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Research paper

Energy use and efficiency in selected rice-based cropping systems of the Middle-Indo Gangetic Plains in India

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ABSTRACT

The use and cost of energy in agriculture have increased, making it necessary to make current agricultural practices more energy efficient. To do this, the prevailing systems must be thoroughly analysed. Studies have focused on assessing the energy performance of individual crops, but notably few studies have investigated different cropping systems. This paper aims to assess the energy performance of the two most used cropping systems of the Indo-Gangetic plains in India, namely Paddy rice–Wheat (PW) and Paddy rice–Potato (PP). The PW system was more energy efficient with Energy Use Efficiency (EUE) of 6.87 ± 1.7 compared to 3.61 ± 0.58 for the PP system. Higher Energy Efficiency Ratio (EER_M) (3.94 ± 1.30) and Specific Energy(4.39 ± 2.06) (SE) were reported for the PW system, compared to 2.62 ± 0.47 and 2.15 ± 0.35 respectively for the PP system. Fertiliser use accounted for the highest input energy consumption in both systems, accounting for 58% and 51% of the energy consumed in PW and PP systems respectively, followed by fuel, seeds and electricity. The net income from the PP system (2295.7 ± 457.4 USD.ha^{-1}.yr^{-1}) was higher than that from the PW system (1555.4 ± 856.6 USD.ha^{-}1.yr^{-1}). The higher return of PP system was attributed to higher yield and better market price for the potato produce. There were no significant differences reported for various energy and economic parameters within different farm sizes in the PP system. However, for PW system, small farms were energy efficient while larger farms were economically efficient.

1. Introduction

Both energy use and costs are ever-increasing in the agricultural sector. Since the green revolution and the promotion of high-input, mechanised, irrigated cropping systems, agriculture uses much energy, directly and indirectly, owing to its many production activities, inputs and requirements: land preparation, tillage, fertilisers and agrochemicals (manufacturing and application), irrigation (pumping), harvesting and the likes. Therefore, increased energy efficiency has become a key objective for both farmers and policy-makers; however, on-going efforts fall short of harnessing the complete economic potential of energy use in agriculture (World Energy Outlook, 2012). From this perspective, the agricultural sector has an important role as both a consumer and a producer of energy. The final products and major by-products of cropping systems contribute to a large amount of nutritive energy for human and animal populations. Several of the crop's by-products may potentially be used as biomass, which may be turned into renewable energy. The growing worldwide demand of energy by the agricultural sector to meet the food demand of more than 7 billion people results in detrimental effects on the environment and the health of the farmers. If the energy in agricultural sector is used judiciously, it will not only reduce the environmental impacts in terms of green house gases (GHG) emissions and other hazardous effects but will also lead to a desirable sustainable form of agriculture (Schroll, 1994; Dalgaard et al., 2001; Nasso et al., 2011). A higher input of energy accounts for higher energy costs, which significantly reduces the net return of the farms and is a challenging issue for the policy makers. In many advanced agricultural systems, an increase in yield is clearly the result of an augmented energy input that is directly related to the use of improved mechanised tools and the introduction of high-yield crop varieties. In most developing nations, agriculture is the mainstay of the economy and a source of employment for a large proportion of the population. Mechanisation reduces human drudgery, ensures timeliness of farm related activities and increases farm output in terms of productivity. In these countries, in addition to the expansion of arable land, increase in total production is also required, which occurs via the use of efficient machinery for farm operations and proper water, chemicals and weed management practices (Faidley, 1992).

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To know more about the energy input and output relationship in the agricultural sector, it is necessary to take account of the proper use of various energy sources, the cost of energy usage and its impacts on the environment (Jones, 1989). To meet the increasing food demand of the ever increasing population of the world, the world's production capacity is expected to increase two folds by 2050 (FAO, 2008) and energy use will be a prime factor in this transformation as the amount of arable land will either decrease or will remain constant.

In Indian agriculture, there is a huge diversity of agro-ecological diversity in soil, rainfall, temperature and cropping systems. To meet the need for operational energy and reduce the share of animate power, the contribution of mechanical energy increased substantially, which directly resulted in increased use of fossil fuels, mainly diesel. The use of mechanical energy in operational energy increased from a very low value of 11% in 1970–71 to a very high contribution of 76% in 2000–01 (Kulkarni, 2010).

Paddy rice-based cropping systems are most common to the middle Indo-Gangetic plains of the Indian subcontinent, which covers an area of 9.64 Mha (Gangwer et al., 2005). The major crops grown in rotation with rice (*Oryzasativa L.*) are wheat, potato, mustard, pulses, maize and other legumes. India is a major paddy rice-producing nation and accounts for approximately 21% of the total white rice production (Ministry of Statistics and Program Implementation, 2012). The middle Indo-Gangetic plains in India cover the states of Uttar Pradesh, Bihar and West Bengal, the major areas of rice production in India. Paddy rice-wheat (PW) and Paddy rice-potato-fallow (PP) are two cropping systems that are extensively practised by farmers of this region; such systems require very high inputs in terms of agricultural machinery, pesticides, fertilisers and other agro-chemicals (Singh and Chancellor, 1975).

The key drivers of energy use in the agricultural sector in India are agricultural production, the extent of arable land used for crop production and the penetration of efficient technologies, such as irrigation facilities and improved mechanisation means (Chaudhary et al., 2009). Currently, cropping systems are increasing their energy inputs; therefore, there is a need to ascertain the efficiency of the system in terms of energy use. In this context, it is imperative to thoroughly budget the energy use of the widely followed cropping systems to identify the processes and systems that are most energy consuming and can be replaced with other low input-energy-consuming practices, in order to conserve energy and achieve sustainable cropping systems (Hatirli, 2006). The farm size distribution in Indian farming households has gone to a major shift, with the percentage of marginal, small and small & marginal categories witnessing an increase while the semi-medium, medium and large farm sizes witnessing a continuous decrease, after the post-independence period (Dev, 2012). There has always been a lot of debate on the economic and environmental performance of smaller farms as compared to larger farms. The study also intends to report the performance of marginal, small and medium farms, in terms of energy indicators and eco-efficiency.

There have been several studies to assess the energy performance of different crops and cropping systems in Upper Indo-Gangetic Plains (Singh et al., 1990; Nassiri and Singh, 2009). However, there are a limited number of studies assessing the key energy indicators and economic performance of cropping systems in the middle Indo-Gangetic plains (Mittal et al., 1992; Tripathi et al., 2013). Therefore, to assess key energy indicators, such as Energy Use Efficiency (EUE), Energy Efficiency Ratio (EER_M) (in terms of the yield of main products) and Specific Energy (SE) of the two most followed cropping systems (Paddy rice–wheat and paddy rice–potato–fallow) in the middle Indo-Gangetic plains of India, this study was conducted along with the calculation of the eco-efficiency indicator in terms of ratio of economic creation to ecological destruction (Saling et al., 2002). The Paddy Rice–Potato–Fallow and paddy rice-wheat systems are henceforth termed as PW and PP systems, respectively in the current study.

Table 1
Average farm sizes in the study areas.
Source: Dev (2012).

