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EDITED BY
Maria Cristina Piccirilli,
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Miguel Ángel Morales Mora,
College of Puebla, Mexico
Muhammad Chattha,
The University of Sydney, Australia

*CORRESPONDENCE
Omid Karami,
karamy_omid@yahoo.com

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Harvesting energy's worth: an economic assessment of energy at wheat farms

Hamed Rafiee[1], Omid Karami[2]*, Atabak Kazempour Kahriz[1], Reza Shakeri Bostanabad[1] and Alireza Kermani[1]

[1]Department of Agricultural Economics, University of Tehran, Karaj, Iran, [2]Department of Agricultural Economics, Purdue University, West Lafayette, IN, United States

Spurred by the need to produce more food for a growing population, the agricultural sector has recently become much more resource-hungry and energy-intensive. Mismanagement and inefficiency in energy (and resource) consumption have conspicuously increased agriculture's footprint over time. Energy use optimization necessitates a careful study of the patterns of energy and resource consumption in agriculture. This study aims to quantify the energy required for irrigated and dryland wheat production in five large wheat-producer provinces in Iran, estimating the economic value of each unit of energy input. Using energy equivalent coefficients, total energy inputs in the form of renewable and non-renewable were estimated for the period of 2001–2019. Then, to obtain the Value of Marginal Product (VMP) of the inputs, the production functions of irrigated and dryland wheat for each province were estimated. The findings show that the average marginal product and the economic value of renewable energy in the production of dryland wheat is greater than the marginal product of these inputs in the production of irrigated wheat across all provinces. Conversely, the average VMP of non-renewable energy in irrigated wheat production is greater than the corresponding amount in dryland wheat production, with the exception of Kermanshah. Renewable energy in dryland wheat has an equal economic value of 0.18 USD/ha with non-renewable energy in irrigated wheat production. Moreover, the VMP of energy contributes to about half of the price of wheat. Finally, the economic value of energy in wheat production became lower after the implementation of the Targeted Subsidies Reform Act. However, raising the energy price simply led to a shrinking of farmers' profit margins; no improvements were achieved in the economic value of energy.

KEYWORDS

Iran, marginal product, non-renewable energy, renewable energy, value of marginal product

1 Introduction

In bygone days, agriculture was characterized by a heavy reliance on manpower and livestock. The mechanization of agriculture, and the use of fossil fuels and electricity, enabled the increase of food production from limited arable land to feed a fast-growing population and improve living standards (Mohammadi et al., 2008). Nowadays, agriculture is driven largely by the energy inherent in fossil fuels, which results in global warming and concomitant climate change effects

