Energy demand and water footprint study of an agricultural machinery industry

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Abstract: The intensification of agricultural production systems demands power, supplied by agricultural machinery, besides more agricultural inputs such as fertilizers, pesticides and seeds. Agricultural mechanization provides increase in the global production of food, fiber and bioenergy; and it brought economic benefits to producers, but causing larger energy consumption. Energy embodiment in agricultural machinery has been done in earlier studies, but data usually are from car industry. This study aimed to determine the energy demand and water footprint in a plant that assembles five types of agricultural machinery from a multinational manufacturer located in Piracicaba municipality in Sao Paulo state, Brazil. That plant assembled two types of sugarcane harvester, coffee harvesters, sprayers and planters. Inputs taken into account were classified as direct inputs (electricity, liquefied petroleum gas - LPG, water etc.) and depreciated inputs (infrastructure, tools etc.), regarding how they are consumed over time. Data about the physical demand were determined, providing the material flows, which were used to estimate the energy and water flows by multiplying them by their respective energy embodiment and water footprint indices. Electricity accounted for the highest share (88.9%) in the total energy demand. From depreciated inputs, buildings accounted for almost the full embodied energy, but this category had a minute participation on the total energy (<2.5%). The industrial assembling required on average 13.49 GJ of energy and 12.29 m^3 of water per machine assembled. Labor's embodied energy was very small, thus can simply be neglected from the energy analysis. The indirect water footprint related to depreciated inputs was very minor and can be neglected without affecting the final result. The direct water demand was from 5.60 to 15.70 m^3 per machine compared to the average indirect water footprint of 1.2 m^3. In terms of per unit mass of assembled machine, the embodied energy demand varied from 1.22 to 2.36 MJ kg^{-1} and the water footprint varied from 1.17 to 2.11 L kg^{-1}.

Keywords: embodiment, machinery industry, life cycle assessment, energy demand, footprint

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1 Introduction

Agricultural machinery industries are characterized as heterogeneous due to the market structure, in which are companies of different sizes, and technical and organizational features (Amato Neto, 1985). Being adopted for most of field operations, agricultural mechanization is one of the tools that supported the increase in world food production, bringing many benefits to farmers, such as cost reduction and higher work rate of field operations (Oliveira et al., 2007).

Energy and water security are one of the main challenges in the 21st century. The growth of either global population or the individual consumption, combined with climate changes requires coordinated and sustainable actions (MAPA, 2009). The use of resources is also a challenge to the paradigm of environmental sustainability, because it is based on the hypothesis of a social and productive model that does not threaten the survival and welfare opportunities of the coming

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generations. Thus, it is important to develop and use renewable resources of energy and materials (Manzini and Vezzoli, 2002).

Energy and water footprint analyses are necessary to manage the use of scarce resources in production systems. Through the identification of production practices, these analyses quantify the energy and water footprints. Besides, it determines the energy embodiment in each phases of the production system, giving proper attention to the environmental improvement to be achieved (Umar, 2003). Moreover, the benefits of applying this kind of evaluation are not limited within the boundaries of the production system but it is extensive to the whole society (Boustead and Hancock, 1979).

Energy is one of the main inputs of modern societies, mandatory to produce goods from natural resources exploitation to service providing (Hinrichs and Kleinbach, 2009). It is defined as the ability to produce heat and work (Boustead and Hancock, 1979). It is important to understand energy not only as a service from the environment, transformed or not, but also as a product of work (Macedônio and Picchioni, 1985). However, energy is better described about what it can do rather than what it is. The thermodynamic laws that control the conversion of energy are first and second laws: the first law or the law of conservation states that energy cannot be created or destroyed, but can be changed from one form to another, the second law or law of entropy denotes about the irreversibility of all natural processes and can be seen as a measure of disorder or disruption of a system (Çengel and Boles, 2001).

Determining energy demand has fundamental importance to managing production processes, identifying and quantifying all used and produced goods (Siqueira et al., 1999; Romanelli, 2009; Andrea et al., 2016). This evaluation considers as input energy not only the energy consumed directly (e.g. fuel and electricity) but that required by manufacturing processes and services supplies embodied in the goods the evaluated system uses.

