Computational Water, Energy, and Environmental Engineering, 2022, 11, 93-115
https://www.scirp.org/journal/cweee
ISSN Online: 2168-1570
ISSN Print: 2168-1562

Energy Analysis in Irrigated Sugarcane Schemes of Awash River Basin, Ethiopia

Yusuf Kedir[1*], Belete Berhanu[2], Tena Alamirew[3]

[1]Addis Ababa Institute of Technology (AAiT), Addis Ababa, Ethiopia
[2]Civil and Environmental Engineering Department, Addis Ababa Institute of Technology (AAiT), Addis Ababa, Ethiopia
[3]Ethiopian Institute of Water Resources, Addis Ababa, Ethiopia
Email: *yuskedd@gmail.com, *yuskedd@yahoo.com, belete.berhanu@aait.edu.et, tena.a@wlrc-eth.org

How to cite this paper: Kedir, Y., Berhanu, B. and Alamirew, T. (2022) Energy Analysis in Irrigated Sugarcane Schemes of Awash River Basin, Ethiopia. *Computational Water, Energy, and Environmental Engineering*, **11**, 93-115.
https://doi.org/10.4236/cweee.2022.114006

Received: November 17, 2021
Accepted: October 14, 2022
Published: October 17, 2022

Abstract

Sugarcane is one of the important irrigated crops in Ethiopia and its production is highly linked with its energy and water use. In this paper, identifications and quantifications of input and output, direct and indirect energy sources, and energy use of farm operations were carried out on 11 irrigation schemes of Awash River Basin. In order to grow 91.8 to 167.6 tons of cane, 47.9 to 143.4 GJ/ha of total energy was used. Average total input energies of gravity, pump surface and sprinkler scheme categories to grow 109.8, 112.7 and 136.3 ton/ha were 53.6, 68.9 and 129.2 GJ/ha, respectively. Around 90% and 74% total energies of gravity surface and sprinkler schemes were consumed as direct and indirect energies, respectively. Irrigation found to be the most energy consuming operation constituting more than 50% input energy of all scheme categories. Energy efficiency of gravity schemes was 152% and 300% higher than pump driven surface and sprinkler schemes. Energy sequestrated in cane straws burned during harvesting found to be higher than fertilizer and pumping energy demands. Use of cane straws as manure and energy sources have the potential to substitute demands which in turn needs further investigations and analysis.

Keywords

Energy Productivity, Energy Sources, Farm Operation, Gravity Scheme, Pump Scheme, Sprinkler

1. Introduction

Agriculture is not only an energy user but also energy supplier in the form of bioenergy [1]. Continuous growth of world population, migration of the labor force, and development of new production techniques substantially increased energy consumptions of crop production [2]. The new production technologies require a large quantity of inputs such as fertilizers, irrigation water, fuels, chemicals, electricity, etc. Application of these inputs demands more and more use of energy [3].

Agricultural water use and energy consumption are linked in which irrigation is commonly regarded as a primary consumer of on-farm energy and higher use of irrigation water which is in turn associated with higher energy input [4]. Sustainable agricultural development depends on high resource use efficiency with the objective of increasing yields and decreasing costs of energy and water [5].

The need to use water wisely has been realized in irrigation sector of Ethiopia. One way commonly suggested for improving efficiency is to replace surface systems with sprinkler and/or drip systems which are assumed to be more efficient [5] [6] [7]. Irrigation schemes in Awash basin of Ethiopia consumed around 3.2 billion m^3 with mean irrigation efficiency of 33.67% [8]. The recent development plan of Ethiopia has considered increasing area coverage of modern irrigation from 2% to 20% [9]. The use of sprinkler has been increasing and currently 22,550 ha of sugarcane is irrigated from which 3820 ha is found in Awash River Basin [10].

Irrigation system upgrades have saved water in many countries while in others this has been at the expense of increased energy use [6] [7] particularly when pumping is required. Farm operators and professionals drive improvements in water use efficiencies but little attention was paid to its relationship with energy [6]. Comprehensive information on these issues needs to be generated.

Energy consumptions in agricultural systems associated with all inputs have to be defined and quantified according to their energy intensities [2]. In fact, determinations of energy consumed in crop production are very complex [11] but different methods are in use [12] [13] [14]. Energy analysis is one of analytical method that provides the information needed to base energy decisions and uses engineering methods [11] and is a tool to define the behavior of agricultural systems [2] [11] [15].

Results of energy analysis studies depend on set of assumptions and an international agreement on how to estimate energy input has been difficult to achieve, and lack of reliable data forces researchers to take values from other countries [2] [14]. Because of these and other, local results may not be representative for others [16]; it is difficult to compare one set of data with other published in different countries, and comparison and evaluation of results from past studies are also difficult [13] [14]. [17] identified a general methodology for performing an energy analysis which was further elaborated by [2]. The method has been used by [18] and was felt to be transparent and reliable, can be applied to a range of agricultural systems, geographical locations and more importantly, it allows a comparison between irrigation schemes and technologies.

Substantial researches have been conducted on different crop production practices which suggested that energy consumptions are highly site specific [5]. For instance, total input and output energies for sugarcane production in Thailand were 24.9 and 248.7 GJ/ha, respectively [19]. A study in Iran showed that total direct and indirect input energies to produce 93.5 ton/ha yield of sugarcane was 148.0 GJ/ha in plant cane farm [20]. [21] estimated the energy inputs to produce 100 ton/ha of irrigated sugarcane to be as high as 150 GJ/ha. According to [7], a high pressure sprinkler would require around 4.5 GJ per year. [22] reported that annual energy requirement of sprinkler system (75% efficiency) from surface supply, from 50 m groundwater lift, and from 100 m groundwater were 57.1, 110 and 162.6 GJ/ha, respectively. Results from a study on pressurized irrigation in Spain confirmed that in order to apply an average of 2589 m^3/ha, 1000 kWh energy is required [5] which is equivalent to 4.6 MJ/m^3. Energy intensities of 0.91 and 0.59 MJ to produce one kilogram of plant cane and ratoons in the Philippines were reported [23] (Mendoza and Samson, 2004) which are lower than 1.6 MJ/kg found in Iran [20]. Energy ratio, energy productivity and net energy gain of 0.76, 0.63 kg/MJ and −35.8 GJ/ha, respectively for irrigated plant sugarcane were also reported by [20].

There are still gaps in applying energy analysis of the irrigated agriculture. Apart from being site specific, most of the above studies were applied for a particular irrigation technology or performance parameter. A single local study so far reported was that of [24]. The study assessed energy use and WEF nexus of Wonji-Shoa, Metehara, and Finchaa sugar factories of Ethiopia. Despite its usefulness, the study was carried out at factory level without segregating different irrigation schemes and technologies existed in each factory and also did not quantify energy outputs obtained from byproducts.

The main objective of this study was to undertake a comprehensive energy analysis within irrigated sugarcane production systems of Awash River Basin of Ethiopia. The specific objectives were to identify and quantify the farm inputs and operations within the production system of 11 irrigation schemes; to estimate energies of each input, farm operation, direct, indirect energy sources together with output energies of the schemes; and then categorically to compare energy productivity, energy intensity, energy efficiency and net energy gain performances of existing irrigation technologies.