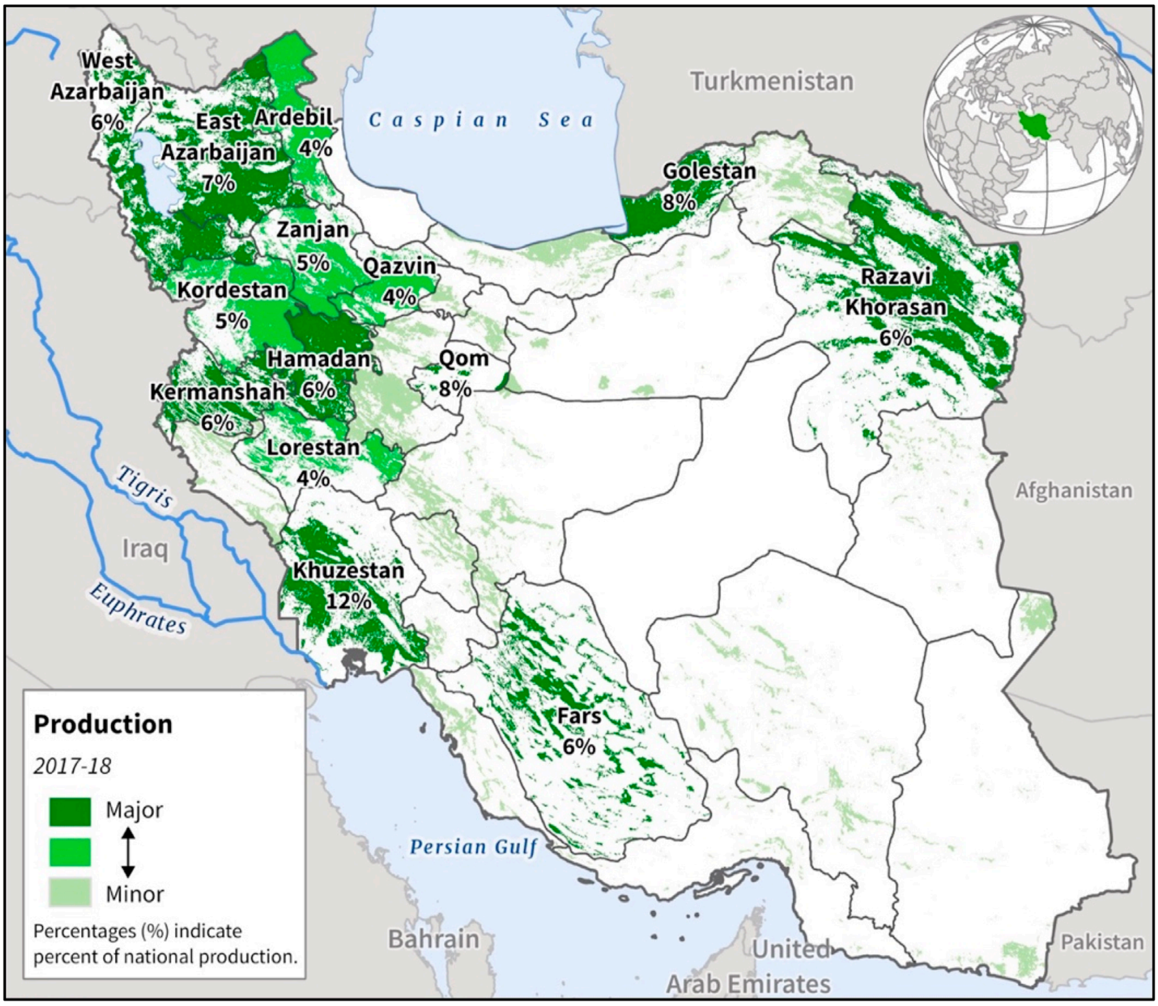

FIGURE 1
Iran wheat production (Foreign Agricultural Service of U.S. Department of Agriculture, 2014).

(Gündoğmuş, 2006). Energy and other industrial inputs have the highest share, and emit 58% of the emissions in agriculture (Laborde et al., 2020). It is predicted that the expansion of irrigated agriculture could increase the energy use by 28%; however, implementing efficient methods has the potential to decrease the energy consumption by 50% and cut CO_{2e} emissions by 90% (Qin et al., 2024). For Iran, it is predicted that the emissions through agriculture reach up to 47 million tons of CO_{2e} emissions by 2050, which is 34% more than 2012 level (FAO, 2018).

Wheat, as one of the major crops of Iran, is cultivated in all provinces (Figure 1). Except for Fars province, Northern and Western provinces are the main wheat producers. In 2021, irrigated and dryland wheat cultivation encompassed 1.96 million hectares (31.3%) and 4.04 million hectares (68.1%), respectively. Between 2000 and 2018, wheat production in Iran fluctuated between 7 and 15 million tons, mainly due to unpredictable droughts (Pakrooh and Kamal, 2023) and the high dependence of dryland wheat farms on rainfall. Concurrently, *per capita* wheat consumption rose from 123.2 to 177.26 kg per person (Pakrooh and Kamal, 2023). The growth in demand, together with the unpredictability of wheat production, has challenged "self-sufficiency in wheat production" policy implemented by the Iranian government.

While an increase in wheat cultivation in the country is vital to ensure self-sufficiency of the staple food, it comes at a price: a rise in energy usage, which will result in more environmental impacts for agriculture. To ensure food security, the government implemented sizable subsidies to the farmers (on average, 1.4 billion USD per year), resulting in energy use inefficiencies. Because the price reflects the scarcity of a commodity, the subsidies hinder an optimal allocation of energy among the diverse sectors of the economy due to their intervention in the price system. These subsidies cause severe challenges in the form of rising GHG emissions in energy-rich countries because subsidizing energy will lead to inefficiencies in energy usage (Raei et al., 2024). Energy subsidies can be destructive due to their burden on the government budget and environmental impacts (Raei et al., 2024). World agriculture is such strongly affected by support policies that removing the subsidies can mitigate emissions in global agriculture by 34 million tons of CO_2 equivalent (Laborde et al., 2020).