State (State Capital)	Farm size classification (ha)		
	Marginal	Small	Medium
Bihar (Patna)	0.30	1.21	5.24
Uttar Pradesh (Allahabad)	0.40	1.41	5.57

2. Materials and methods

The energy analysis presented here compares the energy indicators EUE, EER_M and SE of the two systems as well as their eco-efficiency in terms of economic return per unit of energy consumption. The two systems selected are PW and PP, which are among the most used cropping systems in the middle Indo-Gangetic plains of India. Energy fluxes in the two selected cropping systems were estimated using crop inputs for resource utilisation and biomass production for the crop year 2012–2013. The mechanical energy dissipated in mechanical operations and energy consumed in other activities, such as irrigation, transportation and other inputs, were estimated from on- and off-farm energy inputs.

The actual values of all the inputs used were calculated based on the results of a survey of the target area. Data was collected from the two important districts in the middle Indo-Gangetic plains, namely Patna and Allahabad, through direct face-to-face interviews with the farmers using the two cropping systems during the period of December–January 2013. The sample size was calculated by the formula given by Yamane (1967) and a total of 51 and 48 farmers engaged in the PW (mainly in Patna) and PP (mainly in Allahabad) cropping systems, respectively, were interviewed in the selected areas. This was based on the number of farming households following a particular cropping system in a particular village of the study areas. Table 1 provides the average farm size classification in the study areas.

2.1. Site description

The selected sites for the study were Patna and Allahabad, two cities in the middle Indo-Gangetic plains of India. Allahabad is situated at 24°47' N latitude and 81°19' E, longitude while the latitudinal and longitudinal coordinates for Patna are 25°36'N and 85°7'E. Both areas are drained by the river Ganges and have similar alluvial soil profiles. Both sites have a humid sub-tropical climate with a hot summer from the end of March to early June. South-eastern monsoons prevail from the end of June to early October, and winter lasts from the middle of November to February. Both areas are characterised by three seasons, hot dry summer, cool dry winter and warm humid monsoon. The mean annual temperature for the Allahabad and Patna regions for 2011 was 25.9 °C and 25.8 °C, respectively, and for 2012, it was 26.4 and 26.2 °C, respectively. The mean annual precipitations for the two areas for 2011 were 1188.7 mm and 915.9 mm, and for 2012 the values were 1227.4 mm and 945.4 mm, respectively. In both areas, farmers practice rainfed as well as irrigated farming, depending on the monsoon season.

In both the areas, Paddy-rice is grown in *Kharif* (monsoon; July–October) season while wheat and potato are grown in *Rabi* (winter; October–March) season. Both the cropping systems, PW and PP, have a lot of diversity in terms of various management practices, in both the areas. Most of the pre-harvest processes (tillage, seeding, weed management, irrigation etc.) are mechanised and inorganic fertilisers are preferred over the organic ones. Manual method of harvesting for paddy-rice and wheat, is usually employed, as the farm sizes are not suitable for large harvesting machines, with a

Table 2
Energy coefficients (MJ h^{-1}) for various equipments used in the two cropping systems.
Source: Nassiri and Singh (2009).

Power source	Equipment	Energy coefficient (MJ h^{-1})
Manual	Spade	0.314
	Sickle	0.031
	Sprayer	0.502
Animal	Disc plough	0.627
	Cultivator	1.881
	Disk harrow	3.135
	Planter	1.568
	Seed drill/planter	1.254
Tractor	Moldboard plough	2.508
	Cultivator	3.135
	Disk plough	3.762
	Planter	9.405
	Disk harrow	7.336
	Seed drill/planter	8.653
	Reaper	5.518
	Rotavator	10.283
	Combine harvester	47.025
Others	Thresher/sheller	7.524
	Centrifugal pump	1.75
	Electric motor 35 hp	0.343
	Electric motor (others)	0.216
	Diesel engine	0.581
	Tractor (>45 hp)	16.416
	Tractor (others)	10.944
	Self propelled combine harvester	171.000

very few farmers owning combines. Custom hiring of farm machineries are most common in the two areas, so that the small farmers are also accessible to the mechanisation. Nearly all the farmers have pumping sets to pump underground water for irrigation, in case there is no timely precipitation. It can be summed up that the farmers go for an energy intensive farming in both the areas, for attaining a higher yield.

2.2. Calculation of energy input (EI)

Energy input was calculated using Eq. (1).

$$EI = [\{\sum(E_s * \varepsilon_s)\} + \{\sum(M_m * t_m)\}]/A \quad (1)$$

where EI is the total energy input to a particular type of crop production (MJ ha^{-1}); E_s is the total amount of energy input and output components utilised for agricultural production of a specific crop (the units for different Es has been reported in Table 3), ε_s is the energy equivalent coefficient for various input energy forms (Table 3), M_m is the machinery energy equivalent in MJ.h^{-1} (Table 2), t_m is the actual working time of the machinery or equipment (h), and A is the total cropped area under a particular cropping system (ha).

2.3. Calculation of energy output (EO)

The energy output is calculated using Eq. (2).

$$EO = [\{\sum(P_{mc} * \varepsilon_{om})\} + \{\sum(P_{bc} * \varepsilon_{ob})\}]/A \quad (2)$$

where EO is the net energy content of the output product (MJ ha^{-1}), P_{mc} is the total production quantity of the main crop (kg), P_{bc} is the total production quantity of by-products (kg), ε_{om} and ε_{ob} are the net calorific value (NCV) of the main crop and the by-products (MJ kg^{-1}), respectively, and A is the total cropped area under a particular cropping system (ha).

2.4. Energy indicators

Key energy indicators for the two cropping systems are assessed using the input energy in the form of human and animate energy, use of machinery and other equipment on the farm, diesel oil and gasoline consumption, manufacturing of fertilisers and other agrochemicals, use of organic manure and seed inputs. The output energy was calculated using the energy content (NCV) of useful biomass (grains, straw and tubers) and the total quantity of the biomass produced. The energy indicators are calculated based on equations used by other researchers in their studies (Singh and Chancellor, 1975; Mittal and Dhawan, 1985; Muller and Sturm, 2001a; Nassiri and Singh, 2009). Tables 2 and 3 provide the energy coefficients for various equipment and energy input sources.

