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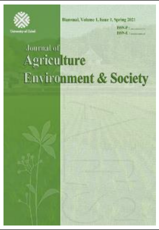

Energy use analyses in Iranian wheat project

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ABSTRACT

The study attempts to analyze the energy input-output relationship during Iranian wheat project from 1990 to 2005. The main sources of evidence for this investigation were obtained from the related companies and different departments of Iran Ministry of Jihad–e–Agriculture including Library. Findings revealed that total energy inputs and output have increased from 26503.5 and 20871.5 MJ ha^{-1} in 1990 to 35466.3 and 30259.8 MJ ha^{-1} in 2005, indicating a 25.27 and 31.03% increase, respectively. Averagely data collection (under both irrigated and dryland conditions), diesel had the highest share, of 37.08%, followed by electricity (21.23%), chemical fertilizers (20.21%), water (8.39%), seed (7.94%), machinery (2.33%) and human labor (2.18%), respectively. There was a significant increase in electricity usage (about 74% increase), and an associated decrease in the diesel usage (about 34% decrease) during 1990-2005 period because electric pumps replaced diesel pumps. Chemical fertilizers rose from 4353.25 to 8659.80 MJ ha^{-1}. In the studied period, the share of nitrogen and potassium in the total fertilizer energy input increased from 72.00 to 84.79% and from 0.00 to 0.65%, respectively, while the share of phosphorus shrunk from 28.31 to 14.56%. There were not significant changes regarding the human labor and machinery annually and seedbed preparation required the maximum energy, followed by harvesting. Pesticides increased extensively in the last year under study, particularly in case of herbicides, and of which 2,4-D/MCPA and Clodinafop-propargyl had the highest share. Values of energy use efficiency (0.70-1.00), specific energy (14.70-21.04 MJ kg^{-1}) and energy productivity (0.05-0.07 kg MJ^{-1}) showed an intensive use of inputs not accompanied by increase in output during wheat project. Most of the total energy inputs were supplied in the non-renewable and direct forms. Also, regression analysis indicated the impact of indirect and non-renewable energy on output was statistically significant.

Highlights

- Total energy inputs and outputs for Iranian wheat production rose significantly between 1990 and 2005.
- Diesel fuel consumption decreased, while electricity usage increased due to the replacement of diesel pumps for irrigation.
- Pesticide use, particularly herbicides, increased substantially in the last year of the study.
- Despite increased energy inputs, output growth did not keep pace, indicating inefficient energy use in the Iranian wheat project.

1. Introduction

Wheat is a strategic crop that has always been the focus of farmers and governments due to its importance in providing food security worldwide as well as Iran. Wheat (total production~ 0.8 billion tons) ranks second after maize (total production~1.16 billion tons) in the world cereal output and it is a staple food for billions of people of the world (FAO, 2023). It is also the most important winter

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cereal grown in Iran (Zand et al., 2007) which contains significant amounts of important nutrients including carbohydrates, proteins, fiber, and minor components including lipids, vitamins, minerals, and phytochemicals which may contribute to a healthy diet (Shewry and Hey, 2015). Wheat is grown under both irrigated and dryland conditions throughout Iran which had higher share of cultivated area than other species (field crops and trees). In general, climate of Iran is mainly dry and warm (Deihimfard et al., 2023). Temperature and precipitation vary with elevation, as winds bring heavy moisture from the Persian Gulf. The Caspian region receives over 40 in. (102 cm) of rain annually. Precipitation occurs mainly in the winter and decreases from northwest to southeast; much of the precipitation in the mountains is in the form of snow. Meltwater is vital for Iran's water supply. The central portion of the plateau and the southern coastal plain receive less than 5 in. (12.7 cm) of rain annually. The country is divided into 31 provinces and 6 regions including arid, semi-arid, Mediterranean, semi-humid, humid, and very humid (Fathi Taperasht et al., 2022). Cultivars of wheat commonly grown in different regions of Iran are listed in alphabetical order as follows: Adl, Alamoot, Alborz, Alvand, Aqua, Argentin, Arvand, Ataei, Atrak, Azadi, Azar, Bakanora, Barekat, Bayat, Bezostaya, Bistoon, Bulani, Chamran, Chenab, C–V3–5, Darab, Dastjerdi, Dehqan, Deihim, Derakhshan, Dez, Falat, Faravan, Firoozeh, Gaskugen, Gaspard, Golestan, Hirmand, Inia, Italyai, Javanjani, Jolgeh, Kalar, Karaj, Kaveh, Kavir, Khalij, Khazar1, Kouhrang, Kouhsar, Mahdavi, Maroon, Marvdasht, Molqani, Moqan, MV–17, Navid, Naz, Niknejad, Omid, Panjamou, Pastour, Pishtaz, Qermezak–e–Varamin, Quds, Rashid, Rasoul, Reihani, Roshan, Saba, Sabalan, Sardari, Sefidak, Shahi, Shahpasand, Shiraz, Shiroodi, Sholeh, Simineh, Star, Tabasi, Taban, Tajan, Tobari, Yavarous, Zarandi, Zarrin.

A national project on wheat production was launched in 1990, the main aim of which was to increase wheat production in Iran in order to be able to cover local demand and minimize imports. In 2002, authorities introduced a new law to facilitate the domestic production of wheat. According to this law, self–sufficiency should be reached during the next 10 years and demand and supply should become equal. Under this law, increasing the yield per area is the main tool to reach self–sufficiency (Deihimfard et al., 2007).

The analysis of energy flows provides us with very relevant information for understanding the type of relationship that each society has established with the natural environment that sustains it. It also provides useful information in understanding the ways in which the land is used and the capacity to satisfy their inhabitants needs (Imran and Ozcatalbas, 2021). Moreover, analyzing energy input flows into agricultural systems can improve energy use efficiency by knowing more details about each input and their contribution in the total energy input entering the farm. Energy use in agricultural production has been increasing faster than that in many other sectors of the world economy because agricultural production has become more mechanized, and use of substitutes for land, such as commercial fertilizers, has increased (Karkacier and Goktolga, 2005; Amiri et al., 2019; Eyni-Nargeseh et al., 2023). Energy use can be divided into direct and indirect. Direct energy use is energy input used in production when such input can be directly converted into energy units (e.g. diesel–fuel, lubricants and electricity for irrigation and drying). Indirect energy use is energy used in the production of inputs used in production when such inputs cannot be converted directly into energy units (e.g. machinery, fertilizers, and pesticides) (Soni et al., 2018; Htwe et al., 2021; Soltanzadeh and Ahmadpour Borazjani, 2022).