2. Materials and Methods

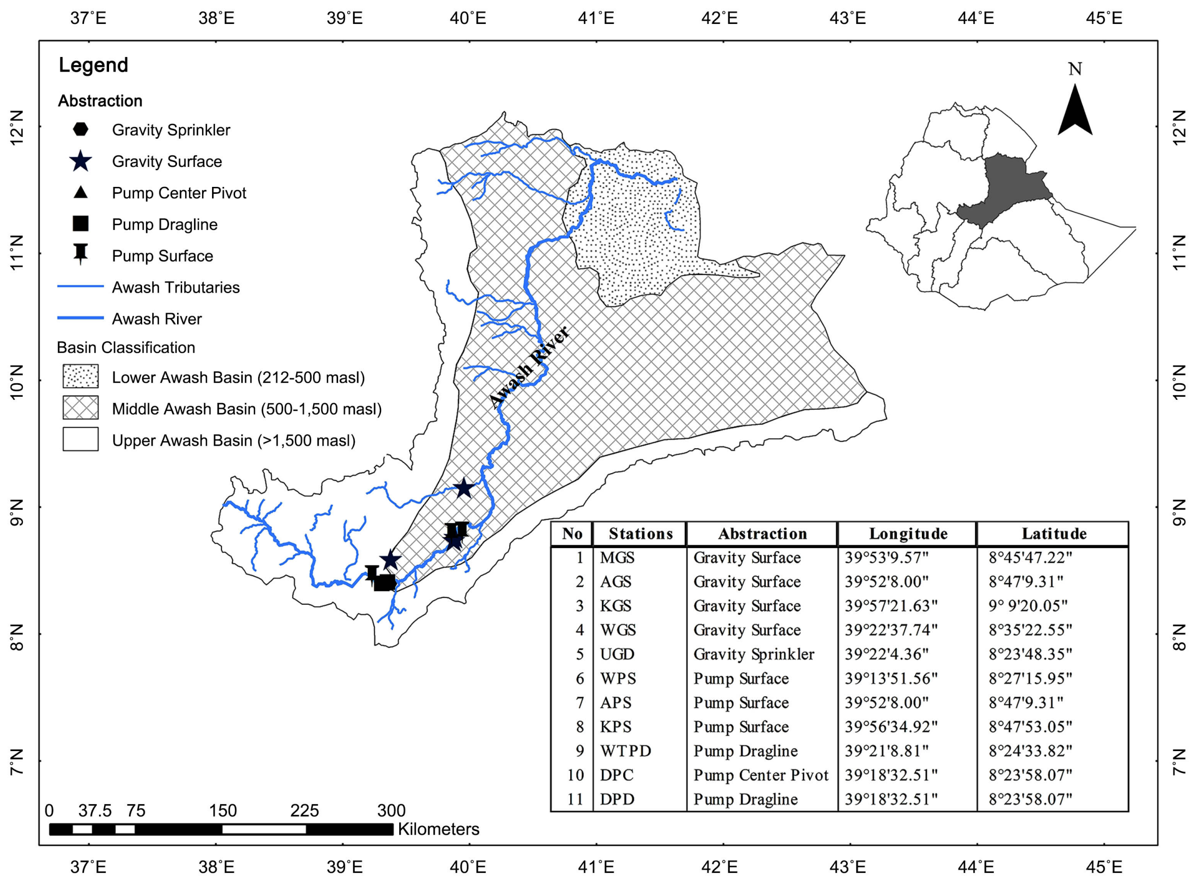
2.1. Descriptions of the Study Area

Awash river basin, one of the 12 river basins of Ethiopia, accounts 25% of national agricultural production; hosts more than 65% of total industries; is the second most populous basin next to Abay by inhabiting 18.6 million people; is fourth in area coverage with 114,123 km^2; the seventh in annual runoff volume; and is the most intensively irrigated basin [25]. The basin lies between 7˚52'12" to 12˚08'24"N and 37˚56'24" to 43˚17'2"E.

Around 2600 equipped surface, dragline and center pivot sprinklers, and drip system irrigation schemes covering around 0.2 million ha (almost 30% of the country) are functioning within the basin. Almost 97.5% area is irrigated with surface methods while shares of sprinkler and drip systems are 1.6% and 0.92%. Almost 23% and 71% irrigated areas use motor pumps and diversion weirs, respectively [26].

More than 50 crops are irrigated but sugarcane, maize, onion, cotton, orange and tomato are dominant covering almost 73% of total irrigated area. Sugarcane was selected for the study due to the following reasons; the crop covers more than 20% irrigated area of the basin [27]; its high energy and water consumption natures compared to other crops [3] [19] and the crop is among the highest energy producer of the world [19]. Moreover, the semi mechanized production systems of the sugar factories encompass different irrigation technologies, energy consuming farm operations and farm inputs.

Wonji, Metehara and Kessem sugar factories are found within Awash River Basin (**Figure 1**). The studied 11 irrigation schemes listed **Table 1** are parts of these sugar factories. Wonji sugar factory comprises Wonji main, Wake Tiyo, North Dodota and Wellenchiti Bofa schemes. Water source of these schemes is Awash River. Except Wonji pump scheme, the others use diversion weirs. Dodota center pivot and dragline schemes have common diversion weir called Dodota North while Wake-Tiyo pump dragline sprinkler use a separate weir.



No	Stations	Abstraction	Longitude	Latitude
1	MGS	Gravity Surface	39°53'9.57"	8°45'47.22"
2	AGS	Gravity Surface	39°52'8.00"	8°47'9.31"
3	KGS	Gravity Surface	39°57'21.63"	9° 9'20.05"
4	WGS	Gravity Surface	39°22'37.74"	8°35'22.55"
5	UGD	Gravity Sprinkler	39°22'4.36"	8°23'48.35"
6	WPS	Pump Surface	39°13'51.56"	8°27'15.95"
7	APS	Pump Surface	39°52'8.00"	8°47'9.31"
8	KPS	Pump Surface	39°56'34.92"	8°47'53.05"
9	WTPD	Pump Dragline	39°21'8.81"	8°24'33.82"
10	DPC	Pump Center Pivot	39°18'32.51"	8°23'58.07"
11	DPD	Pump Dragline	39°18'32.51"	8°23'58.07"

Figure 1. Map displaying locations of selected irrigation scheme of the sugar factories found in Awash basin. Irrigation schemes located at Wonji and Metehara are too close for the scale so geographical coordinates of the schemes are included in the figure.

Table 1. Main characteristics of the selected sugarcane producing irrigation schemes.

No	Schemes	Abbreviations	Sugar factories	Water Abstractions	Field applications	Categories
1	Merti Gravity Surface	MGS	Metehara	Diversion	Furrow	Gravity Surface
2	Abadir Gravity Surface	AGS	Metehara	Diversion	Furrow	
3	Kessem Gravity Surface	KGS	Kessem	Diversion	Furrow	
4	Ulaga Gravity Dragline	UGD	Wonji	Diversion	Dragline	
5	Wellenchiti Gravity Surface	WGS	Wonji	Diversion	Furrow	
6	Wonji Pump Surface	WPS	Wonji	Pumps	Furrow	Pump feed surface
7	Abadir Pump Surface	APS	Metehara	Pumps	Furrow	
8	Kenifa Pump Surface	KPS	Metehara	Pumps	Furrow	
9	Wake Tiyo Pump Dragline	WTPD	Wonji	Pumps	Dragline	Pump Sprinklers
10	Dodota Pump Center pivot	DPC	Wonji	Pumps	Center pivot	
11	Dodota Pump Dragline	DPD	Wonji	Pumps	Dragline	

Plantation schemes of Metehara factory use two diversion weirs constructed on Awash River. Merti weir delivers water for Merti gravity surface scheme while Abadir weir is irrigating Abadir gravity scheme. Kenifa and Abadir pumps are situated along main canals of Merti and Abadir gravity schemes.

Kessem sugar factory crushes sugarcane collected from schemes owned by the factory (2785 ha) and a private scheme (6000 ha). For the study, however, data collected from factory's scheme (KGS) was considered which diverts water released from Kessem dam.

Several electric and diesel driven irrigation pumps are operating at Wonji and Metehara plantations and main features of the major electric pumps are presented in Table 2.

Table 3 presents data related to cropped, harvested and irrigated areas of the studied schemes. Cropped area refers to the area covered by sugarcane crop within a given production year. Harvested areas represent portion of cropped area which are harvested for sugar production.

2.2. Farm Operations of Sugarcane Production

All medium and large scale sugarcane plantations of the country are semi-mechanized irrigated farms and hence, every cultivation practices should synchronize with annual operational plan of the factories; in our case Wonji, Metehara and Kessem. The following descriptions were summarized based on field experiences substantiated with information collected from operation manuals of the factories.

Except minor differences, the major and common farm practices irrigated sugarcane can be grouped as seed cane growing, land development and preparation, planting and cultivation, and harvesting. The crop is propagated by vegetative means from cuttings of young canes previously planted. After preparing and planting of the seed materials, most of the operations are similar with growing of the main sugarcane crops. Nursery management is totally a manual operation.

Table 2. Main characteristics of irrigation pumps of some of the schemes.