Due to the overwhelming amount of energy subsidies, the Iranian government has implemented the Targeted Subsidies Reform Act to liberate the economy by cutting the input and output subsidies (Zytek and Farzin, 2016). Implemented in 2010, the Targeted Subsidies Reform Act made Iran the first major oil-exporting country to eliminate domestic and agricultural energy subsidies up to 20 times (Saeediankia et al., 2023). Known as the most comprehensive economic "surgery" in modern Iran, the Targeted Subsidies Reform Act introduced higher prices for liquid fuels, natural gas, electricity, water, and public transportation (Saeediankia et al., 2023). Although the policy may decrease producers' profits, they are expected to improve production, productivity, and competition, which tend to increase community welfare (Layani et al., 2023).

Several studies assessed the economic value and quantities of energy inputs in agriculture to investigate the optimal consumption of energy usage in Moroccan sugarcane (Mrini et al., 2001); Portuguese wheat, corn, sunflower, and barley; Italian lemon, apple, pear, peach, and apricot (Triolo et al., 1987); Malaysian rice (Bockari-Gevao et al., 2005); Turkish cherries, tomatoes, cotton, sugar beet, and greenhouse vegetables (Demircan et al., 2006; Esengun et al., 2007; Ozkan et al., 2004b; Yilmaz et al., 2005); Indian soybeans and potatoes (Mandal et al., 2002; Yadav et al., 1991); and Iranian wheat (Safa and Tabatabaeefar, 2002). Erdal et al. (2007) concluded that sugar beet consumes 39.7 GJ/ha in the Turkish province of Tokat. In a similar study, Külekçi and Aksoy (2013) found that energy consumption in small and extensive pistachio orchards is 23.45 and 20.5 GJ/ha, respectively. Among Iranian case studies, Moradi et al. (2018) and Houshyar and Grundmann (2017) revealed that conservation tillage is more energy-efficient and environmentally friendly than conventional methods in Fars province. In a more recent study, Rafiee et al. (2022) showed that the average input energy for wheat in Iran exceeds the crop's output energy by 13.7 GJ/ha. The Targeted Subsidies Reform Act in Iran was also studied in several studies. Ahmadpour Borazjani and Sabouhi Sabouni (2015) indicated that raising the prices of the inputs (mainly energy) reduced production, welfare of producers, consumption, and exports in the agriculture sector, dramatically. To assess the environmental impacts of the Targeted Subsidies Reform Act in Iranian agriculture sector, Khaledi et al. (2011) concluded that the policy has the potential to decrease gasoline demand by a maximum of 997 million L/year. The study did not estimate any potential reduction in GHG emissions resulting from the policy, and the reduction in inputs was the only environmental criterion considered. In a more detailed study, Solaymani (2021) concluded that the policy decreased the demand for energy by 10% while causing a 7% decline in CO_2 emissions.

Energy consumption and the economic value of agricultural inputs and outputs have been studied separately in different studies. Also, some studies investigated the impacts of the Targeted Subsidies Reform Act on the energy and environment of Iran. Still, none of the studies have estimated the economic value of wheat in Iran per energy unit before and after the Targeted Subsidies Reform Act. This paper seeks to bridge this gap by estimating the energy value in the production of irrigated and dryland wheat farms in selected provinces in Iran. Furthermore, this paper assesses the impacts of Iran's Targeted Subsidies Reform policy implemented in 2011.

2 Materials and methods

2.1 Study area and data

The study focuses on the five wheat-producing provinces in Iran: Kermanshah, Fars, Kurdistan, Khuzestan, and Golestan. These provinces collectively produce 37 percent of the country's wheat (Figure 1). They were chosen due to their significant contribution to wheat production, diverse climatic conditions, agricultural practices, and data availability. This diversity allows for a comprehensive analysis of energy use patterns and their economic implications in wheat farming nationwide.

To measure the input energy in wheat production, the values of the inputs are required. These data for the study area were obtained from the Iran Ministry of Agriculture-Jahad from 2000 to 2019. The energy equivalent of inputs/outputs of wheat farms sourced from Rafiee et al. (2022) are in Supplementary Table S1. Accordingly, renewable energy covers seed, manure, human labor, and irrigation water. On the other hand, chemical fertilizers, pesticides, electricity, machinery, and diesel fuel are considered non-renewable energy.