The current policy within agriculture seeks to develop crop production systems that minimize energy input mainly fossil fuels for a high level of output. In this respect, the energy balance is important. Energy balance is the numerical comparison of the relationship between input and output of a system or agricultural business in terms of energy units. The main objective of this study was to investigate the energy use patterns and to analyze energy input–output in Iranian wheat project from 1990 to 2005, as overall energy savings and energy efficiency are main factors in agricultural production.

2. Materials and methods

The data used in this study were based on annual data for the period 1990–2005 and were obtained from numerous sources. The main sources of evidence for this investigation were obtained from the related companies and different departments of Iran Ministry of Jihad–e–Agriculture including Library, Deputy of Planning & Economic Affairs, Bureau of Statistics & Information Technology, Deputy of Industries & Infrastructural Affairs, Bureau of Irrigation Networks Development, Bureau of wheat project, Agricultural Mechanization Development Center, Plant Protection Organization, and Agricultural Support Services Company.

Data concerning the amount of electricity, water and fuel used and wells information were obtained from the two companies of Iran's Ministry of Energy, Tavanir Holding Company, and Iran Water Resources Management Specialized Mother Company and from National Iranian Oil Refining & Distribution Company. Further data were come from personal contacts, oral interviews and statistical yearbooks. The study has also benefited from previous researches and studies conducted on energy analysis for different crops in Iran.

First, all inputs and outputs for wheat production under both irrigated and dryland conditions were determined, quantified and entered into Excel spreadsheets, and then, transformed into energy units and expressed in MJ ha^{-1}. The energy equivalents of the inputs and output are shown in Table 1. Data in Table 1 were derived from several sources. Owing to the fact that their respective data were not available, the input from animal labor and from the sun, and output from the straw yield was not included.

Data on total fuel consumption for wheat production were available, but their use in different operations was not clear. Thus, the results of the previous researches conducted in Iran (Hassan–Zadeh–Ghorttapeh et al., 2001; Roozbeh et al., 2002; Haidar–Gholi–Nezhad–Kenari and Hassan–Zadeh–Ghorttapeh, 2003; Sharifi–Ashorabadi et al., 2004; Valdiani et al., 2005; Kohansal and Yazdani, 2006; Komarizade, 2007) were used for the estimation of the duration of tractor and combine usage and diesel requirements. Based on these studies, the values of aforementioned parameters for land preparation, sowing, cultural practices, and harvesting–threshing were 6.1 h and 46.5 l, 0.2 h and 0.5 l, 0.5 h and 1.6 l, and 0.6 h and 20 l, all on ha basis, respectively. Thereafter, total hours and diesel requirements were calculated separately by multiplying percentage of land–area subjected to these mechanical operations by their corresponding values. In their study on energy input–output analysis for crop production in Iran, Gholami and Sharafi (2006) showed that annual energy spent for tractor manufacturing and repair was around 150 MJ ha^{-1}. In the present study, this value was calculated as a part of fuel consumption using conversion factor (52.055 MJ = 1 l diesel ha^{-1}). Gholami and Sharafi (2006) used methodology of Ozkan et al. (2004). The fuel requirements of water pumps (diesel engines) were calculated as total fuel consumption minus fuel consumption in all the above-mentioned mechanical operations.

The assessment of the amount of electricity (all electricity are posited to come from fossil energy sources) used per ha was computed by dividing total electricity power used in agriculture by total cultivated land–area. Almost all electricity power is used by electrical engines for irrigation.

The energy required to manufacture the majority of the pesticides applied were not available directly, although Green (1987) provides values for 24 herbicides, 4 fungicides and 11 insecticides. In accordance with Tzilivakis et al. (2005), the values provided by Green (1987) for specific pesticides were assigned to their chemical group (Table 2). Where there was more than one value for a group, the mean was taken. Those herbicides that did not belong to one of the chemical groups in Green's study were assigned based on value of herbicides from Table 1.

Energy use efficiency was computed by dividing energy output (MJ ha^{-1}) by energy input (MJ ha^{-1}), specific energy was calculated by dividing energy input (MJ ha^{-1}) by grain output (kg ha^{-1}), and energy productivity was obtained by dividing grain output (kg ha^{-1}) by energy input (MJ ha^{-1}) (Mandal et al., 2002).

The input energy was divided into direct, indirect, renewable and nonrenewable forms (Hatirli et al., 2005; Yilmaz et al., 2005; Erdal et al., 2007). Indirect energy consists of the seeds, pesticides, chemical fertilizers, farmyard manure, machinery and direct energy including human labor, diesel and electricity energy used in the wheat production process. On the other hand, non–renewable energy includes diesel, electricity, pesticides, chemical fertilizers, machinery and renewable energy consists of human labor, seeds and farmyard manure.

Due to the fact that wheat is grown under both irrigated and dryland conditions throughout Iran and some energy sources such as insecticides were inseparable between these two conditions and also to avoid a long article and in order that results can be presented as precisely as possible, weights were assigned for each energy source type and weighted averages between the two conditions were calculated according to the area cultivated by each farming system. Multiple regression analysis was performed with 15 years data using PROC REG, Maximum R–Square Improvement Selection Method, in SAS program (SAS version 9.00, SAS Institute Inc., Cary, NC, USA). In the regression analysis, seed yield (kg ha^{-1}) was the dependent variable and other energy sources (MJ ha^{-1}) were considered as independent variables.

3. Results and discussion

3.1. Changes in energy inputs over time

Based on information presented by various sources e.g. (Fathi Taperasht et al., 2022), due to the climatic diversities in Iran, agricultural practices including soil tillage, seedbed preparations, sowing, cultural practices, and harvest during wheat production are applied throughout year. In general, sowing and harvest performed from September until February, and from April to September, respectively in different provinces of Iran. Seeds of different cultivars mentioned in part of introduction are supplied by the related companies and different departments of Iran Ministry of Jihad–e–Agriculture such as Agricultural Support Services Company (ASSC), and Seed and Plant Improvement Institute (SPII), and planting is realized under the supervision of them.