No	Schemes	Number of pumps	Pressure heads, m	Pump mean discharges, lit/sec	Water sources
1	WPS	8	7	450	Awash river
2	APS	2	20	500	Main canal of AGS
3	KPS	6	30	280	Main canal of MGS
4	WTPD	3	45	210	Awash river
5	DPC	3	53	290	Awash river
6	DPD	6	74	290	Awash river

(Sources: Own compilations from respective sugar factories).

Table 3. Average cropped, harvested and irrigated areas of the schemes (Source; factories).

No	Schemes	Cropped areas, ha	Harvested areas, ha/year	Irrigated areas, ha/year
1	MGS	6102.8	3539.6	4717.5
2	AGS	2485.4	1491.2	1921.2
3	KGS	2785.0	1671.0	2367.3
4	UGD	168.03	95.78	137.8
5	WGS	975.60	556.1	799.9
6	WPS	5630.0	3209.1	3378.0
7	APS	493.00	295.8	381.1
8	KPS	1265.0	759.0	974.1
9	WTPD	624.4	355.9	512.1
10	DPC	575.0	327.7	471.5
11	DPD	1684.5	960.2	1381.3

(Sources: Own compilations from data obtained from respective sugar factories).

Matured seed canes will be planted on either old or new developed farm fields. Land development can be done in different modalities but all have more or less the same operations. For virgin lands, it is a one-time operation which covers clearing of trees and termite mounds, and land leveling. For other fields, after completing the cropping cycle removal of cane stable is needed so land preparation comprises uprooting, sub-soiling, ploughing, harrowing, and furrowing. Different tractors and implement models and sizes are used depending on soil type, topography, climate, irrigation system and etc. Number of tillage operations may differ and all the entire land preparation activities are diesel fuel based mechanical operations.

Planting, gap filling, moulding, weeding, chemical and fertilizer applications, ratoon reshaping, furrow corrections, irrigation, and cane pushing are common agronomic practices grouped under cultivation. Planting, gap filling, weeding, furrow correction and cane pushing are manual operations and moulding is done mechanically while chemical and fertilizer applications are semi-mechanized operations.

Diversion weirs and electric pumps are used to abstract the irrigation water from rivers or dams. The most common irrigation method is furrow system. Field irrigation are either manually (for surface methods) or semi-mechanically (sprinklers) operated. In dragline system, the sprinklers are moved from one field to the next between irrigation sets. Operators change the locations of sprinklers at predetermined order and irrigation intervals while center pivots sprinklers have electric driven self-rotating mechanisms. Night time irrigation is common for sprinklers. Furrow irrigation is carried out by a group of human labors mostly 3 to 5 field operators irrigating 25 to 75 ha during 8 hours of the day time. In both cases, numbers of labor depend on irrigation intervals. Mean irrigation interval for schemes at Wonji is within the range of 15 to 38 days. For Metehara and Kessem schemes, the irrigation intervals are around 25 and 15 days, respectively.

Chemical fertilizers and agrochemicals are used in varying amounts depending on recommended practices. Nitrogen (46% urea) and ferrous sulphate ($FeSO_4$) at Metehara, and urea at Wonji-Shoa and Kessem fields are applied. Manures or filter cake might also be used on selected fields. Weeds are controlled through hand weeding as well as mechanical spraying of chemicals. Harvesting is the last farm operation considered for the study in which cane burning and cutting are operated manually.

2.3. Data Collection and Analysis

Parts of the raw data required for the study were recorded for irrigation schemes as part of management operations and were collected from the sugar factories. Whenever possible historical data for some of the parameters were collected otherwise data for the 2019/20 irrigation season were used. Design documents of the sprinkler systems, raw data recorded by Awash River Basin Authority, farm operation manuals of sugar factories, and previous study reports were also used to supplement the data collection. Data were collected for 11 sugarcane producing schemes found in Wonji, Metehara and Kessem sugar factories.

All collected data of farm inputs being used and output obtained were inserted into customized Excel spreadsheets and data analysis was done. Based on pressure heads, the irrigation schemes were grouped into different categories and existences of significant differences among the scheme categories checked using linear ANOVA tests. Finally, based on mean values of selected indicators, comparisons among scheme categories were made [5] and results were discussed.

2.4. Energy Analysis

2.4.1. Identification of Farm Inputs, Outputs and Equivalent Energies

Human labor, machinery, fuel, electricity, fertilizer, chemicals and irrigation water were considered as input sources for sugarcane production of irrigation schemes while harvested cane and straws were the outputs.

The direct sources of energy are those which release the energy directly like human labor, electricity and diesel. Direct energies are the energy which released directly from power sources for crop production [3]. Indirect energy sources are which do not release energy directly but release it by conversion processes like energy consumed in manufacturing, storage, distribution and related activities [3]. It refers to the energy used to produce equipment and other materials that are used on the farm and involved in all the processes in which the food industry, transportation, and distribution take part should be added [2]. The major indirect energies are seed, fertilizers, chemicals, machineries, irrigation water, and so on [3].

The input and output values or the amounts of input and outputs were calculated per hectare and multiplied with their equivalent energies collected from literatures. The values for equivalent energy of farm inputs and outputs are shown in **Table 4**. Overall energy equivalent includes heating value, production, packaging, transportation, and application [2].

Identifying and quantifying of the inputs and outputs were followed by evaluations of the associated input and total energies as well as source and operation wise energy consumptions of the irrigation schemes. Total energy output was considered as summation of main and by-products and can be calculated using Equation (1) as suggested by [19].

$$\text{Total energy output}\left(\text{MJ/ha}\right)=\left(\text{Yield, kg/ha}*\text{Energy equivalent}\right)+\left(\text{By product, kg/ha}*\text{Energy equivalent}\right) \tag{1}$$

Table 4. Equivalent Energy values of various farm productions inputs and outputs.

Input categories	Units	Equivalent Energies, MJ	Sources
Electricity	kWh	11.93	[3] [18] [28] [29]
Diesel	lit	56.31	[3] [30]
Human Labor	hr	1.96	[20] [28]
Irrigation water	m^3	0.84	[30] [31]
Chemicals			
Pesticide	lit	101.2	[30]
Herbicide	Kg	238	[32]
Fungicide	Kg	92	[32]
Adjuvants	lit	20	[2]
Machinery			
Tractor	hr	64.8	[3] [18] [20]
Farm Implements	hr	62.7	[3] [18] [20] [30]
Fertilizers			
Nitrogen	Kg	78.1	[2] [19]
Iron sulphate	Kg	17.4	[2] [19]
Manure/Filter cake	Kg	0.3	[18]
Crops			
Sugarcane	Kg	5.3	[3]
Straw (*leaves and tops*)	Kg	16.1	[3] [33]

2.4.2. Energy Use Performance Indicators

Energy consumption must be normalized to allow comparison among different irrigation systems installed in different locations [12]. One way of normalizing is the use of indicators such as energy productivity, energy intensity, energy efficiency and net energy gain.

Energy productivity is the measure of the amount of a product obtained per unit of input energy and it is specific for each agricultural product, location, and time. To improve energy productivity, it is possible either to reduce the energy sequestered in the inputs or to increase the yield of product [2]. Energy Intensity is the reciprocal of energy productivity [20] and measures the amount of energy used to obtain a unit of product. It is widely used to evaluate energy performance of production system of different configurations. Energy intensity can be used to compare projects within the same irrigation system, and to evaluate the efficiency and depreciation of equipment [12].

Energy use efficiency or ratio is defined as the ratio of total energy of output products and total sequestered energy in the production factors [2]. The expression is extensively used to measure the energy efficiency in agricultural and food systems [34] and the index allows us to know the influence of the inputs in obtaining product. If the output energy is greater than the input, the production system assures its subsistence [2]. Net energy gain or production is the difference between gross energy output produced and total energy required for obtaining it [2].