In energy embodiment analysis of the life cycle of sugarcane harvesters, the maintenance and repair phase require 72% of total energy (3.0 TJ) for the sugarcane harvester with rubber tires and 72.8% (total 3.5 TJ) for those with metallic tracks (Mantoam et al., 2014). These numbers are due to the amount of repair these machines necessary because this kind of machine operates on average 3100 h year^{-1}. For tractors, total demand is from 261 to 787 GJ, respectively, for tractors from 55 to 246 kW (Mantoam et al., 2016).

Machinery operators must be trained for energy conservation; since besides saving fuel they can postpone the machinery replacement (Abubakar and Umar, 2006). The decision making on machinery replacement is economically driven. In energy terms, extending the life cycle of machinery brings less environmental impact (Mantoam et al., 2016).

Operations within assembly lines must be taken into consideration, but few industries monitor energy consumption individually on their production sections (Boustead and Hancock, 1979). Thus, this consumption is generally unknown in details. Knowing this consumption in distinct manufacturing phases is important because of energy cost (electricity and fuel). If a new production line or a modification in it is suggested, energy cost must be compared with the previously existent. Monitoring this cost would allow one to compared operators’ or plants’ performance among them. To do so, cost determination needs a method to indicate energy cost from distinct sources to keep comparisons on a realistic basis (Boustead and Hancock, 1979).

Another reason for industries to have interest on energy analysis is the growing importance of environmental impact analyses. Industries are willing not only to run their production responsibly, but to reduce the gross energy amount necessary for production of goods and services, and consequently to reduce cost (Boustead and Hancock, 1979). This can be done through surveys of efficiency parameters to the storage of goods, waste management, and illumination in the industry, heating and cooling systems (Manzini and Vezzoli, 2002).

Water is also a very important input in the production of goods and services. An increasing number of businesses recognize that reducing the water needed in the production of goods and services should be part of their corporate social responsibility. In order to optimize the water required in the production process, we need to measure the direct and indirect water used along the full supply chain of the product. Water footprint is an indicator of how much water is consumed over the whole supply chain of a product (Hoekstra et al., 2011).

This study aims at determining the material and energy demand, and water footprint of assembling agricultural machinery. The evaluated plant assembles sugarcane harvesters, coffee harvesters, self-propelled sprayers and grain drillers.

2 Material and methods

The evaluated industry produces five distinct products (Table 1). Each machine, it is produced in a unique manufacturing line; the amount of operators and the assembling time cycle are different for every machine.

Table 1 Machinery produced in the industry surveyed

Machine	Power (kW)	Mass (kg)	Observation
Sugarcane harvester single row (M1)	260	14,863 16,972	Rubber tires Metallic track
Small sugarcane harvester (M2)	128	8,000	Rubber tires
Coffee harvester (M3)	40	5,600	Rubber tires
Sprayer (M4)	147	10,100	Rubber tires
Row crop planter, no tillage (M5)	Pull-type	5,119	13 rows

The data surveyed to perform this study was done in a plant, from a multinational company, located in Piracicaba municipality, São Paulo state, Brazil. The steps taken were defined in a flow chart (Figure 1). Electronic spreadsheets (Microsoft Excel® 2007) were used for the material and energy flow determination.