Energy consumption (MJ ha^{-1}) for each item and energy input–output relationships during Iranian wheat project are illustrated in Table 3.

The averages of 1990–2005 for inputs used in wheat production, output and energy equivalences are illustrated in Table 4.

Throughout the period 1990–2005, Iranian wheat project has experienced significant changes in terms of chemical fertilizers (particularly nitrogen), farmyard manure, pesticides, diesel, and electricity usage (Table 3). Table 4 shows that diesel had the highest share, of 37.08%, followed by electricity (21.23%), chemical fertilizers (20.21%), water for irrigation (8.39%), seed sown (7.94%), machinery (2.33%) and human labor (2.18%), respectively. The energy inputs of farmyard manure and pesticides were found to be quite low compared to the other inputs used in production. Singh et al. (2002; 2003; 2004) concluded the major share of source–wise total energy input for cultivating the wheat is contributed through electricity, diesel and fertilizers as 0.3–26.0%, 22.6–26.0%, and 22.5–50.6%, respectively. In their research, the electricity and diesel contribute about 50% of the total energy consumed and the shares of seeds, farmyard manure, human and machinery energy of the total energy were 9.9–12.9%, 3.2–8.6%, 4.5–6.2% and 2.1–2.4%, respectively. Pervanchon et al. (2002) reported the share of fertilizers, pesticides, seeds and machinery production considered for the indirect energy in wheat crop were 31–81%, 3–4%, 6–7% and 12–69%, respectively.

3.2. Energy Sources Contribution

In Iran, an average 213.72 l ha^{-1} diesel was used in wheat production (Table 4) which was about 64 l ha^{-1} higher than value reported by Sayin et al. (2005) for wheat production in Turkey. The energy use in irrigated wheat is heavily dependent on diesel fuel, since most pumps used for irrigation are powered by diesel engines in Iran. Therefore, most diesel fuel consumption is for irrigation (about 54%). Singh et al. (2003) found that the diesel energy was mainly utilized for operating tractors for performing various farm operations.

One of the particularly remarkable findings, presented in Table 3, was a strong and significant increase in electricity usage (about 74% increase), and an associated decrease in the diesel usage (about 34% decrease) in 2005 compared with 1990. The increase in electricity energy use (especially from 1998 onwards) mainly resulted from an annual increment of 6900 in the number of electrified wells and from increment in the wells' depth (Figure 3). Groundwater is estimated to constitute more than 70% of the total volume of irrigation water used in Iran for wheat production and other crops (of which about 70% is from semi–deep and the remaining 30% from deep wells).

Due to national benefits, there was a shift in policies from 1998 toward increasing the number of electrified wells, so that number of these wells reached 124984 in Iran in 2004–2005 which used about 20320530940 kWh (162585.06 kWh per each well). This electricity usage in provinces of Iran which have light precipitations such as Semnan, Khorasan (Mashhad) and Kerman (Figure 1) (2593443.20, 464488.21 and 402497.25 kWh per each well, respectively) was higher. In Iran, particularly in above-mentioned provinces, due to decrease in aquifer water–capacity and decline in groundwater table at an average rate of 1 m every year, farmers attempted to deepen their wells with the expectation that well–water yield would increase and as a result energy usage and costs would be increased. As can be seen in Figure 3, a huge gap exists between total number of wells (with diesel and non–diesel engines) and of electrified wells that must be narrowed.

There is a large range of positive outcomes from electricity rather than diesel use for pumping water. This would save energy, reduce waste and pollution, and reduce costs. Other benefits are reducing groundwater use by identifying and forbidding the wells activity without license as electricity amount can be measured and controlled. In a research by Feiz Bakhsh et al. (2019), they stated that substituting electricity instead of fossil fuel for irrigation reduces energy consumption in farms, and irrigation is performed more easily.

Annual water quantity used during Iranian wheat project was about 4000 m^3 ha^{-1} (Table 4). Gül et al. (2005) by a case study in Syria found values of water consumption for wheat production varied from 3800 to 8300 m^3 ha^{-1}. The volume of water consumption increased until 1999–2000, and from it time onwards decreased (Table 3).

The main factors responsible for this upward and downward trend are increasing the cultivated area (Figure 1) which have caused a decreasing proportion of water consumption per ha (due to water restriction resulted from aquifer depletion in water–scarce areas), and growth of optimized irrigation systems such as sprinkler, center–pivot and wheel move irrigation systems from 108.00 in 1990 to 20853.17 ha in 2005 which showed an improvement in yield and efficiency with the smaller amounts of water that can be applied using these irrigation systems.

Results of Ines et al. (2006) showed that under limited water condition, regional wheat yield could improve further if water and crop management practices are considered simultaneously and not independently. Unfortunately, increasing the cultivated area for wheat production especially from 2003–2004 (roughly coincident with the beginnings of new facilities and other supporting policies which were geared towards expanding wheat production) onwards (Figure 2), unlike general aims of sustainable agriculture (including sufficient food and fiber production, environmental stewardship, economic viability and social justice), has destroyed natural or semi–natural ecosystems such as rangeland, woodland, hedges, etc. so on that can harbor a great number of different plant and animal species. While there is a need to expand the supply of wheat output in general, to feed a growing population in Iran, as much as it, stewardship of natural and semi–natural ecosystems is essential.

The total chemical fertilizers rose from 4353.25 to 8659.80 MJ ha^{-1}, or by nearly 50%. Nitrogen is the most significant fertilizer and its consumption increased around 2.35–fold in the studied period, with an annual average of 84.98 kg ha^{-1}. Nitrogen is followed by potassium and phosphorus and the annual average consumption of phosphorus and potassium was realized as 79.11 and 2.71 kg ha^{-1}, respectively (Table 4).