Equations (2)-(5) were used to calculate energy productivity, energy intensity, energy use efficiency (ratio), and net energy gain, respectively [2] [20].

$$\text{Energy Productivity}\left(\text{Kg/MJ}\right)=\frac{\text{Productivity}\left(\text{kg/ha}\right)}{\text{Energy inputs}\left(\text{MJ/ha}\right)} \tag{2}$$

$$\text{Energy Intensity}\left(\text{MJ/Kg}\right)=\frac{\text{Energy Inputs}\left(\text{MJ/ha}\right)}{\text{Productivity}\left(\text{Kg/ha}\right)} \tag{3}$$

$$\text{Energy Use Efficiency}=\frac{\text{Energy output}\left(\text{MJ/ha}\right)}{\text{Energy inputs}\left(\text{MJ/ha}\right)} \tag{4}$$

$$\begin{aligned}\text{Net Energy Gain}\left(\text{MJ/ha}\right)=&\text{Energyoutput}\left(\text{MJ/ha}\right)\\&-\text{Energy Inputs}\left(\text{MJ/ha}\right)\end{aligned} \tag{5}$$

3. Results and Discussions

3.1. Input Usages of Irrigation Schemes

Identification and quantifications of all inputs and outputs were bounded within seed cane raising and harvesting of matured cane. Haulage operations even pulling of carts or trailers from harvest road to farms and from farms to harvest road were not considered.

Seed cane, fertilizers, chemicals, irrigation water, tractors, farm implements, labor, electricity and fuel are identified inputs which are common in sugarcane producing irrigation schemes of Ethiopia including schemes of Awash River Basin. Lists of the irrigation schemes and the inputs are indicated in Table 5.

Table 5. Types of farm inputs and amounts used by the irrigation schemes.

Input types	Units	MGS	AGS	KGS	WGS	UGD	WPS	APS	KPS	WTPD	DPC	DPD
Seed cane												
Seed rate	kg/ha	266.67	266.67	428.57	185.45	185.45	185.45	266.67	266.67	185.45	185.45	185.45
Fertilizers												
Nitrogen (*including seed cane*)	kg/ha	393.31	393.31	196.46	363.19	363.19	363.19	393.31	393.31	363.19	363.19	363.19
Manure (*including seed cane*)	kg/ha	3444.4	3444.4	3714.3	3309.1	3309.1	3309.1	3444.4	3444.4	3309.1	3309.1	3309.1
Iron sulphate	kg/ha	22.50	22.50	12.00	-	-	-	22.50	22.50	-	-	-
Chemicals												
Herbicides	kg/ha	9.38	9.38	6.00	15.58	15.58	15.58	9.38	9.38	15.58	15.58	15.58
Adjuvants	lit/ha	0.34	0.34	0.21	0.41	0.41	0.41	0.34	0.34	0.41	0.41	0.41
Pesticides	kg/ha	6.00	6.00	7.50	1.87	1.87	1.87	6.00	6.00	1.87	1.87	1.87
Irrigation water	m^3/ha (1000)	30.93	31.03	30.82	38.51	25.97	17.21	17.38	16.65	14.05	12.05	13.85
Tractors												
Tillage	hrs/ha	16.95	16.95	16.29	16.48	16.48	16.48	16.95	16.95	16.48	16.48	16.48
Cultivations	hrs/ha	10.00	10.00	10.00	11.20	11.20	11.20	10.00	10.00	11.20	11.20	11.20
Implements												
Tillage	hrs/ha	21.00	21.00	21.00	21.00	21.00	21.00	21.00	21.00	21.00	21.00	21.00
Cultivations	hrs/ha	14.00	14.00	14.00	14.00	14.00	14.00	14.00	14.00	14.00	14.00	14.00
Labor												
Seed cane	hrs/ha	38.80	38.80	38.25	40.21	26.29	47.95	38.80	38.80	26.29	26.29	26.29
Cultivation	hrs/ha	388.04	388.04	382.50	402.13	262.93	479.47	388.04	388.04	262.93	262.93	262.93
Harvesting	hrs/ha	336.00	336.00	304.00	249.80	249.80	187.64	336.00	336.00	249.80	249.80	249.80
Electricity												
Pumping	kWh/ha	-	-	-	-	-	357.27	2240.99	3856.31	5914.58	8195.98	8790.44
Fuel												
Tillage	lit/ha	30.19	30.19	41.25	30.68	20.10	39.27	30.19	30.19	20.10	20.10	20.10
Cultivation	lit/ha	32.90	32.90	37.23	46.53	31.88	46.53	32.90	32.90	31.88	31.88	31.88
Energy outputs												
Cane yields	ton/ha	134.03	148.64	126.30	167.62	112.60	91.83	126.59	119.92	111.13	109.19	109.19
Straw (20%)	ton/ha	26.81	29.73	25.26	33.52	22.52	18.37	25.32	23.98	22.23	21.84	21.84

All the listed schemes are part of Metehara, Wonji and Kessem sugar factories. MGS, AGS, APS and KPS schemes are owned by Metehara while KGS is owned by Kessem sugar factory. The rest are part of Wonji sugar factory. The first five schemes use diversion weirs while the rest uses electric pumps to abstract water from the sources.

Although input types were similar, there were differences on the amounts being used due to differences of operation standards. The irrigation schemes use urea (46%) as nitrogen fertilizer for seed cane, plant cane and ratoon crops by applying 196 to 393 kg/ha. For seed cane growing, cultivations and harvesting operations, a total of 539 to 763 hours of human labor were used per hectare. However, tractor and implement hours were almost similar across the schemes (62 hours/ha).

Diesel fuel is energy source for tillage and cultivation operations with minimum and maximum consumption rates of 51.98 lit/ha in all sprinkler schemes and 85.8 lit/ha at WPS surface scheme. The difference is attributed to combination of soil types and irrigation technologies. Farm fields of WPS surface scheme is dominated by heavy clay soil while soils of sprinkler schemes are relatively light. Apart from that extra land preparation activities are carried out for surface irrigation schemes.

Electric consumptions were within the range of 357 to 8790.4 kWh/ha. The maximum and minimum water users were WGS and DPC schemes by applying 38.5 and 12.1 m^3 per a hectare of cane field per year.

In general, other than inputs which are related with irrigation technologies particularly pressure heads and water, the schemes had comparable consumption rates. Moreover, applied water had direct relationship with pressure heads which reflected on electric consumptions of the schemes (**Figure 2**). WPS and DPC were the lowest and the highest electric consumers due to pumping the water to 7 m and 74 m, respectively which are the lowest and the highest pressure heads.

Best correlation (R^2 = 0.98) was found between pressure head and electric energy consumption per hectare of sugarcane (**Figure 2**). Moreover, despite some variations, good correlation (R^2 = 0.64) was found between pressure head and total amount of water applied. The relationship of pressure head and water applied of WGS scheme reduced the correlation and if removed the correlation will be 0.75. Hence, pressure head was the key driver for irrigation water and pumping energy use.

The first six (MGS, AGS, KGS, WGS and UGD) are gravity fed surface schemes but UGD is a dragline sprinkler. Based on energy source, the scheme was grouped with gravity surface schemes. The next three schemes (WPS, APS and KPS) are pump based surface schemes with operating pressure of 7, 20 and 30 m while WTPD, DPC and DPD are pump based sprinkler systems with operating pressure of 45, 53 and 74 m, respectively. DPC is center pivot and the others two are draglines.

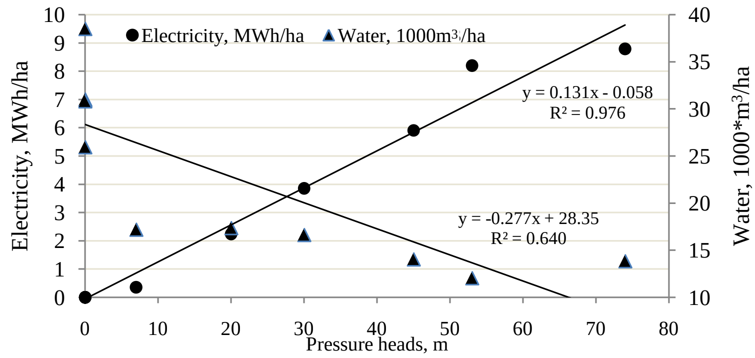


Figure 2. Relationships of water and electricity consumptions with pressure heads of the schemes.

In order to assess existences of significant differences among the groups, the irrigation schemes were categorized as gravity surface, pump surface, and pump sprinklers. The variability between different technologies was tested using linear ANOVA based the values of water applied, land productivity, total input energy, energy productivity, and energy efficiency (Table 6).

The tests results presented in Table 6 indicated that, except land productivity, the scheme categories exhibited significant differences ($p < 0.05$) on water applied, total energy, energy productivity and energy efficiency indicators which will be discussed later.