2.4.1. Energy use efficiency (EUE)

EUE indicates how efficient a crop production system is in terms of its energy input and output where the output is calculated in term of the production of the main product and the by-products. EUE is one of the energy indices that indicates the efficient use of energy in agriculture, and this ratio has been used to express ineffectiveness of an agricultural production system. Any augment in EUE indicates efficient use of available energy for agricultural use, and vice versa.

$$EUE = \text{Total Output Energy (MJ.ha}^{-1}\text{)/Total Input Energy (MJ.ha}^{-1}\text{)} \quad (3)$$

2.4.2. Energy efficiency ratio (EER_M)

EER_M indicates the efficiency of a crop production system in which only the main product is included as a contributor to the pool of output energy.

$$EER_M = \text{Total Output Energy in Main Product (MJ.ha}^{-1}\text{)/ Total Input Energy (MJ.ha}^{-1}\text{)} \quad (4)$$

2.4.3. Specific energy (SE)

SE provides an estimate of the amount of energy used to produce a unit quantity of a crop in a cropping system. A higher value of SE symbolises a less efficient cropping system. All the different approaches to reduce the SE contributes to increase EUE, and vice versa. SE has been used widely in comparison of different farm types.

$$\text{SE (MJ kg}^{-1}\text{)} = \text{Total Input Energy (MJ.ha}^{-1}\text{)/ Total main product yield (kg.ha}^{-1}\text{)} \quad (5)$$

2.4.4. Net return (NR)

Net return is the total economic gain to a farmer in a particular cropping system. It is one of the most important indicators of the farmer's economic perspective and farm profitability. It is calculated as the residual income remained after all the production factors are paid off. It denotes the return for farm labour, management and equity. It also considers any other resources used for production agriculture which are unpaid elsewhere.

$$\text{Net Return (USD.ha}^{-1}\text{.yr}^{-1}\text{)} = \text{Gross Income (USD.ha}^{-1}\text{.yr}^{-1}\text{)} - \text{Total Annual Input Cost (USD.ha}^{-1}\text{.yr}^{-1}\text{)} \quad (6)$$

where gross income is calculated by multiplying the total crop produced by its unit price, and total annual input cost represents all the fixed as well as the variable costs incurred during crop production in the two cropping systems.

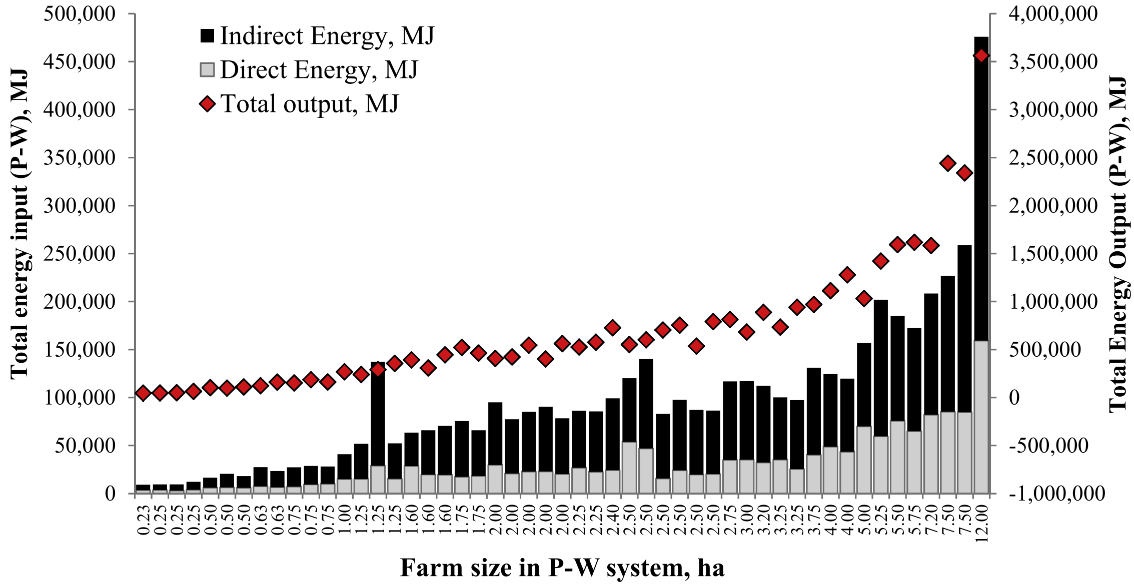

Fig. 1. Share of direct and indirect energy sources to total input energy, and output energy of Paddy–Wheat system.

Table 3
Energy equivalents for various input and output energy forms.

Component (Es)	Unit	Energy equivalent coefficient (MJ/unit)	Source
Human labor			
Adult male	Man-h	2.00	Soni et al. (2013)
Female	Woman-h	1.60	Soni et al. (2013)
Children	Child-h	1.00	Taewichit (2012)
Animal			
Large bullocks	Pair-h	14.10	Taewichit (2012)
Medium bullocks	Pair-h	10.10	Nassiri and Singh (2009)
Diesel	Liter	56.30	Nassiri and Singh (2009)
Electricity	kWh	11.93	Nassiri and Singh (2009)
Chemical fertilisers			
Nitrogen	kg	60.60	Kuswardhani et al. (2013)
P_2O_5	kg	11.10	Chaudhary et al. (2009)
K_2O	kg	6.70	Chaudhary et al. (2009)
Farm Yard Manure (FYM)	kg	0.30	Kizilaslan (2009)
Seed			
Cereals	kg	14.70	Nassiri and Singh (2009)
Potatoes	kg	3.60	Zangeneh et al. (2010)
Straw	kg	14.70	Nassiri and Singh (2009)
Seeds (Cereal)	kg	14.70	Hatirli (2006)
Seeds (Tubers)	kg	3.60	Hamedani et al. (2011)
Agro-chemicals			
Superior chemicals	kg	120.00	Nassiri and Singh (2009)
Inferior chemicals	kg	10.0	Nassiri and Singh (2009)
Zinc Sulphate	kg	20.90	Taewichit (2012)

2.4.5. Eco-efficiency (EE)

Eco-efficiency is a strategy or an approach aimed at de-coupling resource use and pollutant release from economic activity (OECD, 1998) and the eco-efficiency indicator is defined as the ratio between an economic creation and an ecological destruction. The aim of sustainable agriculture is to increase its eco-efficiency by lowering the environmental impacts like energy use & GHG emissions of agriculture while increasing the economic output (Cicek et al., 2011; Taewichit, 2012). EE expresses how efficient an economic activity is, with respect to its impact upon nature. The environmental impact can be measured in terms of energy used (MJ) or the amount of GHG emitted (kg.CO_2eq) by farming practices and the cropping systems. In this paper, EE is expressed as Eq. (7).

$$\text{Eco-efficiency (USD.GJ}^{-1}) = \text{Economic Return (USD.ha}^{-1})/\text{Environmental Impact (GJ.ha}^{-1}) \quad (7)$$

2.5. Statistical analysis

The data analysis was performed both descriptively and qualitatively. The descriptive data analysis was carried out in MS Excel (2010). The qualitative data analysis was done in JMP 12.0 (SAS Institute Inc., Cary, NC, USA). The comparison of means between the two systems and among different farm sizes within the system for different energy indicators was analysed using Analysis of Variance (ANOVA), followed by a post-hoc analysis (using t-test). Prior to mean comparison using ANOVA, the data was checked for normality using quantile plots. Moreover, the statistical analyses were carried out at a 5% level of significance.