For the same period, the share of nitrogen and potassium in the total fertilizer energy input increased from 72.00 to 84.79% and from 0.00 to 0.65%, respectively, while the share of phosphorus shrunk from 28.31 to 14.56%. Nitrogen is one of the important inputs entering farms and plays a significant role in the emission of greenhouse gases (Shrestha et al., 2020).

In previous research, Sayin et al. (2005) indicated in the last decade, nitrogen fertilizers account for more than 60% in total fertilizer consumption for wheat production in Turkey. In a Dutch study, total nutrient energy requirement for wheat production was reported to be about 12.5 GJ ha^{-1} (Brehmer et al., 2008).

The application of small volumes of farmyard manure comprised an insignificant portion of the energy input to wheat grown in Iran (Table 4). The large energy required for the manufacture of fertilizer, in particular nitrogen, or the application of small volumes of farmyard manure reduces the overall sustainability of the system; while manure and organic fertilizers are a suitable alternative to chemical fertilizers and can significantly reduce energy consumption in agricultural systems and have positive effects on the agroecosystems (Mc Laughlin et al., 1997). In this regard, Jiang et al. (2021) concluded that applying organic fertilizers such as compost and biochar had lower environmental effects compared to chemical fertilizers.

In general, there were not significant changes regarding the human labor and machinery year by year. In Iran, number of various machines such as tractors and combine harvesters has increased for wheat production in recent years, but due to increasing the cultivated area, the share of mechanical power per area unit stayed almost constant. However, as can be resulted from Table 3, relatively negative relationships existed between human labor and machinery (r = –0.36) which is consistent with findings of Ozkan et al. (2004b) and Hatirli et al. (2005).

Based on the evaluation of data collected, average human labor required in wheat project was 303.20 h ha^{-1}, and machine power was 11.17 h ha^{-1}. Approximately 94.54% of total machine power was consumed for land preparation consists of plowing, disc operating and leveling, 0.54% was for sowing, 0.90% was for other cultural practices mainly including fertilizer application and spraying, and 3.94% was for harvesting–threshing (Table 4). Canakci et al. (2005) stated that out of all the farm operations for wheat production, seedbed preparation required the maximum energy (65.1%), followed by harvesting (22.9%).

Energy from seed was calculated on average 2383.05 MJ ha^{-1} (Table 4) and increased almost 9.50% in the examined period (Table 3).

Figure 1. Different provinces of Iran for wheat production.

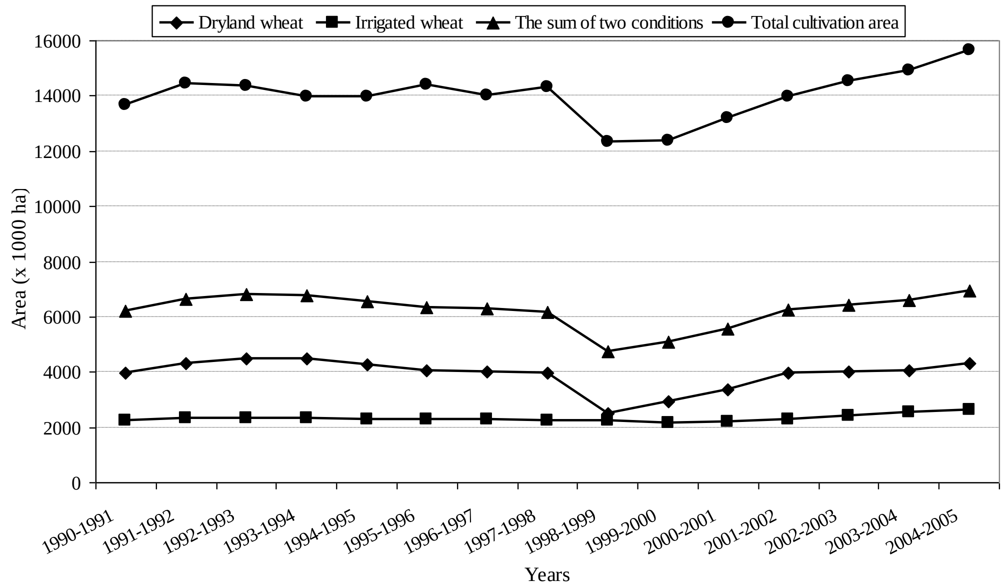

Figure 2. Total cultivation area, and farm area for dryland and irrigated wheat during Iranian wheat project (1990–2005).

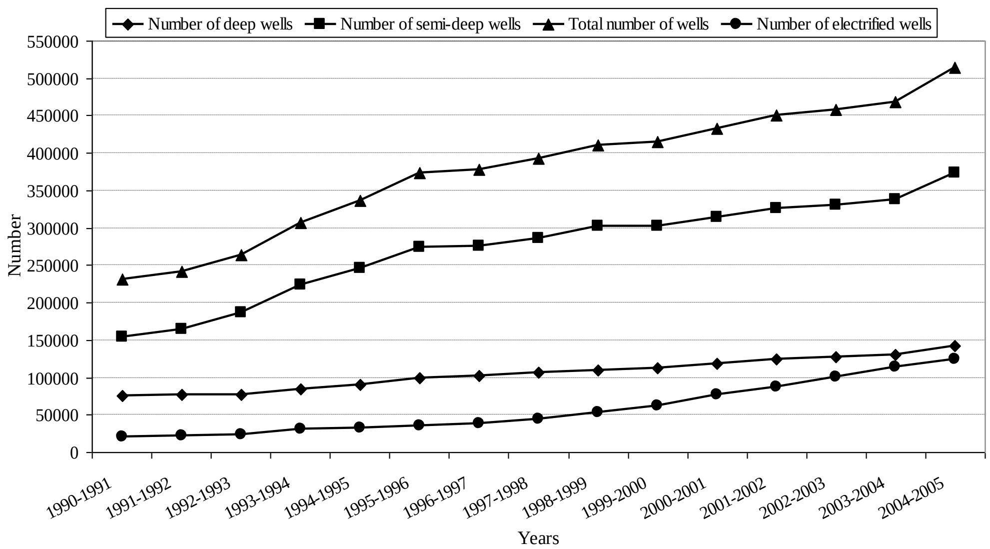

Figure 3. Number of deep, semi–deep and electrified wells during Iranian wheat project (1990–2005).