3.2. Source-Wise Energy Consumptions

The inputs used by the irrigation schemes were multiplied by respective equivalent energies and the results are presented in Table 7. Total energies to grow 91.83 to 167.62 tons of sugarcane were within the range of 47.88 to 143.41 GJ/ha. Amount of energy sequestrated in irrigation water varied from 10.12 to 32.35 GJ/ha while pumping energies were 4.26 GJ/ha for WPS pump scheme and 104.87 GJ/ha for DPD dragline scheme.

Half of total input energy of MGS, AGS, KGS and WGS schemes was irrigation water. Electric consumptions of DPD and WPS schemes were the highest and the smallest, respectively. Almost 73% of total energy of DPD scheme was electricity while water constituted only 8.1% of total input energy.

According to [5], schemes with pumping energy consumption greater than 1000 kWh/ha (11.93 GJ/ha) are classified as big energy consumers, 600 to 1000 kWh/ha (7.2 to 11.93 GJ/ha) are medium consumers, and less than 600 kWh/ha (7.2 GJ/ha) are low consumers. Based on this classification, except WPS scheme, all are categorized under high energy consumers.

Total input energy of WPS pump scheme was lower than even gravity surface schemes because of applying less water. The highest input energy of WGS was irrigation water due to applying of the highest volume.

Average total input energies of gravity surface, pump surface and sprinkler schemes to grow 110, 113 and 136 ton/ha of sugarcane were 54, 69, and 129 GJ/ha, respectively (Figure 3). Irrigation water and fertilizer applied by gravity surface schemes comprised 75% of total energy (49.3 and 25.25%, respectively). However, 80% total input energy of pump schemes was the sum of electricity (37%), fertilizers (22%) and irrigation water (21%). Almost 71% (91 GJ/ha) total energy of sprinklers was obtained from electricity followed by fertilizers (11%) and water (9%).

Operating pressure has significant effect on total input energy of the pump schemes because large part of the total input energies of the schemes were obtained from electricity. Total input energy increases as pumping head increases.

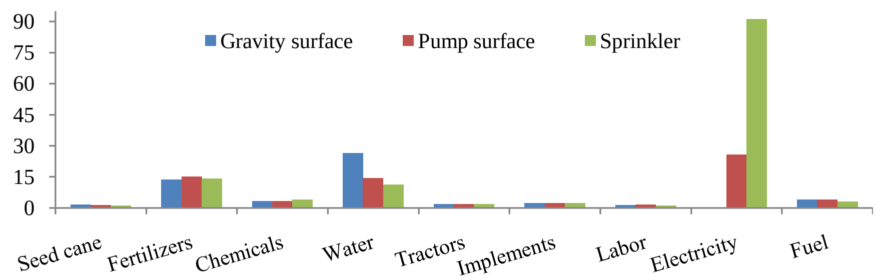


Figure 3. Source wise mean input energy use of irrigation schemes categories, GJ/ha.

Table 6. Results of ANOVA tests of scheme categories for selected indicators.

Categories	Number of schemes	Mean values				
		Water, $1000^{*}m^3$/ha	Productivity, ton/ha	Total energy, GJ/ha	Energy productivity, kg/MJ	Energy efficiency
Gravity surface	5	31.85^a	136.32^a	53.57^a	2.56^a	21.84^a
Pump surface	3	17.08^b	112.78^a	68.94^a	1.69^b	14.41^b
Sprinklers	3	13.32^c	109.84^a	129.17^b	0.86^c	7.35^c
P-values		*<0.05*	*0.076*	*0.0024*	*0.00033*	*<0.05*

*mean followed with the same superscript are not statistically different.

Table 7. Source wise energy use of irrigation schemes and their outputs, GJ/ha.

Energy sources	Types	MGS	AGS	KGS	WGS	UGD	WPS	APS	KPS	WTPD	DPCP	DPD
Seed cane	Indirect	1.41	1.41	2.27	0.98	0.98	0.98	1.41	1.41	0.98	0.98	0.98
Fertilizers	Indirect	15.57	15.57	8.39	14.05	14.05	14.05	15.57	15.57	14.05	14.05	14.05
Chemicals	Indirect	2.85	2.85	2.19	3.91	3.91	3.91	2.85	2.85	3.91	3.91	3.91
Irrigation water	Indirect	25.99	26.06	25.89	32.35	21.82	14.45	14.6	13.98	11.8	10.12	11.63
Tractors, Implements	Indirect	3.94	3.94	3.89	3.98	3.98	3.98	3.94	3.94	3.98	3.98	3.98
Labor	Direct	1.5	1.5	1.42	1.36	1.06	1.4	1.5	1.5	1.06	1.06	1.06
Electricity	Direct	-	-	-	-	-	4.26	26.74	46.01	70.56	97.78	104.87
Fuel	Direct	3.55	3.55	4.42	4.35	2.93	4.83	3.55	3.55	2.93	2.93	2.93
Total inputs		54.80	54.88	48.48	60.98	48.73	47.88	70.15	88.80	109.28	134.81	143.41
Direct sources		5.05	5.05	5.84	5.70	3.98	10.49	31.78	51.05	74.54	101.76	108.85
Indirect sources		49.75	49.83	42.64	55.28	44.74	37.38	38.36	37.75	34.73	33.05	34.56

On the other hand, energy sequestrated in irrigation water is inversely related with pumping heads. Sprinkler schemes had lowest energy of irrigation water but had highest electricity consumption (**Figure 3**).

Contributions of labor and fuel as an input energies in sprinklers were the lowest due to minimum tillage operations and labor required compared to surface schemes. Share of labor energy in sprinkler was below one percent of the total. Energies of tractors and implements were below five percent but uniform for all categories.

3.3. Direct and Indirect Energy Sources

Electricity, labor and fuel are direct energy sources and the rest are indirect energy sources. The proportions varied across scheme categories (**Figure 4**). Mean percentage of direct energy of sprinklers was 164% and 770% higher than mean of pump and gravity surface schemes, respectively.

Water and fertilizers are the indirect energy sources contributing substantial share in gravity surface sugarcane schemes. For sprinklers, pumping electricity had significant share. Around 90 and 74% total energies of gravity surface and sprinkler schemes were consumed as direct and indirect energies, respectively. For pump surface schemes, indirect energy sources were 10% higher than direct energy sources.

3.4. Operation-Wise Energy Consumptions

Operations particularly related with land preparations are a one time activities to be undertaken after harvesting of the last ratoon so quantifying the energies associated with such operations were distributed over number of cuttings. Input energies from farm inputs are regrouped based on farm operations and results are presented in **Table 8**.

Seed cane growing, land preparation or tillage, cultivation, irrigation and harvesting are major farm operation activities in the irrigated sugarcane of Ethiopia. Weeding, moulding, planting, fertilizer and chemical applications, irrigating, furrow correction, field cleaning, and so on activities are grouped under cultivation. The irrigation water and pumping of the water were grouped under irrigation operation. Harvesting operation comprises labor intensive burning and cane cutting activities.

Table 8. Operational energy consumption of irrigation schemes, GJ/ha.

Operations	MGS	AGS	KGS	WGS	UGD	WPS	APS	KPS	WTPD	DPC	DPD
Seed cane growing	1.82	1.82	2.88	1.29	1.27	1.31	1.82	1.82	1.27	1.27	1.27
Tillage	4.11	4.11	4.70	4.11	3.52	4.60	4.11	4.11	3.52	3.52	3.52
Cultivation	22.22	22.22	14.42	22.74	21.64	22.89	22.22	22.22	21.64	21.64	21.64
Irrigation	25.99	26.06	25.89	32.35	21.82	18.72	41.33	59.99	82.36	107.90	116.50
Harvesting	0.66	0.66	0.60	0.49	0.49	0.37	0.66	0.66	0.49	0.49	0.49

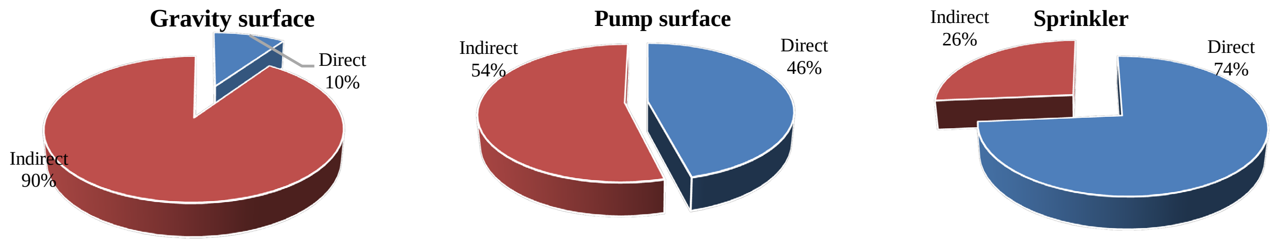


Figure 4. Proportion of direct and indirect energy sources for scheme categories.