2.2 The economic value of energy

Energy use in the agricultural sector can be bifurcated into direct and indirect energy use. It can also be segmented into renewable and non-renewable energy demands (Beheshti Tabar et al., 2010). Direct energy includes all energy used directly in the field, from sowing seeds to harvesting crops; however, indirect energy includes the embedded energy in the production/fabrication/manufacture, packaging, and transport/conveyance of all inputs, such as chemical fertilizers, pesticides, and agricultural machinery (Ozkan et al., 2004a). Likewise, labor, seeds, animal manure, and water are regarded as renewable energy, while the energy embedded in chemical fertilizers, pesticides, and machinery is non-renewable (Erdal et al., 2007; Mohammadi et al., 2008; Zangeneh et al., 2010).

Determining the marginal product of energy in wheat production requires estimating the production function. The production function depends on the production technology adopted. Flexible[1] (translog, generalized quadratic, and generalized Leontief) and inflexible (Cobb-Douglas and transcendental) functions have been commonly used (Ahmadzai and Heydayat, 2020; Betz et al., 2015; Kumbhakar, 1994; Mehmood et al., 2015; Mehrjerdi and Mark, 2018). In this study, to evaluate the marginal production and the economic value of renewable and non-renewable energies, we implemented the classical production functions. After estimating several production forms, we used classical assumption tests and other econometric tests, such as significant percentage and residual normality test (Greene, 2003; Thompson, 1988), to select the best form of the wheat production function. Accordingly, the generalized quadratic

1 Flexibility in functional forms was first proposed by Diewert (1971). It implies the presence of free parameters (flexibility, in other words) to arrive at an approximation (usually second order) of any arbitrary function (Ray et al. 2020).

mentioned in Equation 1 was selected as the best functional form (Chambers, 1988):

$$EW = \alpha_0 + \alpha_1 RE_t + \alpha_2 NRE_t + \frac{1}{2}\alpha_3 RE_t^2 + \frac{1}{2}\alpha_4 NRE_t^2 + \alpha_5 (RE_t * NRE_t) \quad (1)$$

in which renewable (RE) and non-renewable (NRE) energies are the main inputs, and the output (EW) is the amount of energy equivalent to the yield of wheat. As mentioned previously, we used the data from Rafiee et al. (2022), in which seed, manure, human labor, and irrigation water are sources of renewable energy, and chemical fertilizers, pesticides, electricity, machinery, and diesel fuel are non-renewable energy. The abovementioned functional form was estimated for irrigated and dryland wheat in the five Iranian provinces of Kermanshah, Fars, Kurdistan, Khuzestan, and Golestan. First, the marginal product of each variable (MP_{xi}) is estimated by Equation 2 (Varian, 2014):

$$MP_{xi} = \partial(EW)/\partial(X_i) \quad (2)$$

where X_i is the input (RE or NRE).

Subsidies intervene in the markets through price systems. The price reflects the scarcity of that commodity; therefore, information about the price or economic value of energy is necessary for energy demand management. An overestimation/underestimation of the energy value hinders an optimal allocation of energy among the diverse sectors of the economy. According to economic theory, the marginal cost of an operating input should be equal to its marginal price in equilibrium under the assumptions of constant returns to scale and a competitive market (Abraham et al., 2009; Caselli et al., 2021). Therefore, energy forms with higher marginal products should be more expensive than those with lower marginal products (Kaufmann, 1994). Then, the economic value of each input was obtained by Equation 3 (Varian, 2014):

$$VMP_{xi} = P_y \times MP_{xi} \quad (3)$$

in which P_y is the product price (the price per unit of wheat energy) and VMP_{xi} is the value of the marginal product of the input xi or the economic price of xi. MP_{xi} shows how much energy is produced for one unit of consuming X_i. Moreover, VMP is the corresponding value of energy produced for one USD of consuming X_i as an input. Therefore, MP and VMP are efficiency indexes in our study. For the optimal level of production, the value of the marginal product of a factor should equal its price (Varian, 2014). We estimate VMP for the years preceding (S1) and following (S2) Iran's Targeted Subsidies Reform Act. Then, we will compare VMP with the input price under both scenarios to see how the policy could help to achieve the optimal level of production.