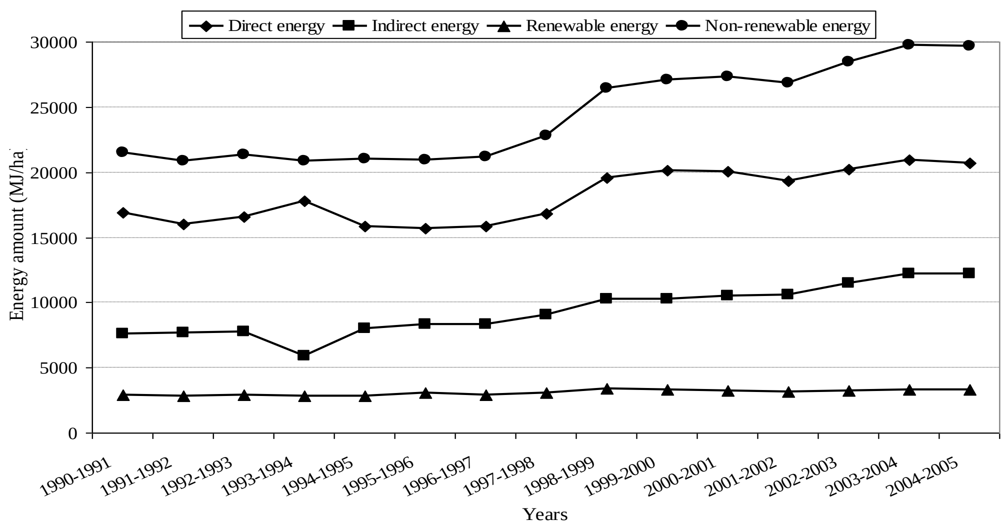

Figure 4. Direct, indirect, renewable and non–renewable energy during Iranian wheat project (1990–2005).

Table 1. Energy equivalences of inputs and output

Energy source	Unit	MJ unit^{-1}	References and remarks
Inputs			
Human labor	h	2.153	The mean of values was presented by Hatirli et al. (2005), Erdal et al. (2007), Strapatsa et al. (2006)
Machinery	h	62.700	Erdal et al. (2007)
Diesel	l	52.055	The mean of values was presented by Erdal et al. (2007), Canakci et al. (2005)
Electricity	kWh	10.590	Canakci and Akinci (2006)
Fertilizers	kg		
Nitrogen (N)		58.106	The mean of values was presented by Hatirli et al. (2005), Erdal et al. (2007), Canakci et al. (2005), Strapatsa et al. (2006), Canakci and Akinci (2006), Sartori et al. (2005), Deike et al. (2008)
Phosphorus (P_2O_5)		13.971	The mean of values was presented by Hatirli et al. (2005), Erdal et al. (2007), Canakci et al. (2005), Strapatsa et al. (2006), Canakci and Akinci (2006), Sartori et al. (2005), Deike et al. (2008)
Potassium (K_2O)		7.947	The mean of values was presented by Hatirli et al. (2005), Erdal et al. (2007), Canakci et al. (2005), Strapatsa et al. (2006), Canakci and Akinci (2006), Sartori et al. (2005), Deike et al. (2008)
Farmyard manure (FYM)	tons	303.100	Erdal et al. (2007)
Pesticides	kg		
Insecticides		199.733	The mean of values was presented by Erdal et al. (2007), Sartori et al. (2005), Deike et al. (2008)
Fungicides		206.000	The mean of values was presented by Erdal et al. (2007), Deike et al. (2008)
Herbicides		267.667	The mean of values was presented by Erdal et al. (2007), Sartori et al. (2005), Deike et al. (2008)
Others		120.000	Canakci and Akinci (2006)
Water	m^3	0.630	Erdal et al. (2007)
Wheat seed sown	kg	15.700	Canakci et al. (2005)
Output			
Wheat grain yield	kg	14.700	Canakci et al. (2005)

Table 2. Energy (MJ kg^{-1}) required for the manufacture of pesticides (based on values from Green, 1987)

Pesticide	Group	Energy
Insectcides		
Fenitrothion	Organophosphate	[a]229
Deltamethrin	Pyrethroid	[a]580
Fenthion	Organophosphate	[a]229
Trichlorfon	Organophosphate	[a]229
Herbicides		
Broadleaf herbicides		
Bromoxynil/MCPA	Hydroxybenzonitrile/Phenoxy	[d]199
2,4–D/MCPA	Aryloxyphenoxy alkanoic acid	[b]108
2,4–D	Aryloxyphenoxy alkanoic acid	85
Tribenuron–methyl	Sulfonyl urea	[a]365
Bromoxynil	Hydroxybenzonitrile	[e]268
Dichlorprop–P/Mecoprop–P/MCPA (DMM)	Aryloxyphenoxy alkanoic acid	[b]108
Triasulfuron/terbutryne	Sulfonyl urea/Triazinone	[c]278
Grass herbicides		
Diclofop–methyl	Aryloxyphenoxy alkanoic acid	[b]108
Fenoxaprop–P–ethyl	Aryloxyphenoxy propionic acid	[b]108
Clodinafop–propargyl	Oxyphenoxy acid	[e]268
Tralkoxydim	Oxime	[e]268
Difenzoquat	Amide	[e]268
Flamprop–M–isopropyl	Arylalanine	[e]268
Dual–purpose herbicides		
Mesosulfuron–methyl/iodosulfuron–methyl (MI)	Sulfonyl urea	[a]365
Sulfosulfuron	Sulfonyl urea	[a]365
Imazamethabenz–methyl	Imidazolinone	[e]268

[a] The values were assigned to their chemical group.
[b] The mean of values of 2,4–D and MCPA.
[c] The mean of values of Chlorsulfuron and Atrazine.
[d] The mean of values of Bromoxynil and MCPA.
[e] The value of herbicides is given in Table 1.