The dominant energy consuming operations of all gravity surface schemes including WPS (pump surface scheme) were irrigation and cultivation. Proportionally, harvesting and seed cane growing operations of all schemes consumed very small energies. The total energy consumed by irrigation and cultivation operations in KGS (gravity surface) and DPD (pump driven dragline sprinkler) schemes were 83% (40 GJ/ha) and 96% (138 GJ/ha) of total input energies. Except KGS scheme, to cultivate one hectare of irrigated sugarcane, around 22 GJ of energy was required.

Energy consumptions of the schemes for irrigation activities had considerable variation. Around 40% and 81% total energies of WPS and DPD schemes were sequestrated in irrigation water and pumping electricity.

Irrigation is the most energy consuming operation which constituted about 49%, 58% and 79.2% total input energy of gravity surface, pump surface and sprinkler schemes, respectively followed by cultivation (**Figure 5**).

Manual burning and cutting of sugarcane are the only activities included in harvesting operation. Input energies of the operation were quantified based on working norms *i.e.* 0.030 - 0.035 ton/head/day for cutting and 8 ha/day/head for burning. Total harvesting time will depend on land productivity. Land productivities of pump schemes were lower than gravity schemes so as lowering input energy of human labor.

3.5. Output Energies

Harvested cane and associated straw at farm level were considered for the analysis because of predefined boundary of the study. Factory byproducts such as bagasse and molasses were not considered. Straw was estimated as 20% of cane yield (ton/ha). The cane and straw yields were multiplied by their equivalent energies and summed up (**Table 9**).

Total output energy is directly related to land productivities. The highest and the lowest total output energies were that of WGS and WPS schemes, respectively. Both schemes are part of Wonji sugar factory but there was 45% variation between them.

Calorific or equivalent energy content of cane straw is three times higher than main product. Output energies obtained from the straws were almost 61% of energy obtained from the main products. Energies embedded in cane straw were 340% (DPD sprinkler scheme) to 7000% (WPS pump scheme) higher than the respective pumping energy consumptions.

Table 9. Sources and quantities of output energies of irrigation schemes, GJ/ha.

Output energies	MGS	AGS	KGS	WGS	UGD	WPS	APS	KPS	WTPD	DPC	DPD
Cane yield	710.4	787.8	669.4	888.4	596.8	486.7	670.9	635.5	588.9	578.7	578.7
Cane straw	431.6	478.6	406.7	539.7	362.6	295.7	407.6	386.1	357.8	351.6	351.6
Total outputs	1141.9	1266.4	1076.1	1428.1	959.3	782.4	1078.6	1021.7	946.8	930.3	930.3

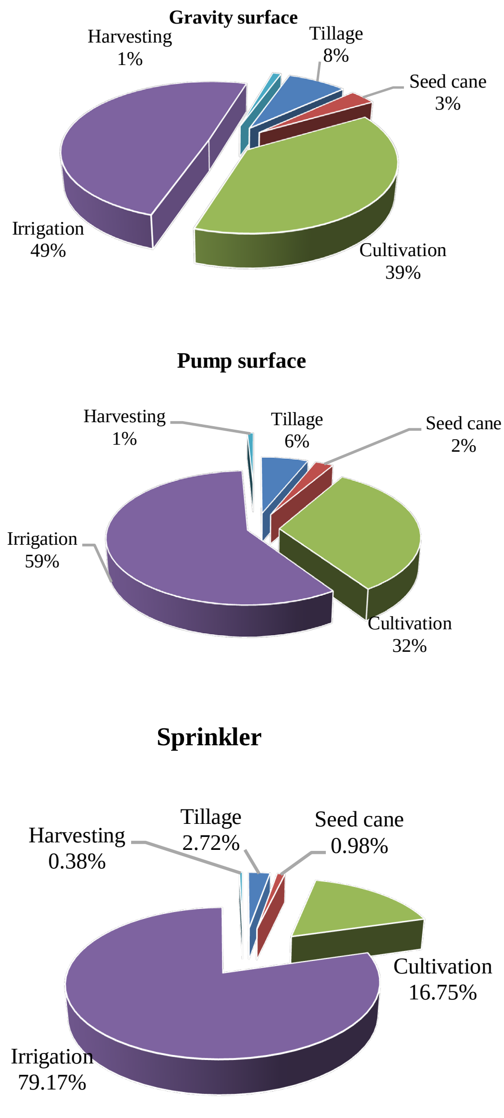


Figure 5. Energy consumption shares of farm operations.

There was no significant difference on land productivity among the scheme categories; however, pumped sprinklers had 20% lower output energy than gravity fed surface schemes (Figure 6).

Practically, cane fields are burned before harvest to remove leaves and tops with equivalent energy ranging from 295.7 to 539.7 GJ/ha without any beneficial use for the schemes.

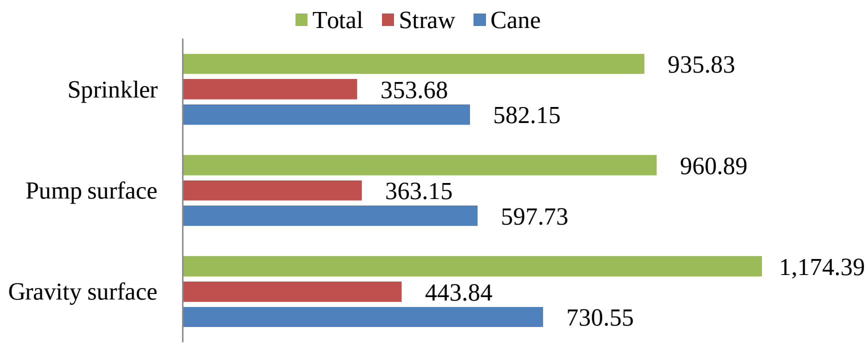


Figure 6. Output energies obtained from cane and straw of the three scheme categories, GJ/ha.

3.6. Energy Productivity and Energy Intensity

Energy productivity and specific energy are inversely related and Equation (2) and (3) were used. The highest energy productivity was obtained from WPS scheme while the lowest was from DPD scheme indicating that in order to produce one kilogram of cane, 3.2 times more input energy was used by DPD sprinkler than WGS surface scheme (**Table 10**).

Despite the fact that total input energy of WGS schemes was the highest among gravity surface schemes, cane productivity of the scheme was much higher than others. On the other hand, pumping energy consumed by DPD scheme was more than double of WGS scheme.

Energy productivity becomes lower and lower towards pump surface and sprinkler schemes and there is significant difference ($p < 0.05$) among scheme categories. In order to produce one kilogram of sugarcane, on average, 156 and 300% more energies were used by pump surface and sprinkler schemes, respectively, than gravity surface schemes (**Figure 7**).

3.7. Energy Use Efficiency and Net Energy Gain

The values of energy efficiency (Equation (4)) and net energy gains (Equation (5)) were determined based on the summation of cane and straw obtained yields from a hectare of land. Results of energy efficiency and net energy gain are presented in **Table 11**.

The respective energy efficiency and net energy gain of WGS scheme were 361 and 174% higher than that of DPD scheme. Energy efficiency value of DPC center pivot was in between WTPD and DPD dragline sprinkler schemes.

WGS gravity scheme had the highest land productivity (167 ton/ha) which yielded the highest energy efficiency and net energy gain. On the contrary, WPS scheme had the lowest net energy gain due to having lowest cane yield (92 ton/ha).

From ANOVA test, significant difference ($p < 0.05$) on energy efficiency was observed among scheme categories. Differences among the scheme categories are shown in **Figure 8**.