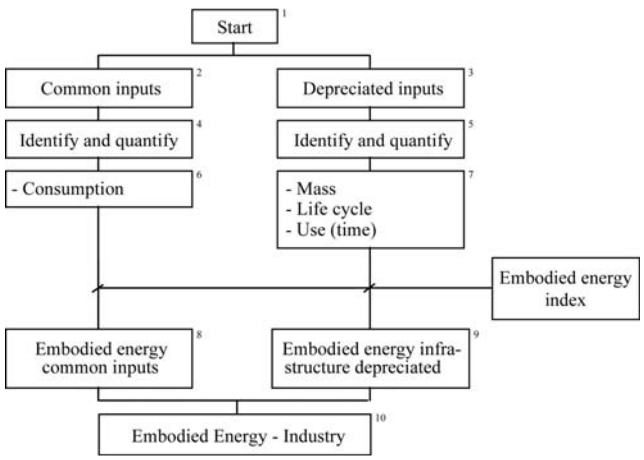


Figure 1 Flowchart of embodied energy determination in machinery assembling

Common inputs (2) refer to inputs such as electricity, water, liquefied petroleum gas (LPG), because these inputs provide services to the production systems, being intangible in the final product although mandatory as well. These inputs do not have their consumption specified by every kind of machine produced, because the plant produces distinct kind of products, and consequently their demand varies. Identification and quantification of the required inputs (4) were made based on the survey of 36-month production, from 2012 to 2015. Equations (1) to (3) indicate the average consumption per unit of machine produced. So, to determine the specific consumption for every produced machine, we determined the participation of each production line in the total plant consumption in a certain period (Equation (1)). Labor time required was surveyed on the database of the company.

$$PMP = \frac{UMP_i \times TGM_i \times 100}{\Sigma TP_i} \tag{1}$$

where, PMP = participation of the machinery in the total production in the i^{th} year (%); UMP_i = units of machinery produced in the i^{th} year (unit yr^{-1}); TGM_i = time spent to produce a single machine (h unit^{-1}); $\sum TP_i$ = sum of total time to produce all the machines in the i^{th} year (h yr^{-1}); i = year.

With the data of the participation of the machinery in the total production, the annual input consumption and divided by units of machinery produced, we could determine the annual consumption of each input for each machine in a 1-year period (Equation (2)).

$$CMA_i = \frac{\frac{PMP}{100} CIA_i}{UMP_i} \tag{2}$$

where, CMA_i = input consumption in the year (kWh unit^{-1}; m³ unit^{-1}; kg unit^{-1}); CIA_i = total consumption in the i^{th} year (kWh yr^{-1}; m^3 yr^{-1}; kg yr^{-1}).

The average annual consumption was determined (Equation (3)) considering the total annual consumption and the period of observation (2012 to 2015). This was further related to the units of machinery produced in each year (Equation (4)). Equation (4) also uses the energy embodied in every input to determine the energy flows.

$$CMT = \frac{\Sigma CMA_i}{N} \tag{3}$$

where. CMT = total average consumption (kWh unit^{-1}; m^3 unit^{-1}; kg unit^{-1}); N = evaluated years; i = year.

$$EIIC = CMT\, EI_{DI} \tag{4}$$

where, $EIIC$ = embodied energy in the direct inputs (MJ); EI_{DI} = embodied energy in direct input (MJ kWh^{-1}, MJ m^{-3}; MJ kg^{-1}).

Similarly, the water footprint (WF) of the direct inputs is determined as follows:

$$WF_d = CMTwf_d \tag{5}$$

where WF_d = water footprint related to the direct inputs (m^3); wf_d = the water footprint in each of the direct inputs (m^3 $unit^{-1}$). The indices for EI_{DI} and wf_i were collected from literatures (Table 2).

Table 2 Energy embodiment indices

Input	Unit	Embodied energy (MJ $unit^{-1}$)	Water footprint (L $unit^{-1}$)**	Reference
Aluminum	kg	231	13	Stodolsky et. (1995); Margolis and Sousa (1997)
Carbon steel	kg	51.5	2.97	Berry and Feld (1973)*; Margolis and Brindle (2000)
Copper	kg	140	93.2	Stodolsky et al. (1995); Tikana et al. (2005)
Electricity	kWh	15	0.68	Boustead and Hancock (1979); Sheehan et al. (1998)
Building	m²	3500	6300	Tavares (2006); Crawford and Treloar. (2005)
Labor	h	2.2	-	Serra et al. (1979)
Lead	kg	17.3	37	Porameswaren and Nadkami (1975)*; European Commission (2017)
LPG	kg	58.9	2.5	Boustead and Hancock (1979); Francke and Castro (2013)
Polypropylene	kg	110.2	1.16	Boustead and Hancock (1979); Franklin Associates (2011)
Water	m³	2.4	1	Leach and Slesser (1974)*
Zinc	kg	56.6	393	Porameswaren and Nadkami (1975)*; European Commission (2017)

Note: * apud Boustead and Hancock (1979); ** for all the items the water footprint refers to blue water.