3.3. Energy Use Efficiency

On the other hand, energy use efficiency varied from 0.70 in 1999–2000 to 1.00 in 1997–1998, specific energy (MJ kg^{-1}) from 14.70 in 1997–1998 to 21.04 in 1999–2000, and energy productivity (kg MJ^{-1}) from 0.05 to 0.07 (Table 3). As seen in previous researches, energy use efficiency, specific energy (MJ kg^{-1}) and energy productivity (kg MJ^{-}

[1]) varied from 1.00 to 7.50, from 2.74 to 11.40 and from 0.00 to 0.15, respectively (Mandal et al., 2002; Singh et al., 2002; Singh et al., 2003; Singh et al., 2004; Canakci et al., 2005; Singh et al., 1999; Singh et al., 2007; Venturi and Venturi, 2003; Ramachandra, T.V., Nagarathna, 2001; Ozkan et al., 2004a; Christersson, 2008). It can be seen from the presented values that the output did not increase as much as in energy input use during Iranian wheat project and wheat productivity in Iran is still lagging behind the world's average. The Food and Agricultural Organization of the United Nations (FAO) reported that in many countries average wheat yields for the period 1996–2000 were below the agro–ecologically attainable yield levels. For example, in India, Argentina, Brazil, Ethiopia, Tanzania and Turkey, wheat yields were calculated to be 45%, 57%, 54%, 30%, 50% and 44%, respectively, of the attainable yield. Several industrialized regions also had yields that were below the agro–ecologically attainable yield levels, such as Australia and the USA, where the average wheat yields were 48% and 47% of the attainable yield, respectively (Smeets et al., 2007).

In order to understand better the direction of agricultural energy use, it is important to investigate the tendency of energy forms. For this purpose, energy input as direct, indirect, renewable and non–renewable forms used during Iranian wheat project were also examined. As can be seen from cure 4, for wheat production most of the total energy inputs were supplied in the non–renewable and direct forms in the period examined. Furthermore, this Figure showed upward trends and the use of all energy forms were realized as 27.31%, 18.48%, 38.14% and 11.98% increase in non–renewable, direct, indirect and renewable energy forms, respectively. Singh et al. (2003) indicated 80.9% of total energy input for wheat production resulted from non–renewable and 18.1% from renewable energy and 58.1% from direct energy and 41.9% indirect energy.

The results of regression analysis of the effects of energy consumption on grain yield are presented in Table 5. The results of the regression indicate that there is a strong relationship between energy use and yield. The values of the coefficient of determination (R^2) showed the impact of electricity, indirect and non–renewable energy on output was statistically significant. Hence, 69 and 15% of the total variation in grain yield could be expected by variation in electricity and other energy input parameters, respectively. The unexplained variation, 16% of the total, may be due to variation in the energy components under consideration and aborted grain formation due to environmental conditions, etc. It is clear from Table 5 that yield and thus energy output are greatly influenced by subtle shifts in, for example, human labor, machinery, pesticides and seed sown. Hence, it should be noticed the timing, method, rate and type of applications of inputs in each region. Mäder et al. (2002) from a 21–year study of agronomic and ecological performance of biodynamic, bioorganic, and conventional farming systems in Central Europe found wheat yields to be 20% lower in the organic systems, although input of fertilizer and energy was reduced by 34 to 53% and pesticide input by 97% and they expressed these systems were less dependent on external inputs.

During the years 1990–2005, the variation in pesticides application with respect to their types has been found considerably high and increased extensively in the last year under study, particularly in case of herbicides. Among the different herbicides, 2,4–D/MCPA and Clodinafop–propargyl (Topic) had larger crop protection energy costs than others (Table 3). Approximately 51.06% of total pesticides were devoted to herbicides, 31.91% to insecticides, 14.89% to fungicides, and 2.13% to other pesticides (Table 4). In pervious researches, when considering the energy inputs for producing a hectare of wheat, pesticides represent about 0.4–3% of the total energy inputs (Singh et al., 2003; Singh et al., 2004; Ferraro, 2003). Although the energy input of pesticides was found to be quite low compared to the other inputs used in production, results of Deihimfard et al. (2007) showed increase in pesticides, particularly in case of herbicides, has not led to a similar increase in wheat yield, which could be attributed in part to the negative impact of high herbicide consumption in wheat fields of Iran and subsequent threat to the long–term sustainability of these agro–ecosystems.

During the investigation period, although some fluctuations were observed, total energy inputs and output during wheat project (Table 3) increased gradually from 26503.5 and 20871.5 MJ ha^{-1} in 1990 to 35466.3 and 30259.8 MJ ha^{-1} in 2005, indicating a 25.27 and 31.03% increase, respectively. The annual average total energy equivalent of inputs was calculated as 30007.82 MJ ha^{-1}. The average grain yield was found 1761.91 kg ha^{-1} and its energy equivalent was calculated to be 25900.02 MJ ha^{-1} (Table 4). In previous reports, energy use for wheat production was between 8496 and 30000 MJ ha^{-1} (Dalgaard et al., 2001; Mandal et al., 2002; Singh et al., 2002; Singh et al., 2003; Singh et al., 2004; Canakci et al., 2005; Singh et al., 1999; Singh et al., 2007; Venturi and Venturi, 2003). The results of Mandal et al. (2002) indicated that the total energy requirement was the greatest for wheat, followed by soybean, mustard and chickpea. As Table 3 shows, a sudden decrease in grain yield in 1999–2000 had taken place mainly due to extreme drought conditions.

4. Conclusions

The study concludes that diesel, electricity and application of chemical fertilizers share the major portion of total energy inputs consumed for wheat crop production during Iranian wheat project. Most diesel fuel consumption was for irrigation and the share of diesel decreased, but electricity showed an increase in the total energy use over the examined period because of increasing the number of electrified wells and depths. Due to mainly increasing the cultivated area and growth of suitable irrigation systems, the volume of water consumption increased until 1999–2000, and from it time onwards decreased. Among the chemical fertilizers' types, nitrogen had a very significant role in wheat production and its consumption increased around 2.35–fold in the studied period, with an annual average of 84.98 kg/ha. In general, there were not significant changes regarding the human labor and machinery year by year and out of all the farm operations, seedbed preparation required the maximum energy, followed by harvesting. Pesticides increased extensively in the last year under study, particularly in case of herbicides, and among the different herbicides, 2,4–D/MCPA and Clodinafop–propargyl (Topic) had higher share than others. During the investigation period, total energy inputs and output increased 25.27 and 31.03%, respectively. Values of energy use efficiency (energy output–input ratio), specific energy and energy productivity showed that the output did not increase as much as in energy input use during Iranian wheat project. During this project most of the total energy inputs were supplied in the non–renewable and direct forms and all energy forms have risen. Also, the results of regression analysis indicated the impact of indirect and non–renewable energy on output was statistically significant.