3. Results and discussion

3.1. Energy input

Prevailing management practices and the energy input source involved in each of the activities for the three crops are summarised in Table 4. Energy inputs for both the cropping systems are reported in Table 5. The PW and PP systems required an average energy input (±SD) of 39.74 ± 17.23 GJ.ha^{-1} and 65.82 ± 9.11 GJ.ha^{-1}, respectively. The results showed that fertiliser use was the greatest input energy in both the systems, comprising approximately 58% of the total input in the PW system and approximately 51% in the PP system. Nitrogen in particular was the largest contributor of the fertiliser input followed by phosphorus, and the smallest contribution was from potash. These values reflect the mind-set of the farmers, who believe that yield depends directly on the amount of fertilisers used and have no concerns about the environmental impacts created by fertiliser usage. Fuel was the second highest contributor, responsible for 22% and 15% of the total energy inputs in PW and PP cropping systems, respectively. Most of the fuel-based energy inputs were attributed to the consumption of diesel oil in various on-farm agricultural activities, with gasoline consumption mainly attributed to spraying operations during plant protection measures. Higher fuel consumption in the PW system can be attributed to higher mechanisation in that system compared to the PP system. Seeds counted for 14% and 6% of the input energy in the PP and PW cropping systems, respectively. Energy input in the form of human power was higher in the PP system because farmers mainly depended on human labour to harvest potatoes to avoid tuber damage. There was a higher use of potato seeds for planting (32,000 kg.ha^{-1} seeds on an average) compared to the very small amount of seeds for Paddy rice and wheat cultivation. Electricity was another large contributor to input energy, contributing 5% and 6% of the total input energy, mainly for irrigation purposes. FYM and agrochemicals contributed approximately 3% of the input energy each in the PP system, while the values were 0.05% and 0.4%, respectively, in the PW system. The farmers following the PP cropping system extensively used both FYM and agrochemicals for the potato crop and did not feel a need to use a high dose of fertilisers in the Paddy rice once the potato was harvested because the soil was believed to be nutrient rich due to the earlier fertiliser application.

Classification of total energy inputs as direct, indirect, renewable and non-renewable can be inferred from Table 5. PW and PP systems had comparable contributions in terms of direct and non-renewable energy, but the PP system used more renewable and indirect energy. Direct energy contributed 30.81% and 24.84% of the total energy input in the PW and PP cropping systems, respectively. Renewable energy use was higher in PP systems, with a contribution of 21.66% compared to 9.59% in the PW system. The higher renewable energy input in the PP system can be explained by the higher human and animal energy input in the system. Figs. 1 and 2 illustrate the share of direct and indirect energy inputs and the output energy in the two systems.

Fig. 3 shows the effect of farm size on total renewable and non-renewable energy inputs in the two systems. The PW system exhibits a higher correlation with non-renewable energy, while the PP system had a higher correlation with renewable energy. The difference in energy inputs between the two systems can be explained by these variations. The findings of this study are in line with those of other similar studies that were carried out for the selected crops (Paddy rice, wheat and potato), which reported fertilisers and fuel as the main contributors to the energy input pool (Dev, 2012; Bohra, 1998; Sahan et al., 2008; Hadi, 2012; Alluvione et al., 2011; Azarpour, 2012). Azarpour (2012) and Baruah et al. (2004) reported an input energy for the production of wheat crop in agreement with the results of this study. Studies on energy use for Paddy rice and wheat crops (Ozkan et al., 2004; Chauhan et al., 2006; Koga and Tajima, 2011; Hamedani et al., 2011; Koga et al., 2012) reported input energies either comparable to or less than the energy input calculated in this study, which can be attributed to the increased productivity of Paddy rice and wheat crops at the study sites. Chaudhary et al. (2009) and Dev (2012) reported a higher input energy for the Paddy rice–wheat rotation cropping system, but the rotation either included sesbania or green gram as the third crop in the rotation. The same study reported a comparable value of input energy for the Paddy rice–Potato–Wheat rotation in the Indo-Gangetic plains. Although the current study focuses on the PP system, the use of higher input energy as compared to PW can be explained by the increased use of fertilisers and agrochemicals by potato farmers. Koga and Tajima (2011) and Hamedani et al. (2011) reported the energy use for conventional and HYV crop systems used for bio-ethanol production, which is similar to the results obtained in the current study. For the potato production, Hamedani et al. (2011) and Koga et al. (2012) reported a very high energy input in the Hamedan province of Iran, which corresponds to the higher irrigation inputs for potato production in the Iranian province. Some studies in Japan and Iran (Komleh et al., 2012; Harbans and Sharma, 2006; Devi and Ponnarasi, 2009) reported input energy for potato production in line with the values reported in the current study.

3.2. Energy output

Energy output from the two systems is attributed to average crop biomass production, which included grains and straw for the yield of Paddy rice and wheat, while for potato crops only tubers were considered. The energy output from different crop biomass production is given in Table 6.

The output energy in the PP system (236.95 ± 22.66 GJ.ha^{-1}) was lower than that of the PW system (250.89 ± 40.13 GJ.ha^{-1}). For the input energy, the trend was reversed, with the PW system consuming less input energy than the PP system. The higher output energy in the case of the PW system can be attributed to the different forms of the yield compared to the PP system. The PW system contributed same amount of energy from straw and grains on average, which was not the case in the PP system. The higher yield of potatoes (23,341.6 kg.ha^{-1}) somehow compensated for this difference in the energy output of the two systems. Some studies calculated energy indicators only for a particular crop i.e., Paddy rice, wheat and potato separately, and very few studies have focused on a particular cropping system (Dev, 2012; Bohra, 1998; Hadi, 2012; Alluvione et al., 2011; Azarpour, 2012; Baruah et al., 2004; Singh et al., 1990; Chauhan et al., 2006; Koga and Tajima, 2011; Hamedani et al., 2011; Koga et al., 2012; Komleh et al., 2012; Harbans and Sharma, 2006; Devi and Ponnarasi, 2009; Singh, 2006). The results reported in such studies are either in line with the results obtained in the current study or there is some difference that can be explained by the different productivity values of the crops at different geographical locations. Some of the studies (Dev, 2012; Bohra, 1998; Chauhan et al., 2006) reported a higher output energy value due to the inclusion of a third crop in the cropping system in the same area.

3.3. Energy indicators

The three energy indicators calculated in the current study were EUE (Energy Use Efficiency), EER_M (Energy Efficiency Ratio in terms of the main product) and SE (Specific Energy). All three indicators were significantly different ($p \leq 0.05$) between the two systems. The EUE was higher in the PW system (6.87 ± 1.74) compared to 3.60 ± 0.58 for the PP system, which suggests that the former

Table 4
Management practices involved in the cropping system and the corresponding energy source.
Source: Field Survey, 2013.

Management practice	Crop	Energy input source
Tillage of the main field	Rice, Wheat, Potato	Human, Equipment, Fuel, Electricity
Nursery preparation	Rice	Human, Equipment, Fuel, Electricity, Seeds, Fertiliser, FYM, Agrochemicals
Transplanting	Rice	Human, Electricity, Fertiliser, Agrochemicals
Seeding/Planting	Wheat, Potato	Human, Equipment, Fuel, Agrochemicals, Electricity, Seeds, Tubers, Fertiliser, FYM
Soil loading	Potato	Human, Equipment
Weeding	Rice, Potato	Human
Irrigation	Rice, Wheat, Potato	Human, Electricity, Equipment
Fertilisation	Rice, Wheat, Potato	Human, Fertiliser, FYM
Plant protection	Rice, Wheat, Potato	Human, Agrochemicals, Equipment, Fuel
Harvesting	Rice, Wheat, Potato	Human, Equipment, Fuel
Winnowing and threshing	Rice, Wheat	Human, Equipment, Fuel, Electricity

Table 5
The source wise utilisation of energy (in GJ ha^{-1}) in the two cropping systems.