Since we are using time-series data, we need to check whether the variables are stationary. Considering the wide application of time-series data in various types of research, it is always assumed that the time series is stationary. Otherwise, the statistical tests based on t, F, etc., are doubted, and spurious regression exists (Dougherty 2011). For the Unit Root Test, we implemented the Augmented Dickey-Fuller (ADF) test developed by Dickey and Fuller (1979) to determine the stationarity of time series data. The test considers first-order autoregressive process in Equation 4 to investigate the existence of a unit root (Dickey and Fuller, 1979):

$$y_t = \rho y_{t-1} + u_t \quad (4)$$

where y_t and y_{t-1} are each variable in time t and in time t-1, respectively. For testing autocorrelation, we used the Durbin-Watson statistic, which was introduced by Durbin and Watson (1971). We also used SHAZAM 10.2, first introduced by White (1978), to estimate the econometric models.

3 Results and discussion

Data regarding the energy input and output for both irrigated and dryland wheat production are provided in Supplementary Figures S1-4 in the Supplementary Material. Also, the descriptive statistics of energy consumption for wheat production in five provinces over the 20-year time period of 2000–2019 are provided in Supplementary Tables S1-4. Accordingly, Fars province had the highest energy consumption for irrigated wheat, with an average of 36.2 GJ/ha. For dryland wheat, farmers in Golestan province consumed the most energy, with 15.56 GJ/ha. For energy output, Kermanshah topped the list for irrigated wheat with an average of 56.8 GJ, while Golestan was the first for dryland wheat with an average energy output of 28.7 GJ. However, earlier studies such as Singh et al. (2002) concluded that energy input at wheat farms can be as low as 8.73 GJ/ha due to the lower consumption of inputs in India; later studies estimated more comparable energy inputs to the current study. Ashraf et al. (2020) also investigated wheat production in Pakistan and estimated an average input energy consumed of 27.06 GJ/ha. In a similar study, Du et al. (2022) estimated 27.1–30.4 GJ/ha farm-level energy inputs for wheat in China. Regarding the energy output, Meena et al. (2025) reported the energy output of 72.94 GJ/ha for wheat, which is comparable to our results. Table 1 provides more comparable studies.

Figures 2, 3 illustrate the renewable and non-renewable energy shares (%) in irrigated and dryland wheat production, respectively. In general, the share of non-renewable energy is more than renewable energy for both irrigated and dryland wheat production; however, irrigated wheat in Kurdistan is an exception. For irrigated wheat in Kurdistan, more than 55% of energy consumption comes from renewable sources. Ashraf et al. (2021) also concluded that non-renewable energy has a higher share at wheat farms in Pakistan. In a more comparable study to the current study, Soltani et al. (2013) concluded that renewable energy accounts for 18% of the total energy input, and non-renewable energy comprises 82% of the total energy at wheat farms in Iran.

The results of the estimation of the production functions are provided in Supplementary Tables S5, S6. Accordingly, all the variables in the estimated production functions have significant impacts on production. Singh et al. (2002) also came upon a non-linear relationship between wheat yield and energy production. F-statistic shows that the total estimated regression is significant (see Supplementary Tables S5, S6). Durbin-Watson statistic also indicates the absence of autocorrelation in the disturbance components of the patterns. Also, the Dickey-Fuller test statistic for the residuals of all models is significant, which points to the absence of spurious regression.

Table 2 provides the estimated marginal product (MP), the economic value of renewable energy (VMP), and the ratio of VMP to the price of wheat. Houshyar et al. (2015) also obtained comparable MP for farm-level renewable energy in Iran. These results indicate

TABLE 1 Summary of studies Related to the energy input/output at wheat farms.

Author(s)	Study area	Energy input (GJ/ha)	Energy output (GJ/ha)
Singh et al. (2002)	Jodhpur, India	8.7	27.9
Soltani et al. (2013)	Gorgan, Iran	15.6	94.4
Ziaei et al. (2015)	Sistan and Baluchestan, Iran	32.5	48.5
Gökdoğan and Sevim (2016)	Eskil, Turkey	25.9	77.0
Imran and Özçatalbaş (2020)	Punjab, Pakistan	31.4–49.1	60.5–65.9
Ashraf et al. (2021)	Mailsi, Pakistan	20.2–34.5	83.6–125.4
Du et al. (2022)	Huang-Huai-Hai, China	37.5–57.8	16.0–24.2
Meena et al. (2025)	Uttar Pradesh, India	-	72.94