All findings presented here indicate that energy use during Iranian wheat project has significantly increased over the last 15 years and these results can serve as a basis for developing sustainable wheat production systems. For development, yield growth, poverty alleviation, and environmental sustainability, agreed standards and effective approaches to certification will be essential to protect society from the potential adverse effects of inappropriate policies.

Table 3. Energy consumption (MJ ha^{-1}) and energy input–output relationships for wheat production in Iran between 1990 and 2005

Inputs\Years	90–91	91–92	92–93	93–94	94–95	95–96	96–97	97–98	98–99	99–00	00–01	01–02	02–03	03–04	04–05
Human labor	546.64	663.10	657.47	628.42	576.61	701.99	629.07	637.08	737.99	723.32	715.58	689.92	585.93	656.14	642.53
Machinery	746.67	684.03	706.09	690.87	720.26	649.94	640.70	743.06	712.57	682.78	701.61	704.24	697.21	706.17	716.58
Land preparation	694.43	655.93	677.52	661.60	684.90	622.30	611.62	711.09	676.78	644.35	658.71	658.87	649.55	657.99	670.47
Sowing	0.68	0.85	1.18	2.16	3.03	3.44	3.84	4.17	4.12	4.36	4.68	5.44	5.56	5.41	6.05
Cultural practices	9.16	4.57	5.02	5.17	6.89	4.66	4.26	6.62	5.44	6.12	6.10	8.04	8.52	8.21	8.64
Harvesting	42.40	22.67	22.38	21.94	25.44	19.54	20.99	21.18	26.22	27.95	32.11	31.89	33.57	34.56	31.41
Chemical fertilizers	4353.25	4710.66	4633.02	2845.78	4956.71	5227.30	5235.91	5746.97	6782.67	6835.81	7170.21	7273.19	7937.31	8605.15	8659.80
Nitrogen (N)	3121.00	3481.70	3505.21	2196.58	3865.79	4122.90	4188.95	4744.71	5675.86	5672.61	6031.04	6120.83	6682.82	7318.64	7342.25
Phosphorus (P_2O_5)	1232.24	1228.60	1120.04	647.59	1083.93	1100.29	1034.18	981.67	1075.56	1126.73	1107.51	1123.90	1213.00	1243.12	1261.00
Potassium (K_2O)	0.00	0.36	7.77	1.61	6.99	4.10	12.78	20.59	31.25	36.48	31.66	28.46	41.49	43.39	56.55
Farmyard manure	40.41	10.75	9.30	11.70	12.44	23.36	23.84	30.44	112.51	85.44	69.98	53.93	62.94	96.26	96.42
Pesticides	127.63	156.20	148.84	152.34	86.50	83.76	141.66	116.84	122.45	141.94	135.50	169.41	153.06	163.27	218.77
Insecticides	41.19	41.01	39.44	34.48	37.14	43.32	50.78	35.47	46.74	54.35	48.11	42.96	55.26	55.03	41.00
Fenitrothion	41.19	41.01	39.44	34.48	37.14	43.32	50.78	35.47	38.66	36.28	35.33	34.47	36.92	24.08	15.24
Deltamethrin	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	8.08	9.54	7.83	7.85	13.84	30.39	25.76
Fenthion	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	8.53	4.95	0.53	4.47	0.45	0.00
Trichlorfon	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.12	0.04	0.12	0.00
Herbicides	86.44	115.19	99.40	110.60	41.11	40.44	90.88	58.46	36.82	57.05	56.46	49.49	58.81	67.58	96.68
Bromoxynil/MCPA	–[a]	–	–	–	0.00	0.00	–	0.00	0.00	0.00	0.00	0.00	0.00	0.09	0.90
2,4–D/MCPA	–	–	–	–	23.17	0.00	–	36.37	21.92	30.52	23.59	19.24	21.26	23.77	28.59
2,4–D	–	–	–	–	0.00	17.74	–	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Tribenuron–methyl	–	–	–	–	0.07	0.08	–	0.46	0.47	0.70	0.87	0.94	1.19	1.27	1.49
Bromoxynil	–	–	–	–	1.58	1.30	–	2.65	1.09	1.13	0.92	0.63	0.00	0.00	0.00
(DMM)	–	–	–	–	0.00	0.00	–	0.00	0.00	0.00	0.53	0.49	0.33	0.79	1.96
Triasulfuron/terbutryne	–	–	–	–	0.00	0.00	–	0.00	0.00	0.00	0.00	0.00	0.00	0.13	0.52
Diclofop–methyl	–	–	–	–	6.70	4.10	–	2.28	1.81	1.58	1.03	1.34	1.09	0.93	2.45
Fenoxaprop–P–ethyl	–	–	–	–	1.05	1.14	–	2.85	2.70	4.86	7.19	8.94	5.47	5.86	3.74
Clodinafop–propargyl	–	–	–	–	1.25	2.43	–	7.27	6.22	12.60	15.42	11.07	26.12	33.00	44.93
Tralkoxydim	–	–	–	–	6.58	7.04	–	2.01	0.00	0.00	0.62	0.72	0.64	0.13	0.27
Difenzoquat	–	–	–	–	0.73	6.61	–	1.32	2.60	4.52	4.48	3.84	1.51	0.60	0.61
Flamprop–M–isopropyl	–	–	–	–	0.00	0.00	–	3.25	0.00	0.00	1.10	1.40	0.43	0.72	0.27
(MI)	–	–	–	–	0.00	0.00	–	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Sulfosulfuron	–	–	–	–	0.00	0.00	–	0.00	0.00	0.00	0.00	0.00	0.00	0.00	10.94
Imazamethabenz–methyl	–	–	–	–	0.00	0.00	–	0.00	0.00	1.13	0.71	0.87	0.77	0.29	0.00
Fungicides	0.00	0.00	10.00	7.26	8.25	0.00	0.00	22.91	38.89	30.54	30.93	59.53	28.38	29.45	69.66
Others	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	17.43	10.61	11.21	11.43
Diesel	13385.3	12707.0	12918.9	13217.8	11159.7	10752.9	10646.8	11137.2	11910.1	11567.5	10467.1	9260.07	9553.01	9298.72	8898.99
Electricity	2933.63	2622.29	2962.20	3921.59	4096.04	4216.87	4544.96	5021.61	6889.52	7838.46	8887.70	9412.91	10088.8	10996.3	11147.1
Water	2072.11	2214.97	2224.06	2338.39	2378.81	2496.77	2539.11	2592.18	2894.78	2968.59	2700.27	2682.51	2606.01	2528.09	2547.64
Seed sown	2297.88	2121.45	2225.30	2204.76	2249.08	2327.48	2275.48	2410.19	2534.51	2518.95	2463.73	2380.01	2596.25	2602.19	2538.50
Sum	26503.5	25890.4	26485.2	26011.6	26236.2	26480.3	26677.6	28435.5	32697.1	33362.8	33311.7	32626.2	34280.5	35652.3	35466.3
Output															
Grain yield	20871.5	22534.8	23172.8	23564.2	25131.3	23264.9	23442.1	28436.7	26903.0	23307.9	25040.0	29325.9	30823.7	32421.9	30259.8
Energy use efficiency	0.79	0.87	0.87	0.91	0.96	0.88	0.88	1.00	0.82	0.70	0.75	0.90	0.90	0.91	0.85
Specific energy (MJkg^{-1})	18.70	16.89	16.80	16.23	15.35	16.73	16.73	14.70	17.87	21.04	19.56	16.35	16.35	16.16	17.23
Energy productivity (kgMJ^{-1})	0.05	0.06	0.06	0.06	0.07	0.06	0.06	0.07	0.06	0.05	0.05	0.06	0.06	0.06	0.06