Input category	Paddy–Wheat	%[a]	Paddy–Potato	%[a]
Human	1.25±0.52[b]	3.14	2.52±0.58[c]	3.83
Animal	0 ± 0.00	0.00	0.36 ± 0.49	0.55
Fuel	8.75±4.04[b]	22.02	10.12±4.55[b]	15.37
Electricity	2.24±1.36[b]	5.64	3.36±3.84[b]	5.10
Machinery	0.97±0.36[b]	2.44	1.88±0.41[c]	2.86
Fertiliser	23.1±10.11[b]	58.13	33.61±8.38[c]	51.06
FYM	0.02±0.07[b]	0.05	2.14±2.47[c]	3.25
Seeds	2.54±0.96[b]	6.39	9.24±0.98[c]	14.04
Equipment	0.71±0.27[b]	1.78	0.68±0.40[b]	1.03
Agrochemical	0.16±0.32[b]	0.40	1.91±0.64[c]	2.95
TOTAL	**39.74 ± 17.23**	**100.00**	**65.82 ± 9.11**	**100.00**
Form of energy				
Direct Energy[b]	12.25 ± 3.08	30.81	16.35 ± 4.04	24.84
Indirect Energy[c]	27.50 ± 9.61	69.19	49.47 ± 7.87	75.16
TOTAL	**39.74 ± 17.23**	**100.00**	**65.82 ± 9.11**	**100.00**
Renewable Energy[d]	3.81 ± 1.23	9.59	14.26 ± 2.92	21.66
Non-renewable Energy[e]	35.94 ± 11.15	90.41	51.56 ± 10.37	78.34
TOTAL	**39.74 ± 17.23**	**100.00**	**65.82 ± 9.11**	**100.00**

Mean ± Standard Deviation.
[a]Represents the % value of each input source to the total input energy.
$N = 51$ for Paddy–Wheat and N= 48 for Paddy–Potato cropping systems.
Mean followed by same letters are not significantly different in a row at $p \leq 0.05$.
[b]Indicates human labor, animal power electricity and fuel.
[c]Indicates seeds, fertiliser, manure, chemicals and machinery.
[d]Indicates human labor, animal power, seeds and manure.
[e]Indicates fuel, electricity, fertiliser, chemicals and machinery.

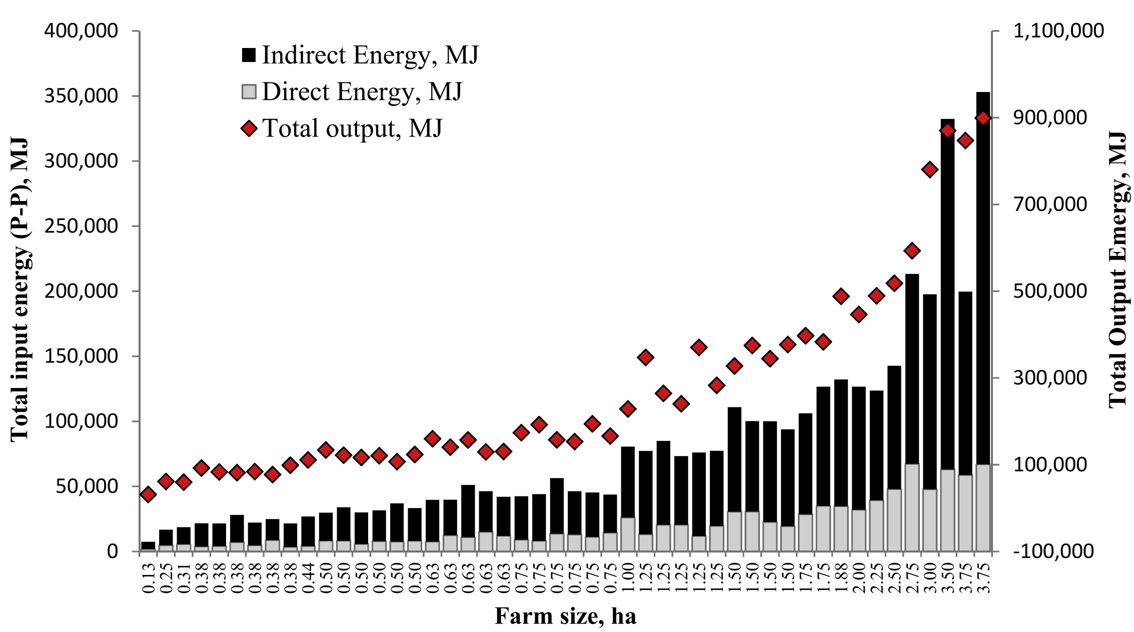

Fig. 2. Share of direct and indirect energy sources to total input energy, and output energy of Paddy–potato system.

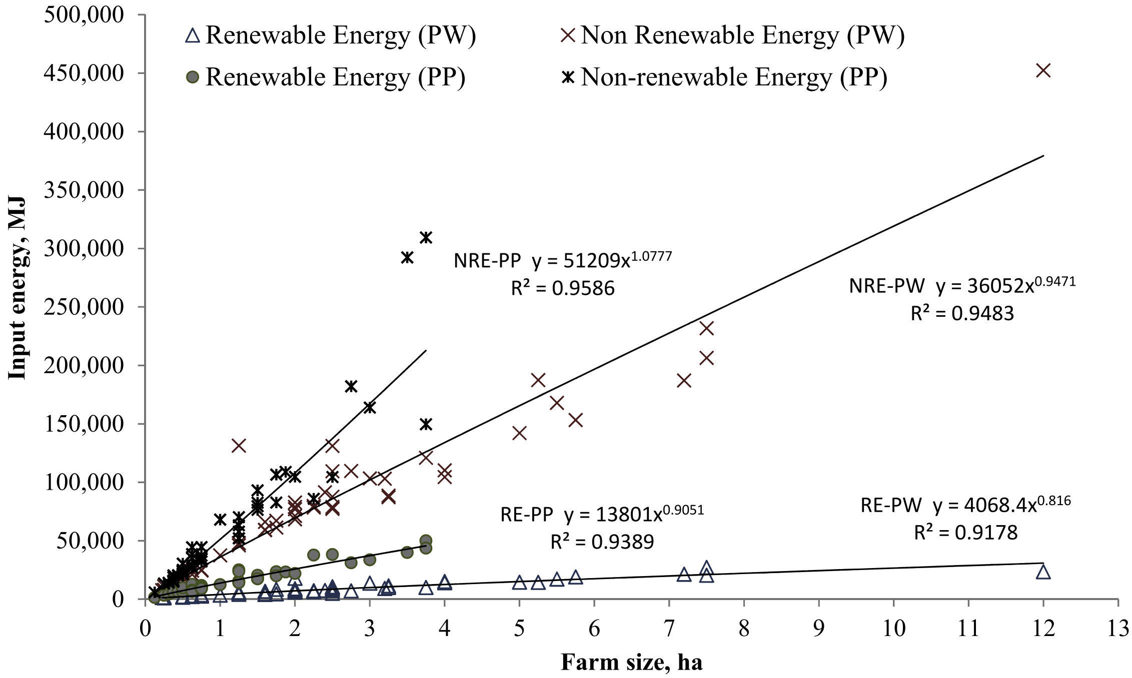

Fig. 3. Variations in input energy in the form of renewable and non-renewable energies with farm size.