Table 10. Results of energy productivity and specific energy of irrigation schemes.

	MGS	AGS	KGS	WGS	UGD	WPS	APS	KPS	WTPD	DPC	DPD
Energy productivity, Kg/MJ	2.45	2.71	2.61	2.75	2.31	1.92	1.81	1.35	1.02	0.81	0.76
Specific energy, MJ/kg	0.41	0.37	0.38	0.36	0.43	0.52	0.55	0.74	0.98	1.24	1.31

Table 11. Results of energy use efficiency and net gain of sugarcane producing irrigation schemes.

Indicators	MGS	AGS	KGS	WGS	UGD	WPS	APS	KPS	WTPD	DPC	DPD
Energy efficiency	20.8	23.1	22.2	23.4	19.7	16.3	15.4	11.5	8.7	6.9	6.5
Net energy, GJ/ha	1087.1	1211.5	1027.6	1367.2	910.61	734.6	1008.4	932.9	837.6	795.5	786.9

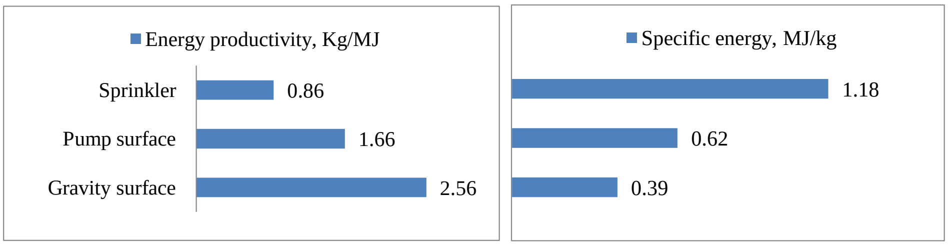


Figure 7. Graph of mean energy productivity and specific energy of scheme categories.

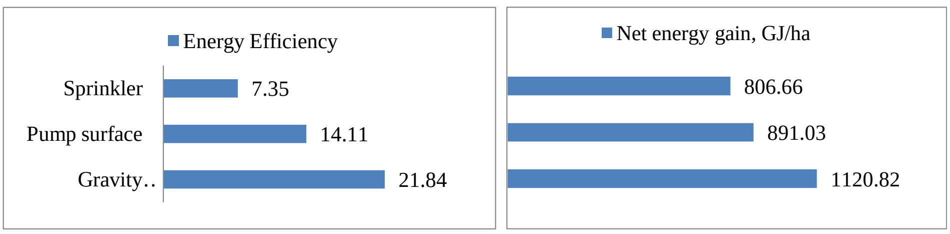


Figure 8. Graph of mean energy ratio (left) and net energy gain (right) of scheme categories.

Energy use efficiency of gravity schemes were 152% and 300% higher than pump surface and sprinkler schemes, respectively. This may be attributed to first, land productivity of gravity surface schemes were higher so as the quantities of output energy. Second, pumping energies of these gravity schemes was zero which significantly reduced total input energy.

With the same reasons, net energy gain of pump sprinklers were almost 30 and 10% lower than gravity surface and pump surface schemes, respectively.

In general, the studied sugarcane producing irrigation schemes of Awash basin used similar farm inputs and had similar farm operations. Irrigation water and fertilizer were major energy sources of gravity fed surface schemes while pumping energy for sprinkler schemes. Electricity, fertilizers and irrigation water had comparable contribution for pump driven surface schemes.

Gravity surface schemes had much better performances in relation to all energy use indicators when compared to sprinkler schemes while pump driven surface schemes were in the middle. In order to produce the same amount of cane yields, the sprinklers are consuming 300% more energy than gravity surface schemes. Moreover, net energy gain of gravity surface scheme is 30% higher than the sprinklers.

Sprinkler schemes of the basin are excessively consuming the scares resource of the basin without providing the expected advantages. The reasons might be related with design of the schemes or management of farm operations. Whatever the reasons, which is beyond the scope of the paper, proper managements of farm inputs particularly fertilizer, pumping energy and irrigation water will have effects on performances of the schemes. For instance, improving irrigation efficiency of pump driven schemes will reduce pumping energy consumptions. Reducing water pumping heads and the amount of fertilizer being used might not be a short term remedy. However, significant improvement can be obtained through the use of cane straws as source of pumping energy, fuel energy and soil fertilizers.

Trash farming conserves considerable amount of nitrogen in the soil. In Brazil, gains in soil nitrogen equivalent to 54 kg/ha per year from unburned cane was reported. In Brazil, where trash farming is practiced, only 60 kg of nitrogen per ha was applied while 150 - 300 kg was used in most cane producing countries [33]. For a yield of 90 ton/ha, the nutrient in sugarcane tops and leaves is estimated to be 35.5 kg/ha of N, 7.4 kg/ha of phosphate (P_2O_5) and 128.3 kg/ha of K_2O [20]. Research in Puerto Rico indicated that whole-plant harvesting could provide 25% more total biomass than that from traditional harvesting of stalks only. According to [2], burning of cane tops and straw practices remove an equivalent of 6 - 10 barrels of oil per hectare.

Bagasse is used as source of electricity for sugar processing operations while pump driven irrigation schemes of the sugar factories are fully dependent on electricity of the national grid which is frequently interrupted. Shortages of imported inorganic fertilizers and fossil fuels are also serious problems within the sugar industries. On the contrary, the energy embedded in straws burned on harvested fields were in excess of 230 up to 520 GJ/ha (or 3 up to 32 folds) higher than the sum of fertilizer, pumping electricity and machinery fuel consumptions of the irrigation schemes signifying the capacity of cane straws to substitute the imported fertilizers, fossil fuel and pumping energy demands of the schemes. Such interventions will guarantee sustainable development through resource use self-sufficiency or security.

However, use of cane straws as energy source might affect the current production systems as a whole; might alter the quality of factory sugar due to green harvesting; might affect communities who are dependent on cane straws as feed source of their livestock and energy source for cooking; might also demanded modification of some farm operations and/or introduction of new systems so the option should further be investigated and optimized.

4. Conclusions

Identification and quantification of input and output energy sources, direct and indirect energies, energy consumptions of farm operations and energy use performances of sugarcane producing schemes found in Awash River Basin of Ethiopia were carried out. Seed cane, fertilizers, chemicals, irrigation water, tractors and implements, labor, electricity for pumping and diesel fuel for machineries were identified as input energy sources. Seed cane growing, land preparation, cultivation, irrigation and harvesting were identified as energy consuming farm operations.

Pumping energy, irrigation water and fertilizer found to the major input energy contributors in the production systems of each irrigation scheme. Despite applying less irrigation water, pumping energies of pump schemes increased due to increasing pumping pressures.

Relationships between electric consumption against pressure head and water applied have been established in which electric energy found to be the major energy supplier of pump schemes. On the other hand, pumping energy restricted the volume of water to be applied. The relationship will provide preliminary information about energy consumptions while modernizing irrigation schemes.

Based on pumping heads, the schemes were categorized into gravity surface, pump driven surface and sprinkler technologies and irrigation was the most energy consuming operation by utilizing 49%, 58% and 79.2% total energies of the respective scheme categories followed by cultivation. In order to produce one kilogram, 156% and 300% more energies were used by pump surface and sprinkler schemes, respectively than gravity schemes. Energy efficiency of gravity surface schemes was 152% and 300% higher than pump surface and sprinkler schemes. Due to lower input energy consumption and high land productivities, the values of energy productivities, energy efficiencies, net energy gains of gravity surface schemes found to be the highest.

Energy lost in burned cane straws while harvesting was higher than fuel, fertilizer and pumping energy demands of the schemes. Use of straws as manure and/or biofuel has the potential to substitute pumping energy demands which is supplied from the national grid as well as the imported inorganic fertilizer requirements of the schemes which in turn needs in-depth analysis and investigations.

Acknowledgements

The authors highly appreciate reviewers of this article.