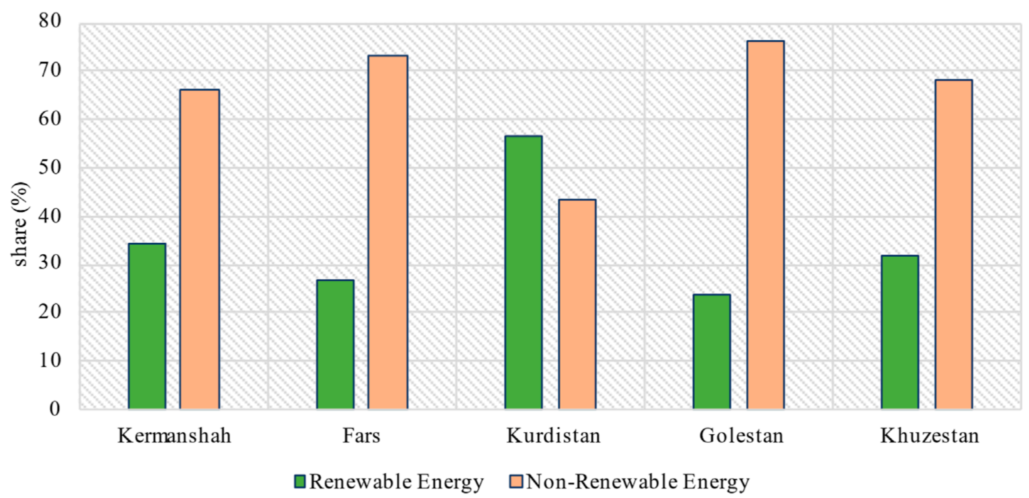

FIGURE 2
Renewable and non-renewable energy shares (%) in irrigated wheat production.

that the average marginal production of renewable energies in the production of dryland wheat for all provinces is greater than the marginal product of the inputs for irrigated wheat. The biggest gap is for Kermanshah, where the MP of renewable energies in dryland wheat is 215% greater than the corresponding amount for irrigated wheat. The greater MP of renewable energy in dryland wheat resulted in a higher economic value. In Kermanshah, the average economic value of renewable energies for irrigated and dryland are \$0.49 and \$2.35 per GJ, respectively[2]. The higher MP of renewable energy in dryland wheat production has caused a higher share of this input in VMP.

Due to the decrease in the real prices of energy carriers, along with the rapid growth of energy consumption and the increase in the financial burden of subsidies on the government's general budget, the Targeted Subsidies Reform Act was implemented by Iranian government, and legislation came into force in 2011. In this research, to investigate the impact of this policy on the economic value of energy in the agricultural sector, the average economic value of energy has been investigated in two time periods—before (S1) and after (S2) the targeted subsidies. In order to ensure comparability, the number of years in each of the two periods is considered to be the same. As shown in Table 2, after the implementation of the targeted subsidies policy in Iran, the average economic value of renewable energy in wheat production has decreased in all five provinces. It is thereby clear that the policy not only did not lead to an improvement of the economic value of energy in wheat production but also resulted in a negative performance in this area. The reason is that the government's intention or objective behind this legislation was to increase the price of direct energy, and it was believed that this would lead to an optimization of energy use in the agricultural sector. As this study has shown, the economic value of energy in

2 In order to eliminate the effect of inflation, all prices are converted to the base year of 2016 by the producer price index (PPI) in the agricultural sector.