Table 6
Energy output (GJ ha^{-1}) for the two cropping systems.

Output	Crop	Energy coeff.[a] (MJ kg^{-1})	Total-yield (kg ha^{-1}) (Paddy–Potato)	Total-yield (kg ha^{-1}) (Paddy–Wheat)	Total energy output (GJ ha^{-1})	Total energy output (GJ ha^{-1})
					Paddy–Wheat	Paddy–Potato
Grain	Paddy	14.7	6580.4	5033.8	250.89	236.95
	Wheat	14.7		3091.4		
Straw	Paddy	14.7	4364.2	5316.4		
	Wheat	14.7		3626.4		
Tuber	Potato	3.60	21,128.99			

[a]Source: Nassiri and Singh (2009); Hatirli (2006); Hamedani et al. (2011).
Field Survey, 2013.

is more efficient than the latter in terms of energy use. As far as the value of the EER_M is concerned, the two systems differed significantly, but the difference was not as high as in the case of EUE. The values were 3.94 ± 1.31 and 2.61 ± 0.47 for the PW and PP systems, respectively. The main products were considered to be grains (Paddy rice and wheat) and tubers (potatoes), with straw as the by-product. The values of SE also indicated the higher efficiency of the PW system (4.40 ± 2.08 MJ.kg^{-1}) compared to the PP system (2.16 ± 0.34 MJ.kg^{-1}). Other studies have reported different values for these energy indicators. Azarpour (2012) and Baruah et al. (2004) suggested an EUE for wheat crop of 2.47, which is less than the value reported in this study. This is because straw was not included in the output energy pool. Only one study (Dev, 2012) reported energy indicators of PW and PP cropping systems in the Indo-Gangetic plains; it reported an EUE value of 3.5 compared to the value of 6.87 reported in this study for the PW cropping system. The study was conducted based on the data from 2000–2004, and there has been a considerable increase in the productivity of cereal crops in the study area since then. Additionally, an increase in the use of mechanised methods for farm operations has lowered the human energy used in farming practices.

Fig. 4 shows the energy indicators for the two systems and the statistical comparison between their mean values at $p \leq 0.05$.

3.4. Economic return

The net return to the farmers was obtained as the difference between gross income and total input cost. Total input cost (USD.ha^{-1}.yr^{-1}) for the PP system was (1957.30 ± 240.84), which was notably higher than the input cost of (876.54 ± 273.17) for the PW cropping system. This significant difference between the input costs of the two systems can be attributed to the high cost and large quantity of potato seeds used in the PP system. Additionally, the PP system uses more fertiliser and agrochemicals compared to the PW system.

The net return was higher for the PP cropping system (2295.78 ± 457.42 USD.ha^{-1}.yr^{-1}) compared to the net return of the PW system (1555.4 ± 856.6 USD.ha^{-1}.yr^{-1}), but the ratio of net return to the net output was 1.8 in the latter compared to approximately 1.2 in the PP system. Fig. 5 shows the Paddy rice production for various farm sizes in the two systems. For the PW system, the production value tends to decrease gradually. With every increase in farm size, there is a reduced input to the production pool. The PP cropping system provides higher returns compared to the PW system because farmers can sell their crop to middle men who keep potatoes in cold storage so that they can sell them for a higher price later. For Paddy rice and wheat, the government operated Paddy rice purchase centres that are not easily accessible to farmers, who then had to sell their produce at a lower price to avoid waste, incurring an economic loss. The prevalent labour

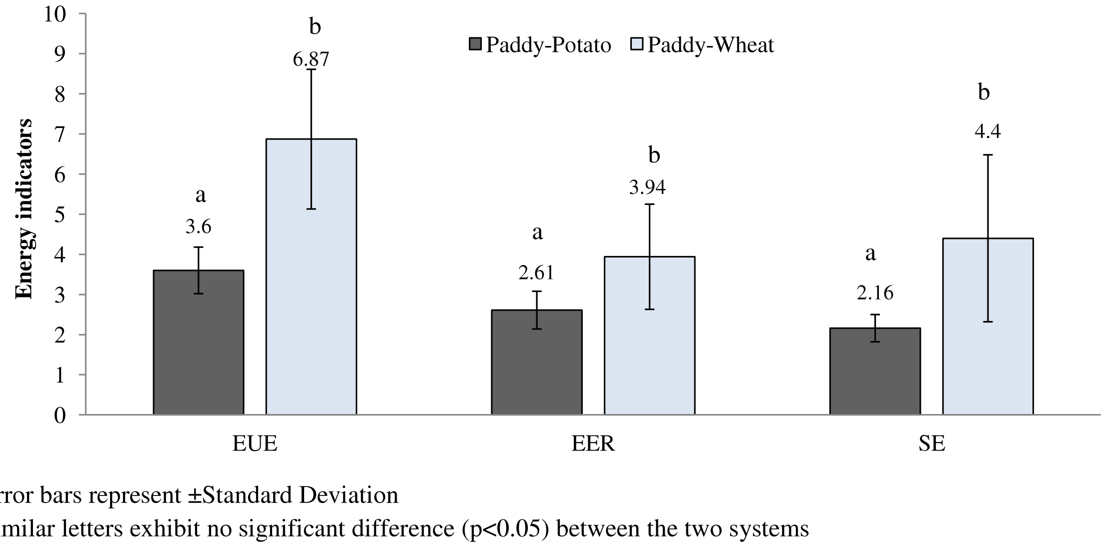

Fig. 4. Comparative analysis of the assessed energy indicators of the two systems.

wage system in the harvesting of cereal crops was also a factor in the lower economic return of the PW system. Due to various government employment schemes (Mahatma Gandhi National Rural Employment Guarantee Act), there is an acute labour shortage, and the available labourers bargain for higher wages. Based on survey responses, labour wages constituted about a quarter to one-third of the total expenses of the farmers. The economic return reported in the study is confirmed by very few of the previous studies (Singh, 2006; Muller and Sturm, 2001b; Soni et al., 2013) that focused on these crops in India. Singh (2006) and Muller and Sturm (2001b) assessed the net return from conventional and SRI (System of rice Intensification) methods of Paddy rice cultivation. SRI generated higher returns for the farmers due to higher yields. Prasannakumar and Hugar (2011) and OECD (1998) reported that the cost of the input energy for irrigated Paddy rice in India was 803 USD.ha^{-1}, while Cicek et al. (2011) and Saling et al. (2002) showed that the total cost for rain-fed wheat production was 1205 USD.ha^{-1} in Turkey.