The depreciated inputs (3) are infrastructure, machine, equipment and tools, used to manufacture the machines. These inputs do not have their consumption specified by every kind of machine produced.

Identification and quantification (5) were made to determine the mass and lifecycle. The average consumption was determined through the utilization rate surveyed from 36-month production. It indicated the utilization rate for each input for unit of produced machine (Equation (6)).

$$TUI = \frac{\Sigma PMP_i 100}{N} \tag{6}$$

where, TUI = Rate utilization of inputs (%).

With TUI multiplied by the infrastructure used, such as shipment area; stock parts area; training center area; computer equipment mass, we could determine the consumption for each depreciated input per unit of produced machine (Equation (7)).

$$CMD = \frac{TUI}{100} IEU \tag{7}$$

where, CMD = depreciated consumption (m^2; kg); IEU = total infrastructure used (m^2; kg).

With data depreciated average consumption, life cycle and knowing the time of participation (7) that determinate equipment have in the production process, resulted in depreciated mass to manufacture the machinery. Equations (8) and (9) also use the energy embodied and water footprint in every input to determine the energy flows and water footprints.

$$EIDI = \frac{CMD}{VU} TC\ EI_{DA} \tag{8}$$

$$WF_i = \frac{CMD}{VU} TC\ wf_i \tag{9}$$

where, $EIDI$ = embodied energy in depreciation of infrastructure (MJ); VU = life cycle in the i^{th} year of tools, factory (h); TC = time cycle spent by tool, factory on manufacturing of a machine (h); EI_{DA} = embodied energy in depreciated assets (MJ m^{-2}, MJ kg^{-1}); WF_i = the water footprint in the depreciation of infrastructure (m^3); wf_i = the water footprint of each of the inputs (m^3 kg^{-1}; m^3 m^{-2}).

The life cycle adopted for the infrastructure materials were those considered by the Brazilian income tax (BRASIL, 1998). Manual tools, devices for telecommunication and telephony present 43,200 h of life cycle (5 yr); electric, pneumatic and hydraulic tools and design devices present 86,400 h of life cycle (10 yr); buildings present 216,000 h (25 yr).

The sum of embodied energy in direct inputs (8), and in infrastructure depreciated (9), provides the embodied energy and water footprint on industry (10) (Equations (10) and (11)).

$$EII = EIIC + EIDI \tag{10}$$

$$WF = WF_d + WF_i \tag{11}$$

where, EII = embodied energy on industry (MJ) and

WF = the total water footprint of machine (m^3).

3 Results and discussion

Table 3 presents the material flow in assembling phase, per unit of machinery produced. From the table, electricity and labor represents 1,113.8 kWh and 127.0 h, respectively per unit of sugarcane harvester machine, M1. Electricity is used for illumination, electric tools, air compressor; air conditioner and computer equipment. The labor hours are due to the manual work on the assembling phase of machines.

Table 4 presents the embodied energy and water footprint of the direct inputs. While electricity is the largest energy demanding input with 88.9%, labor takes the largest share (97%) of the water footprint. Although water consumption per machine is high, it presents low energy value 0.2%. The water footprint of the labor is related to the water footprint of food and goods consumed by employee.

