwestern Australia. *Ecol. Model.* **2003**, *161*, 195–211.
16. Cannon, K. Soil Organic Matter. Organic Carbon and Nitrogen. Available online: http://www1.agric.gov.ab.ca/$department/deptdocs.nsf/all/aesa1861/$file/organicmatter.pdf?OpenElement (accessed on 13 April 2016)
17. Lal, R. Agroforestry systems and soil surface management of a tropical Alfisol: II. Water runoff, soil erosion, and nutrient loss. *Agrofor. Syst*. **1989**, *8*, 97–111.
18. Cohen, M.J.; Brown, M.T.; Shepherd, K.D. Estimating the environmental costs of soil erosion at multiple scales in Kenya using emergy synthesis. *Agric. Ecosyst. Environ.* **2006**, *114*, 249–69.
19. Cook, B.G.; Pengelly, B.C.; Brown, S.D.; Donnelly, J.L.; Eagles, D.A.; Franco, M.A.; Hanson, J.; Mullen, B.F.; Partridge, I.J.; Peters, M.; Schultze-Kraft, R. Tropical Forages: an interactive selection tool. CSIRO, DPI&F(Qld), CIAT and ILRI, Brisbane, Australia. 2005. Available online: http://www.tropicalforages.info/key/Forages/Media/Html/Leucaena_leucocephala.htm (accessed on 15 April 2016).
20. World Bank. Labour force statistics. 2011. Available online: http://data.worldbank.org/indicator/SL.TLF.TOTL.IN (accessed on 15 April 2016).
21. Brown, M.T.; Bardi, E. *Handbook of Emergy Evaluation: A Compendium of Data for Emergy Computation Issued in a Series of Folios*; Folio #3—Emergy of Ecosystems. University of Florida: Gainesville, FL, USA, 2001.
22. Agyeman, K.O.; Amponsah, O.; Braimah, I. Commercial charcoal production and sustainable community development of the Upper West Region, Ghana. *J. Sustain. Dev.* **2012**, *5*, 149–164.
23. Thomsen, S.; Heiske S. Personal communication, 2014.
24. Burri, M.; Martius, G. Biogas from solid waste: Conception and construction of a dry fermentation pilot plant for developing countries. M.Sc. Thesis. Swiss Federal Institute of Technology in Zürich (ETH), 2011.
25. Ngambeki, D.S. Economic evaluation of alley cropping leucaena with maize-maize and maize-cowpea in Southern Nigeria. *Agric. Syst*. **1985**, *17*, 243-58.
26. INRA (Institut National de la Recherche Agronomique). Centre de Coopération en Recherche Agronomique pour le Developpement, Associación Française de Zootechnie and Food and Agriculture Organization. 2012. Available online: http://www.feedipedia.org/node/11662 (accessed on 15 April 2016).