3.5. Eco-efficiency

Eco-efficiency is expressed in terms of economic gain per unit energy inputs for a unit area (USD.GJ^{-1}). For the two cropping systems studied here, the eco-efficiency was 35.39 $\pm$ 8.07 for the PP system and 41.7 $\pm$ 23.9 for the PW system. The higher standard deviation value for PW system can be attributed to the high variation in terms of input resources, as compared to PP system.

Fig. 6 is a box-whisker plot for the various parameters assessed in the two systems. The variation of all the assessed parameters was higher for the PW system because in the same area, farmers practised different management practices, and there was a vast difference in their socio-economic status.

3.6. Effect of farm sizes

The effect of variation in farm size was assessed for all the parameters including energy source, energy indicators, net return and the eco-efficiency of the two systems. Table 7 summarises the values of these indicators for different farm sizes. The influence of farm size on EUE was also assessed and statistically analysed. In the PW system, the maximum EUE was found in the marginal farm category with an average value of 8.18. The EUE decreased as the farm size increased. For small land holdings, the EUE averaged 6.74 and was further reduced to 5.93 for the medium land holdings. The average farm size in the India is becoming smaller, and small land holdings are becoming predominant. In both the systems, a trend of increasing input energy was observed with the increase in farm size. Input energy in the form of human power decreased as the land size increased, which clearly reflects the dependency of farmers with small land holdings on human labour. In the study area, it was noted that use of family labour was higher in the small land holdings. A similar result for use of human power in different land holdings in the Indo-Gangetic plains was reported by Nassiri and Singh (2009) and Bohra (1998). The reduction in fuel use in the PW system as the size of land holdings increased can be attributed to the productive time in using mechanised equipment. Small farms clock more time per unit area (less productive time) compared to large farms owing to the time lost in turning (unproductive time) in the small holdings. The PP system exhibited a trend of increasing machinery and fertiliser use as the farm size increased. In the study area, it was observed that farmers were not following the recommended dose of fertilisers, and the actual fertiliser application was dependent on the financial condition of the farmers. Farmers with large holdings were usually financially strong and used more fertiliser on their farms. A similar trend was noticed for other resources. The values of energy indicators for the PP system did not differ significantly among the different farm sizes because similar management practices were followed by the farmers using this cropping system. For the PW system, interesting differences were observed in the values of energy indicators and net return to the farmers. The EUE value for the system decreased significantly with the increase in farm size, which can be attributed to the significant difference in the yields of Paddy rice and wheat crops as the farm size increased. The productivity of the farms increased with the increase in farm size, which occurred because of the difference in the farming practices. The small farmers followed conventional farming methods, while the farmers with large holdings tended to follow the SRI method of cultivation. The yield of Paddy rice was the highest in medium farms (5948.57 kg.ha^{-1}) and lowest in marginal farms (3572.65 kg.ha^{-1}). For small farms, the yield was slightly less than that of the medium farms (5291.67 kg.ha^{-1}). The ANOVA showed a significant difference among the Paddy rice yields of different farm sizes ($p \leq 0.05$). The net return for the farmers using the PP system increased with an increase in farm size because of the higher yield from the larger farm. The statistical analysis did not show any significant difference in the mean values. For the PW system, larger farms (small and medium categories) yielded significantly higher returns. No available recent

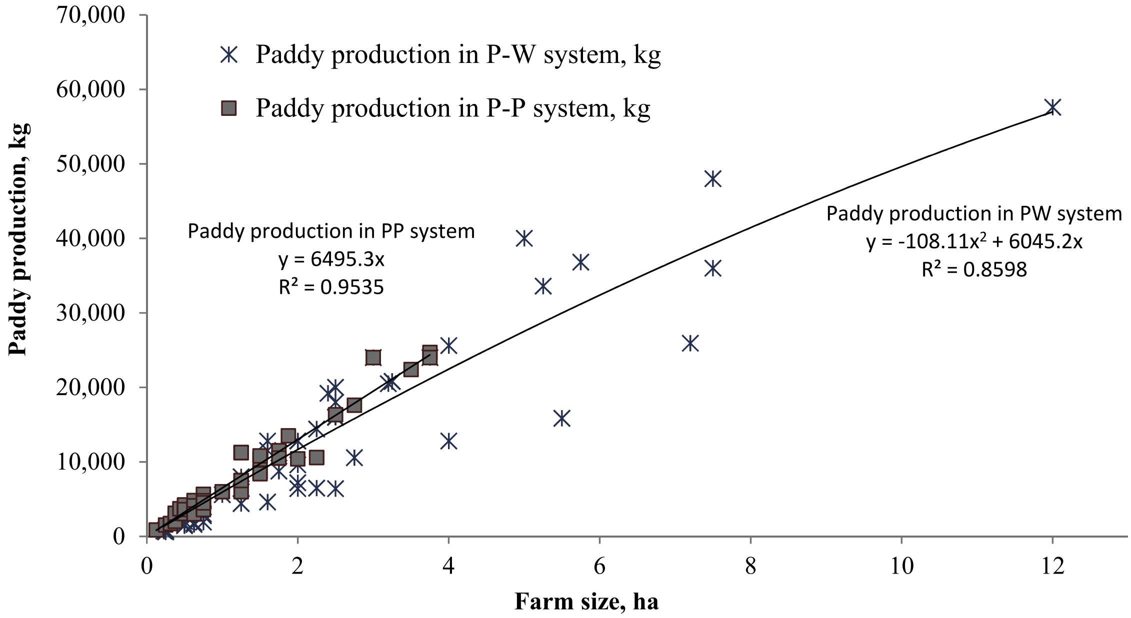

Fig. 5. Paddy production performance of the two systems.

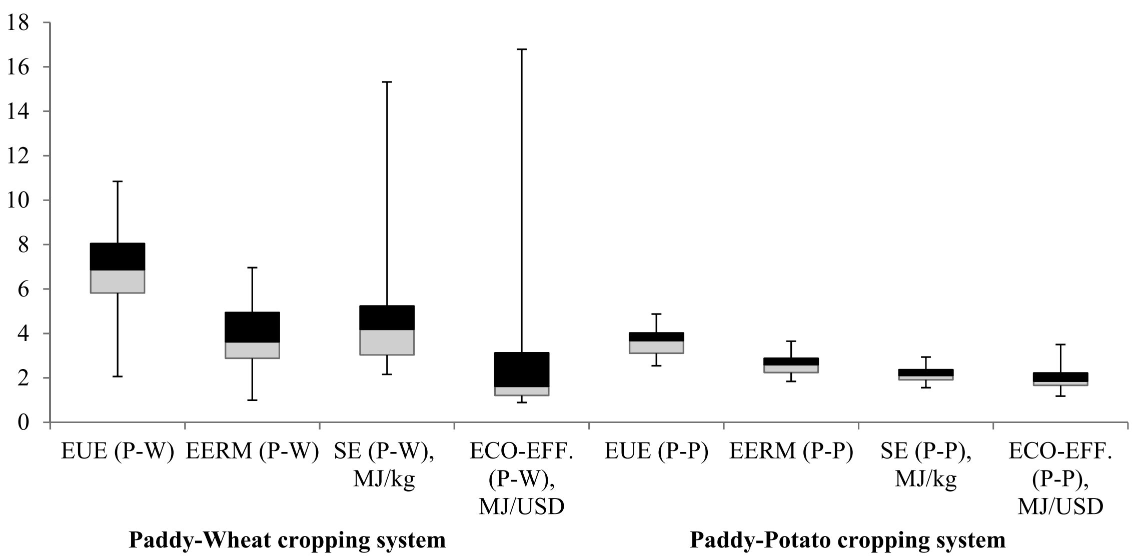

Fig. 6. Box-Whisker plot for the indicators assessed for the two systems.

study focused on the net return of a farming system in India. In the small farms (with low mechanisation), harvesting was carried out manually. Labourers demanded crops as their wages, which ranged from a quarter to one-third of the total produce of the farmers' fields. Larger farms (higher mechanisation) mostly used combine harvesters, and all the produce remained with the farmers. This, along with increased yield, was observed as the main reason for the significantly different net returns with increased land size in the PW cropping system.