Table 3 Material demand by produced machinery

Machinery	Electricity (kWh)	LPG (kg)	Labor (h)	Direct water (m^3)
Sugarcane harvester single row (M1)	1113.8	30.1	127.0	15.7
Small sugarcane harvester (M2)	559.5	16.7	66.6	8.6
Coffee harvester (M3)	771.6	20.9	88.0	10.9
Sprayer (M4)	1052.1	28.4	120.0	14.8
Row crop planter, no tillage (M5)	394.6	10.7	45.0	5.6

Table 4 Energy demand and water footprint by produced machinery

Machinery	Electricity	LPG	Labor	Direct water	Electricity	LPG	Labor
	MJ				m^3		
Sugarcane harvester single row (M1)	16707	1773	280	37.1	0.76	0.08	32.0
Small sugarcane harvester (M2)	8392	986	147	20.4	0.38	0.04	16.8
Coffee harvester (M3)	11573	1228	194	25.7	0.53	0.05	22.2
Sprayer (M4)	15782	1675	264	35.1	0.72	0.07	30.2
Row crop planter, no tillage (M5)	5918	628	99	13.1	0.27	0.03	11.3
Average	11674	1258	197	26	0.53	0.05	22.51

Figure 2 summarizes the participation of direct inputs per unit of machine. Electricity is the most important one (~90%), while LPG, used as fuel to the forklift truck, represents around 9%. Labor and water may be neglected in further evaluations due to their minute participation in energy terms (Bridges and Smith, 1979; Mantoam et al., 2014).

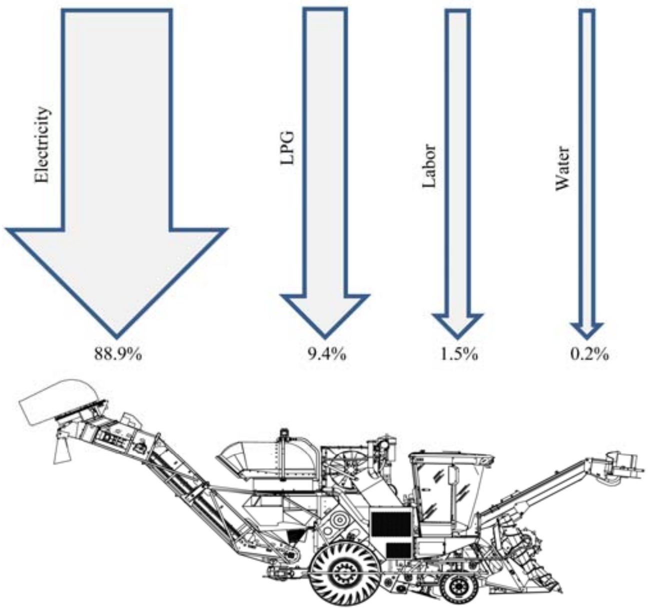


Figure 2 Input participation on energy demand

Table 5 presents the material flow to the depreciated inputs. The largest manufacturing area is assigned to machine M1, because it requires more area for its assembling line. Occupied area weights the building depreciation into the assembling lines it hosts. Assets used in the factory management, such as computers stratified due to their composition referenced in Microelectronics and Computer Technology Corporation (1996) and Itautec (2010), the life time of computers present 43,200 h (5 yr) and its use time regards its participation on the assembling cycle.

Table 5 Infrastructure depreciation demand by factory

Input	Unit	M1	M2	M3	M4	M5
Building area	m²	16308.9	1357.4	1526.2	4511.7	1514.1
Carbon steel	kg	3592.4	173.1	135.5	159.1	113.8
Aluminum	kg	176.3	10.3	8.3	38.2	8.1
Polypropylene	kg	284.4	10.1	13.4	61.7	13.1
Copper	kg	87.6	8.4	4.1	19.0	4.0
Lead	kg	75.0	3.1	3.5	16.3	3.5
Silica	kg	289.8	2.7	13.6	62.8	13.4
Zinc	kg	26.1	0.9	1.2	5.7	1.2

Table 6 presents the energy demand and water footprint in the infrastructural requirement in the manufacturing of the machines. The machine M4 require higher energy and water consumption in the factory, followed by machine M1. The embodied energy in depreciated computers is low.