(*continued on next page*)

[a] Data not available.

Table 4. Quantities and energy values for wheat production in Iran (the average of 15 yr)

Inputs	Quantity per ha	Energy equivalent (MJunit^{-1})	Total energy equivalent (MJ)	percent
Human labor (h)	303.20	2.153	652.79	2.18
Machinery (h)	11.17	62.700	700.19	2.33
Land preparation	10.56		662.41	2.21
Sowing	0.06		3.66	0.01
Cultural practices	0.10		6.49	0.02
Harvesting	0.44		27.62	0.09
Chemical fertilizers (kg)			6064.92	20.21
Nitrogen (N)	84.98	58.106	4938.06	16.46
Phosphorus (P_2O_5)	79.11	13.971	1105.29	3.68
Potassium (K_2O)	2.71	7.947	21.57	0.07
Farmyard manure (tons)	0.163	303.100	49.31	0.16
Pesticides (kg)			141.21	0.47
Insecticides	0.18	[a]252.703	44.42	0.15
Herbicides	0.38	[a]186.764	71.03	0.24
Fungicides	0.11	206.000	22.39	0.07
Others	0.03	120.000	3.38	0.01
Diesel (l)	213.72	52.055	11125.41	37.08
Land preparation	80.50		4190.43	13.96
Sowing	0.15		7.81	0.03
Cultural practices	0.32		16.66	0.06
Harvesting	14.67		763.65	2.54
Tractor manufacturing and repair	3.00		156.17	0.52
Irrigation	[b]115.08		5990.49	19.96
Electricity (kW h)	601.70	10.590	6372.00	21.23
Water (m^3)	3998.34	0.630	2518.95	8.39
Seed sown (kg)	151.79	15.700	2383.05	7.94
Sum			30007.82	100.00
Output				
Grain yield (kg)	1761.91	14.700	25900.02	

[a] Weighted mean value.
[b] The fuel requirements of water pumps.

Table 5. Summary of multiple regression analysis of grain yield (GY) and various energy input parameters for wheat production

Regression equations	Coefficient of determination
GY = 1350.42 + 0.06 E[a]	0.69***
GY = 2191.87 – 0.06 D[b] + 0.04 E	0.73
GY = 1224.87 + 2.96 M[c] – 0.14 D	0.78
GY = 916.28 + 2.45 M – 0.09 D + 0.03 E	0.81
GY = 732.03 + 2.46 M – 0.85 FYM[d] – 0.08 D + 0.04 E	0.81
GY = –179.08 + 2.31 M – 1.95 FYM – 0.07 D + 0.03 E + 0.43 SS[e]	0.82
GY = –791.16 + 2.28 M – 2.06 FYM + 1.35 P[f] – 0.09 D + 0.81 SS	0.83
GY = –1418.12 + 0.36 HL[g] + 2.59 M – 2.70 FYM + 1.48 P – 0.09 D + 0.89 SS	0.83
GY = –1451.07 + 0.46 HL + 2.81 M – 0.04 CF[h] – 2.24 FYM + 1.70 P – 0.12 D +1.00 SS	0.84
GY = –1468.05 + 0.70 HL + 2.79 M – 0.05 CF – 2.11 FYM + 1.63 P – 0.13 D – 0.10 W[i] + 1.11 SS	0.84
GY = –1452.56 + 0.70 HL + 2.78 M – 0.05 CF – 2.12 FYM + 1.60 P – 0.12 D + 0.001 E – 0.10 W + 1.10 SS	0.84
GY = 795.93 + 0.10 Indirect energy	0.66***
GY = 798.23 – 0.0002 Direct energy + 0.10 Indirect energy	0.66
GY = 479.80 + 0.05 Non–renewable energy	0.60***
GY = 1022.46 – 0.30 Renewable energy + 0.07 Non–renewable energy	0.62

*** Significant at the 0.001 probability level.
[a] E – Electricity.
[b] D – Diesel.
[c] M – Machinery.
[d] FYM – Farmyard manure.
[e] SS – Seed sown.
[f] P – Pesticides.
[g] HL – Human labor.
[h] CF – Chemical fertilizers.
[I] W – Water.

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