Contributions of Authors

Yusuf Kedir contributed on the acquisition, collection, analyses and interpretation of the data and also on the preparation of the full write up. Belete Berehanu and Tena Alamirew contributed by checking the quality of the data, repeatedly revising the drafts, the analyses methods, and integrity of the paper.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

References

[1] Alam, M.S., Alam, M.R. and Islam, K.K. (2005) Energy Flow in Agriculture: Bangladesh. *American Journal of Environmental Sciences*, **1**, 213-220. https://doi.org/10.3844/ajessp.2005.213.220

[2] Kitani, O. (1999) CIGR Handbook of Agricultural Engineering, Volume V: Energy and Biomass Engineering. American Society of Agricultural Engineers, St. Joseph, Michigan, 13.

[3] Singh, S. and Mittal, J.P. (1992) Energy in Production Agriculture. Mittal Publications, New Delhi.

[4] Khan, S. and Hanjra, M.A. (2008) Footprints of Water and Energy Inputs in Food Production—Global Perspectives. *Food Policy*, **34**, 130-140.

[5] Rodríguez Díaz, J.A., Camacho Poyato, E. and Blanco Pérez, M. (2011) Evaluation of Water and Energy Use in Pressurized Irrigation Networks in Southern Spain. *Journal of Irrigation and Drainage Engineering*, **137**, 644-650. https://doi.org/10.1061/(ASCE)IR.1943-4774.0000338

[6] Eyre, D.N. and Alexandra, J. (2014) The Water and Energy Nexus: A Multi-Factor Productivity Challenge. NSW Farmers Association, Greenwich, NSW.

[7] Welsh, J.M. and Powell, J.W. (2017) Opportunities for Energy Innovation in Australian Irrigated Sugarcane. Ag Econ, Sugar Research Australia Report, Burren Junction, NSW.

[8] Kedir, Y., Berhanu, B. and Alamirew, T. (2021) Comparative Efficiency Analysis of Irrigation Scheme Categories of Awash River Basin, Ethiopia. *Journal of Resources Development and Management*, **79**, 21-35.

[9] PDC (2021) Ten Years Development Plan: A Pathway to Prosperity 2021-2030. Planning and Development Commission of Federal Democratic Republic of Ethiopia, Addis Ababa.

[10] Kedir, Y. (2021) The Stumbling Irrigation Sector of Ethiopia: Critical Review and Analysis. *Irrigation & Drainage Systems Engineering*, **10**, Article No. 32021.

[11] Safa, M. (2011) Determination and Modelling of Energy Consumption in Wheat Production Using Neural Networks: "A Case Study in Canterbury Province, New Zealand". *Energy*, **36**, 5140-5147. https://doi.org/10.1016/j.energy.2011.06.016

[12] Conforti, P. and Giampietro, M. (1997) Fossil Energy Use in Agriculture: An International Comparison. *Agriculture, Ecosystems & Environment*, **65**, 231-243. https://doi.org/10.1016/S0167-8809(97)00048-0

[13] Barbosa, B.D.S., Colombo, A., de Souza, J.G.N., da Silva Baptista, V.B. and de Araújo, A.C.S. (2018) Energy Efficiency of a Center Pivot Irrigation System. *Engenharia Agrícola*, **38**, 284-292. https://doi.org/10.1590/1809-4430-eng.agric.v38n2p284-292/2018

[14] Sartori, L., Basso, B., Bertocco, M. and Oliviero, G. (2005) Energy Use and Economic Evaluation of a Three Year Crop Rotation for Conservation and Organic Farming in NE Italy. *Biosystems Engineering*, **91**, 245-256. https://doi.org/10.1016/j.biosystemseng.2005.03.010

[15] Stout, B.A. (1990) Handbook of Energy for World Agriculture. Elsevier, Applied Science, London and New York.

[16] Liu, J. (2009) A GIS-Based Tool for Modeling Large-Scale Crop-Water Relations. *Environmental Modeling & Software*, **24**, 411-422. https://doi.org/10.1016/j.envsoft.2008.08.004

[17] Fluck, R.C. (1992) Energy Analysis in Agricultural Systems. In: Fluck, R.C., Ed., *Energy in Farm Production*, Elsevier Science, Amsterdam, 45-52. https://doi.org/10.1016/B978-0-444-88681-1.50010-7

[18] Jackson, T. (2009) An Appraisal of the On-Farm Water and Energy Nexus in Irrigated Agriculture. Ph.D. Thesis, Charles Sturt University, Bathurst.

[19] Chamsing, A., Salokhe, V. and Singh, G. (2006) Energy Consumption Analysis for Selected Crops in Different Regions of Thailand. *Agricultural Engineering International*: *The CIGR E-Journal*, **8**, 1-18.

[20] Karimi, M., Rajabi Pour, A., Tabatabaeefar, A. and Borghei, A. (2008) Energy Analysis of Sugarcane Production in Plant Farms: A Case Study in Debel Khazai Agro-Industry in Iran. *American-Eurasian Journal of Agricultural & Environmental Sciences*, **4**, 165-171.

[21] Coombs, J. (1984) Sugarcane as an Energy Crop. *Biotechnology and Genetic Engineering Reviews*, **1**, 311-346. https://doi.org/10.1080/02648725.1984.10647789

[22] Smerdon, E.T. and Hiler, E.A. (1985) Energy in Irrigation in Developing Countries. *Proceeding of the International Conference on Water and Energy Policy in World Food Supplies*, Texas A & M University, USA, 26-30 May 1985.

[23] Mendoza, T.C. and Samson, R. (2002) Energy Costs of Sugar Production in the Philippine Context. *Philippine Journal of Crop Science*, **27**, 17-26.

[24] Wasihun, G.H., Silalertruksa, T., Gheewala, S.H. and Jakrawatana, N. (2019) Water-Energy-Food Nexus of Sugarcane Production in Ethiopia. *Environmental Engineering Science*, **36**, 798-807. https://doi.org/10.1089/ees.2018.0549

[25] AwBA (2018) Awash River Basin Atlas. Awash River Basin Authority (AwBA), Addis Ababa.

[26] Yibeltal, T. (2013) Awash River Basin Water Audit: Synthesis Report. Food and Agriculture Organization (FAO) and Federal Democratic Republic of Ethiopia, Addis Ababa.

[27] AAiT and AwBA (2016) Awash River Basin Water Allocation Modeling and Conflict Resolution Study Project. Draft Final Report: WP3 Water Demand. Addis Ababa Institute of Technology (AAiT) and Awash Basin Authority (AwBA), Federal Democratic Republic of Ethiopia, Addis Ababa.

[28] Gundogmus, E. (2006) Energy Use on Organic Farming: A Comparative Analysis on Organic versus Conventional Apricot Production on Small Holdings in Turkey. *Energy Conversation Management*, **47**, 3351-3359. https://doi.org/10.1016/j.enconman.2006.01.001

[29] Yavuz, D., Topaz, R. and Yavuz, N. (2014) Determining Energy Consumption of Sprinkler Irrigation for Different Crops in Konya Plain. *Turkish Journal of Agricultural and Natural Sciences*, **1**, 312-321.

[30] Sadeghi, S.H., Moghadam, E.S., Delavar, M. and Zarghami, M. (2020) Application of Water-Energy-Food Nexus Approach for Designating Optimal Agricultural Management Pattern at a Watershed Scale. *Agricultural Water Management*, **233**, Article ID: 106071. https://doi.org/10.1016/j.agwat.2020.106071

[31] Zahedi, M., Mondani, F. and Reza, H. (2015) Analyzing the Energy Balances of Double Cropped Cereals in an Arid Region. *Energy Reports*, **1**, 43-49. https://doi.org/10.1016/j.egyr.2014.11.001

[32] Wakil, M. Umar, S.S., Abubakar, I. and Zubairu, M. (2018) Energy-Use Efficiency of Rice Production under Irrigation in Jere Bowl Borno State, Nigeria. *American Journal of Environmental and Resource Economics*, **3**, 6-11. https://doi.org/10.11648/j.ajere.20180301.12

[33] Vergara, J.C., Rojas, G. and Ortegon, K. (2020) Sugarcane Straw Recovery for Bioenergy Generation: Case of an Organic Farm in Colombia. *ACS Omega*, **5**, 7950-7955. https://doi.org/10.1021/acsomega.9b04340

[34] Hadi, S.H. (2006) Energy Efficiency and Ecological Sustainability in Conventional and Integrated Potato Production System. *Proceeding of the IASTED Conference on Advanced Technology in the Environmental Field*, Lanzarote, Canary Islands, Spain, 6-8 February 2006.