Table 6 Infrastructure depreciation energy and water demand by factory

Input	M1	M2	M3	M4	M5
	---------------------- Embodied energy (MJ) ----------------------				
Building	550.3	176	197.8	584.8	122.7
Carbon steel	4.8	0.9	0.6	1.0	0.4
Aluminum	2.0	0.3	0.4	1.6	0.2
Polypropylene	1.5	0.2	0.3	1.3	0.2
Copper	0.6	0.1	0.1	0.5	0.2
Lead	0.1	0.0	0.0	0.1	0.0
Silica	0.0	0.0	0.0	0.0	0.0
Zinc	0.1	0.0	0.0	0.1	0.0
	------------------------ Water footprint (L) ------------------------				
Building	991	317	356	1053	221
Carbon steel	0.28	0.05	0.03	0.06	0.02
Aluminum	0.11	0.02	0.02	0.09	0.01
Polypropylene	0.02	0.00	0.00	0.01	0.00
Copper	0.40	0.07	0.07	0.33	0.13
Lead	0.21	0.00	0.00	0.21	0.00
Silica	0.00	0.00	0.00	0.00	0.00
Zinc	0.69	0.00	0.00	0.69	0.00

The embodied energy in the industry is represented mostly by direct inputs 65.77 GJ (97.6%) – Table 7. Depreciated inputs account for the remaining 1.65 GJ (2.4%). The industry requires on average 13.49 GJ to manufacture a machine. The total water footprint per machine varies from 6.12 m^3 for row-crop planter to 17.53 m^3 for sugarcane harvester, with an average water footprint of 12.29 m^3 per machine. The direct water footprint (11.1 m^3), accounts for 90% of the average water footprint and the indirect water footprint accounts for the remaining 10% (1.2 m^3) (Table 7).

Table 7 presents embodied energy demand on industry. The distinct magnitude between direct and depreciated inputs allows further research to ignore the latter. Similarly, the contribution of depreciated products to the indirect water footprint is very minor (see Table 6). Thus, we may safely neglect the water footprint related to depreciated products without underestimating the total water footprint. Although assembling contributes little to the embodied energy in the final product (Mantoam et al., 2014), this kind of assessment is useful for the industry to be able to focus effort on reducing input consumption and, consequently, reduce negative environmental impacts and production cost.

Table 7 Embodied energy and water footprint on assembling for distinct machinery

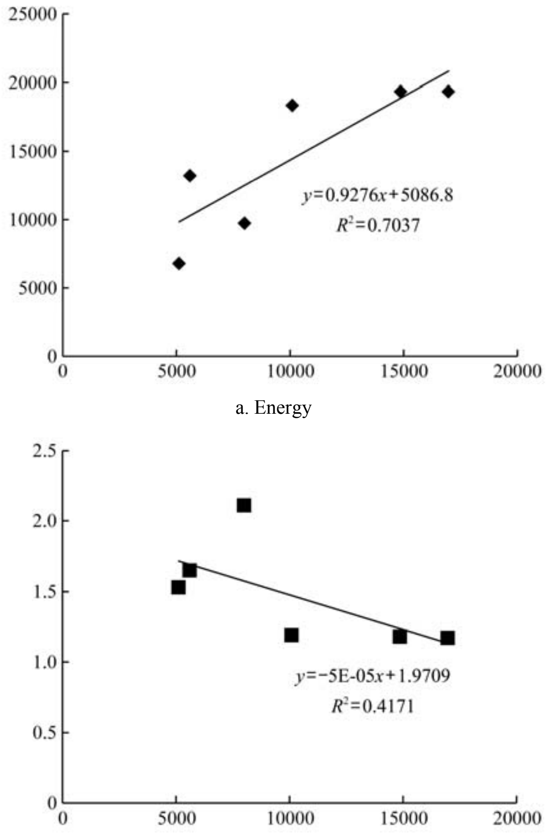
Machinery	Power (kW)	Mass (kg)	Embodied energy (GJ)			Water footprint (m^3)		
			Depreciated inputs	Direct inputs	Total	Indirect inputs	Direct inputs	Machinery Total
Sugarcane harvester (M1)	260	14863	0.56	18.79	19.36	1.83	15.70	17.53
Small sugarcane harvester (M2)	128	8000	0.18	9.55	9.72	0.74	8.60	9.34
Coffee harvester (M3)	40	5600	0.2	13.02	13.22	0.93	10.90	11.83
Sprayer (M4)	147	10100	0.59	17.75	18.35	1.84	14.80	16.64
Row crop planter (M5)	-	5119	0.12	6.66	6.78	0.52	5.60	6.12
Category average			0.33	13.16	-	1.17	11.18	
Category Total			1.65	65.77	67,42	5.58	55.60	61.46