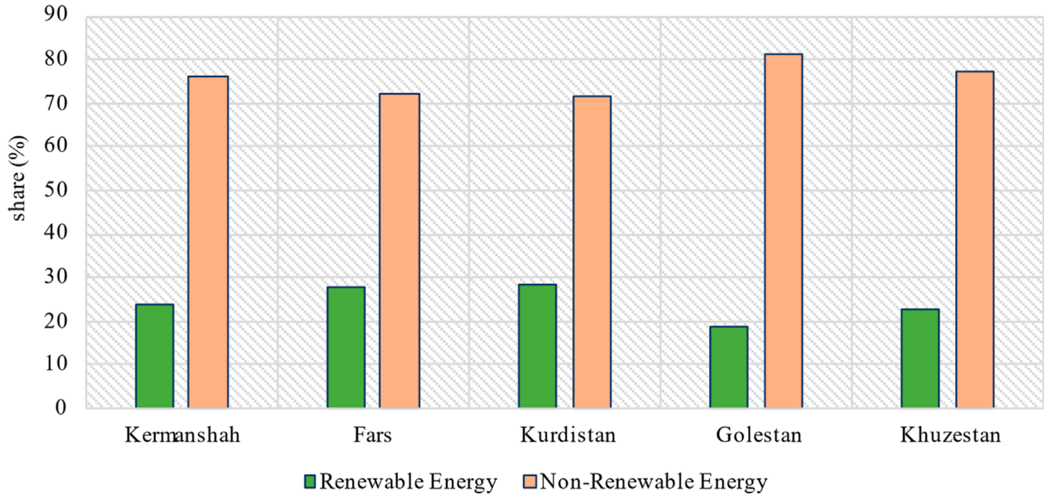

FIGURE 3
Renewable and non-renewable energy shares (%) in dryland wheat production.

TABLE 2 Average marginal production (MP) and economic value (VMP[a]) of renewable energy in wheat production.

Province	Product	MP	VMP	VMP (S1)	VMP (S2)	VMP/P_{wheat}
Kermanshah	irrigated	2.0	0.49	0.49	0.34	0.155
	dryland	6.3	2.35	4.14	1.20	0.483
Fars	irrigated	3.1	1.05	1.24	0.83	0.238
	dryland	3.3	0.90	1.30	0.86	0.258
Khuzestan	irrigated	3.3	0.74	0.83	0.74	0.255
	dryland	3.7	0.77	0.65	0.65	0.282
Kurdistan	irrigated	3.7	0.96	0.96	0.59	0.266
	dryland	4.4	1.70	2.97	0.96	0.342
Golestan	irrigated	2.4	0.62	0.68	0.65	0.182
	dryland	3.5	1.24	1.45	1.27	0.270

[a]VMP in USD per GJ of energy.

wheat production became lower after the Targeted Subsidies Reform Act. The price increase simply led to a shrinking of farmers' profit margins without any gains in improving the economic value of renewable energy. Increasing productivity in wheat production and improving the marginal production of energy should have been given serious attention by policymakers before the energy prices were hiked.

Similar to Tables 2, 3 provides the results for non-renewable energy. Unlike renewable energy, the average MP of non-renewable energy in the production of irrigated wheat is greater than the MP for dryland wheat in all provinces except in Kermanshah province. The average MP of non-renewable energy in the production of irrigated wheat is 75% greater than that for dryland wheat. In the same way, except in Kermanshah province, the VMP of non-renewable energy of irrigated wheat is greater than that for dryland wheat. For example, in Fars province, the economic value of non-renewable energy for irrigated and dryland wheat is equal to $1.7 and $0.37 per GJ, consecutively. Similar to the results of renewable energy, the economic value of non-renewable energy input after implementing the Targeted Subsidies Reform Act has decreased.

Table 4 summarizes the results of the economic value of renewable and non-renewable energies in the production of irrigated and dryland wheat. Non-renewable energy has more economic value than renewable energy in irrigated wheat; however, it is the opposite for dryland wheat. Renewable energy has a higher share in dryland wheat than irrigated wheat (32.7% versus 21.9%).

TABLE 3 Average marginal production (MP) and economic value (VMP) of non-renewable energy in wheat production.

Province	Product	MP	VMP	VMP (S1)	VMP (S2)	VMP/P_{wheat}
Kermanshah	irrigated	2.8	0.71	0.77	0.71	0.217
	dryland	3.5	1.30	1.91	1.05	0.269
Fars	irrigated	5.0	1.70	1.88	1.45	0.383
	dryland	2.0	0.37	0.22	0.56	0.151
Khuzestan	irrigated	5.2	0.99	1.27	1.11	0.398
	dryland	3.0	0.68	0.56	0.68	0.234
Kurdistan	irrigated	4.9	1.39	1.48	1.54	0.394
	dryland	1.6	0.43	0.40	0.37	0.125
Golestan	irrigated	3.0	0.80	0.80	0.90	0.232
	dryland	1.9	0.59	0.71	0.40	0.143

[a]VMP in USD per GJ of energy.

TABLE 4 The average economic value of energy in wheat production.