For both cropping systems, the input energy increased with an increase in farm size. Marginal farms performed better with less input energy, 64,181.34 and 28,421.40 MJ.ha^{-1} for the PP and PW cropping systems, respectively. The input energy increased considerably, to 65,780.02 and 77,063.84 MJ.ha^{-1}, for the PP system in small and medium farms, although the mean value was significantly different at the 5% level. The same trend was observed in the PW system, and the input energy for small and medium farms were 45,075.40 and 48826.00 MJ.ha^{-1}, respectively. For the PW system, the EUE was highest for marginal farms (8.18), and it differed significantly from the small and medium farms (6.74 and 5.93, respectively).

The study revealed that the net return (USD.ha^{-1}.yr^{-1}) of the PP system did not vary significantly with farm sizes. For the PW system, the net returns varied significantly with farm size, with large farms performing better than small farms. The marginal farms had the lowest return of 632.99 USD.ha^{-1}.yr^{-1}. The small and medium farms yielded a total of 1744.83 and 2192.99 USD.ha^{-1}.yr^{-1}.

Eco-efficiency in USD.GJ^{-1} was sensitive to farm size in the PW system, but the mean values of eco-efficiencies in the PP system were not significantly different. For the PW system, marginal farms reported the lowest eco-efficiency (20.68 USD.GJ^{-1}) and the highest value was for medium farms (62.42 USD.GJ^{-1}).

Fig. 3 shows the dependency of the input and output energy on farm size with an $R^2 > 0.85$ generally.

Table 7
Source wise utilisation of energy (MJ ha^{-1}) and various energy indicators for the two systems for different farm sizes.

	Paddy–wheat			Paddy–potato		
	Farm sizes			Farm sizes		
Input energy(MJ/ha)	Marginal (<1ha)	Small (1-3ha)	Medium (>3ha)	Marginal (<1ha)	Small (1-3ha)	Medium (>3ha)
Human	1702.08^a	1269.86^b	800.48^c	2777.62^a	2263.28^b	1853.79^b
Animal	0	0	0	493.31^a	180.6^a	169.54^a
Fuel	9078.13^a	9221.83^a	7658.95^a	10208.4^a	9218.81^a	13323.3^a
Electricity	2065.95^a	1895.68^a	2995.53^a	2155.53^a	5704.68^b	1520.38^a
Machinery	1188.03^a	934.98^b	820.94^b	1805.65^a	1952.06^a	2130.01^a
Fertiliser	21542.0^a	27342.3^b	17278.1^c	32112.44^a	33107.01^a	45818.49^b
Chemicals	141.54^a	164.52^a	175.13^a	1985.33^a	1829.8^a	1774.45^a
Manure	0^a	33.44^a	2.86^a	2581.03^a	1764.00^a	750.00^a
Seeds	2943.2^a	2492.19^a	2263.34^a	9289.85^a	9194.62^a	9135.2^a
Equipments	684.20^a	696.85^a	765.91^a	772.22^a	564.98^a	588.66^a
Total	28421.40^a	40576.40^b	48826.00^b	64181.34^a	65780.02^a	77,063.84^b
No. of Farmers	13	24	14	27	17	7
Energy Indicators						
EUE	8.18^a	6.74^a	5.93^b	3.66^a	3.67^a	3.39^a
EER_M	7.51^a	6.38^a	7.26^a	2.7^a	2.55^a	2.37^a
SE	5.36^a	4^a	4.15^a	2.09^a	2.18^a	2.43^a
Other Parameters						
Net-Return (USD/ha)	632.99^a	1744.83^b	2192.99^c	2242.81^a	2559.65^a	2587.96^a
Eco-Efficiency (MJ/USD)	83.06^a	27.13^b	18.23^c	30.77^a	28.42^a	29.58^a

Note: Different letters with mean show significant difference in the means values at 5% level within a cropping system.

4. Conclusions

This study attempted to explain the intricacies of two of the most used cropping systems of the Indo-Gangetic plains of India based on their energy and economic performance. The PW system was more energy efficient with higher values of energy indicators in the system compared to the ones in the PP system. The EUE value for the PW system (6.87) was higher than that of the PP system (3.6). Similarly, the EER_M and SE values were higher in the PW system. The total input energy for the PW and PP systems were 39.74 ± 17.23 GJ/ha and 65.82 ± 9.11 GJ.ha^{-1}, respectively. The net return for the PW and PP systems was 876.54 ± 273.17 USD.ha^{-1}.yr^{-1} and 1957.30 ± 240.84 USD.ha^{-1}.yr^{-1}, respectively. The total output energy was also higher in PW system (250.89 GJ/ha) compared to the PP system (236.95 GJ.ha^{-1}).

The following conclusions can be drawn from this study:

(a) The use of fuel as a source of energy was higher in the PW system (22.02%) compared to the PP system (15.37%), which was due to the higher use of renewable energy, which accounted for 9.59% and 21.66%, respectively, in the two systems. Fertiliser use accounted for the highest energy consumption with a total contribution of 58.13% and 51.06%, respectively, in the PW and PP systems. There was no use of animal power reported in the PW system.

(b) The yield of Paddy rice was higher (6580.4 kg.ha^{-1}) in the PP system compared to the PW system (5033.8 kg.ha^{-1}). Additionally, a better price for the potato crop helped farmers to obtain higher net returns in the PP system.

(c) The lowest input energy was reported in marginal farms and the highest in medium farms in both the systems. It was also observed that smaller farms were more energy efficient compared to larger farms in terms of various energy indicators.

(d) The use of fertiliser was highest in the small farm category in the PW system while it was highest in the medium farm category for the PP system. Farm-yard manure use was highest in the medium farm category and lowest in the marginal farm category for the PP system, whereas for the PW system, the use of FYM was minimal.

(e) The use of human power tended to decrease with the increase in farm size in the PW system, exhibiting increasing dependence on mechanised means of farming as farm size increased.

(f) The larger farms had higher economic returns compared to the smaller farms in both systems, but the mean values for net return were significantly different only in the PW system.

(g) The eco-efficiency values were higher for larger farms in the PW system, and the mean values differed significantly, whereas for the PP system, no obvious trend was observed.

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