The individual and average numbers for the indicators considering energy demand on assembling and the machinery mass and power can be found in Table 8. Apparently, neither mass nor power has straight correlations with energy demand (Figure 3a) or water footprint (Figure 3b) on assembling. Energy demanded increases as mass increased, while water footprint is inversely proportional. Although, mass presents higher level of coefficient of determination than power did (R^2 ~ 0.51 for energy and ~ 0.38 for water footprint).

Assembling energy requirements varies from 1.22 to 2.36 MJ kg^{-1}. This magnitude represents 1% to 3% of those found for tractors, which excludes assembling phase (62.7 to 122.7 MJ kg^{-1} from Mantoam et al. (2016)). Regarding the same machine, assembling is 1.3 out of 202.6 MJ kg^{-1} (rubber tires) and 204.3 MJ kg^{-1} (metallic track) for sugarcane harvester (Mantoam et al., 2014). Similarly, for coffee harvester, assembling is 2.36 MJ kg^{-1}, which turn the 71.8 MJ kg^{-1} (no assembling considered) for coffee harvester (Mantoam et al., 2017) into 74.2 MJ kg^{-1}, representing 3.1%.

Table 8 Embodied energy and water footprint indicators for assembling machinery

Machinery	Embodied energy		Water footprint	
	per power (MJ kW^{-1})	per mass (MJ kg^{-1})	per power (L kW^{-1})	per mass (L kg^{-1})
Sugarcane harvester (M1)	74.4	1.3	67	1.18
Small sugarcane harvester (M2)	76	1.22	73	1.17
Coffee harvester (M3)	330.5	2.36	296	2.11
Sprayer (M4)	124.8	1.82	113	1.65
Row crop planter (M5)	-	1.32		1.19
Average	151.4	1.67	137	1.53



a. Energy

b. Water footprint

Figure 3 Energy and water footprint of assembling by machinery mass

4 Conclusions

Due to high energy demand in manufacturing, electricity needs to be considered for energy embodiment in agricultural machinery industry, while due to low energy embodied in labor and infrastructure, both safely be neglected in the energy embodiment analysis. Water demand per unit on machine is high, although has low energy value. However, the contribution of labor in indirect water footprint is very significant and cannot simply be neglected in the water footprint assessment. On the other hand, the contribution of infrastructures in the total water footprint of machinery production is very minor. This kind of assessment is useful for the industry to be able to focus effort on reducing input consumption and, consequently, reduce negative environmental impacts and production cost.

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Abbreviations

PMP = participation of the machinery in the total production per year (%)

UMP = units of machinery produced per year (unit yr^{-1})

TGM = time spent to produce a single machine (h unit^{-1})

TP = total time to produce all the machines per year (h yr^{-1})

CMA = input consumption in the year (kWh unit^{-1}, m^3 unit^{-1}, kg unit^{-1})

CIA = total consumption per year (kWh yr^{-1}, m^3 yr^{-1}, kg yr^{-1})

EIIC = embodied energy in the direct inputs (MJ)

EI_{DI} = embodied energy in direct input (MJ kWh^{-1}, MJ m^{-3}; MJ kg^{-1})

TUI = Rate utilization of inputs (%)

CMD = depreciated consumption (m^2, kg)

IEU = total infrastructure used (m^2, kg)

EIDI = embodied energy in depreciation of infrastructure (MJ)

VU = life cycle of tools, factory (h)

TC = time cycle spent by tool, factory on manufacturing of a machine (h)

EI_{DA} = embodied energy in depreciated assets (MJ m^{-2}, MJ kg^{-1})

EII = embodied energy on industry (MJ)

WF = water footprint of a product (m^3)

wf = the water footprint in each of the inputs (m^3 unit^{-1})

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