Energy type	VMP	Irrigated	Dryland
Renewable	VMP (USD/GJ)	0.83	2.10
	VMP (USD/kg of wheat)	0.12	0.18
	VMP share in wheat price (%)	21.9	32.7
Non-Renewable	VMP (USD/GJ)	1.14	0.68
	VMP (USD/kg of wheat)	0.18	0.10
	VMP share in wheat price (%)	32.5	18.4
Total share of energy in wheat price (%)		54.4	51.1

Therefore, considering the average price of Iranian wheat ($0.56), the economic value of renewable energy per kg of irrigated and dryland wheat are 0.12 USD and 0.18 USD, respectively. Interestingly, renewable energy in dryland wheat has equal economic value (0.18 USD/hg) with non-renewable energy in irrigated wheat production. Finally, examining the share of the final production value of renewable and non-renewable energies from the real price of wheat shows that the VMP of energy is almost 50% of the selling price of wheat.

In a similar study to our study, Shokoohi et al. (2022) investigated the impacts of Iranian Targeted Subsidies Reform Act on dairy farms. Their results showed that the dairy farms' efficiency has decreased after the Targeted Subsidies Reform. They estimated a 17% decrease in production efficiency compared with the period before implementing the policy. According to (Shokoohi et al., 2022), the policy negatively impacted structural changes in Iran's economy and also caused instability in the market. They suggested policies to support the producers in managing the market risk. Barkhordar et al. (2018) also investigated the role of Iranian Targeted Subsidies Reform in energy efficiency. They mainly focused on the barriers to energy efficiency improvements after implementing Targeted Subsidies Reform. They concluded that there are informational, financial, and regulatory barriers that impede energy efficiency across different sectors in Iran.

4 Conclusion

Optimizing energy use in the agricultural sector is indispensable and of paramount importance globally. The authors were motivated by the need to examine the pattern of energy consumption in the economy in general, the agricultural sector in Iran in particular, and irrigated and dryland wheat production in five selected provinces in the country. Energy inputs were categorized as renewable and non-renewable. Of the five provinces, Fars and Golestan had the highest amount of input energy used in the production of irrigated and dryland wheat, respectively. The results of investigating the energy content of irrigated and dryland wheat in the study area showed that the highest amount of "embedded" crop energy of irrigated and dryland wheat products was in Kurdistan and Golestan provinces, respectively.

Estimated MP showed that the average marginal product and the economic value of renewable energy in the production of dryland wheat in all five provinces is greater than the marginal product of these inputs in the production of irrigated wheat. In contrast, the average MP of non-renewable energy in irrigated wheat production is greater than the MP of the inputs in dryland wheat production in all provinces except Kermanshah. Moreover, non-renewable energy in irrigated wheat has a higher economic value, but renewable energy dominates in the production of dryland wheat. The comparison of the share of VMP of renewable and non-renewable energy from the actual price of wheat shows that the economic value of these inputs is about half of the price of wheat. The total economic value of renewable and non-renewable energy in irrigated and dryland wheat production is 54.4% and 51.1% of the price of wheat, respectively.

The low economic value of energy in Iran is due to the fact that policymakers have not prioritized improvements in production efficiency. To boost food production, and improve self-sufficiency, fertilizer and pesticide subsidies have been provided to farmers, and this has obliterated any motivation for optimizing resource usage. The current study emphasizes that the increase in the price of energy alone, without paying attention to energy efficiency improvements in wheat production, will not suffice. Existing subsidies deserve consideration. It, however, goes without saying that providing food to the population and targeting self-sufficiency will surely remain topmost on the agenda of the policymakers. If this can be done sustainably, it would be a win-win-win for sure—environmentally, economically, and socially.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material, further inquiries can be directed to the corresponding author.

Author contributions

HR: Supervision, Validation, Writing – original draft, Writing – review and editing, Conceptualization, Methodology. OK: Supervision, Validation, Writing – original draft, Writing – review and editing, Funding acquisition, Project administration, Visualization. AK: Data curation, Formal Analysis, Investigation, Software, Visualization, Writing – original draft, Writing – review and editing. RS: Data curation, Formal Analysis, Investigation, Software, Visualization, Writing – original draft, Writing – review and editing. AK: Data curation, Formal Analysis, Investigation, Software, Visualization, Writing – original draft, Writing – review and editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fenrg.2025.1522280/full#supplementary-material

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