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Research article

Dynamic energy efficiency assessment of dairy farming system in Iran: application of Window Data Envelopment Analysis

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Abstract

Livestock production systems, such as dairy farming, are one of the most important contributors to resource use and if not managed well, it can be environmentally detrimental. Iranian livestock sector faces a variety of the challenges such as high costs of energy and environmental legislations as well as an increasing demand for dairy products to respond the growing population. This paper aims to contribute to the discussion on technical efficiency as a key indicator of energy use within dairy farming systems. A Window Data Envelopment Analysis (W-DEA) with energy use as inputs and milk production as output was modelled with data from 25 provinces during the last 22 years (1994-2016) in Iran. In addition, the Slack-Based Model (SBM) was used to compare the radial DEA model with non-radial SBM, both in a dynamic environment (window analysis). The average efficiency score of Iranian dairy farming production system was estimated at approximately 0.85. Through the years, three provinces including Zanjan, Ardabil and Hormozgan had the highest technical efficiencies. Window analysis represented that provinces are distinctive in terms of their technical efficiencies and energy consumption over the years. Applying the SBM model improved the accuracy of the estimated efficiency scores compared to the radial (DEA) model. Further analysis represented a significant difference between the technical efficiency of different milk production levels. Provinces that produced higher volumes of milk had lower technical efficiencies. Based on the results it can be concluded that there is a substantial space for upgrading technical efficiency of dairy farming in Iran by improving resource use efficiency which leads to an optimized energy consumption. It is recommended to reform Iranian livestock farming policies by applying mechanized systems, optimal strategies for water, electricity and fossil fuel consumption, use of renewable energy and better feed management while enhancing milk productivity and technical efficiency. In this respect, it is suggested that policy makers consider different indicators such as energy use efficiency and environmental impacts when allocating subsidies and resources to different provinces and farms.

Keywords: Dairy farming; Energy use; Data envelopment analysis; Window analysis.

1. Introduction

Livestock production systems, such as milk production farms, are quite energy and fossil-fuels dependant and may have adverse environmental impacts arising from the excess consumption of natural resources; however, the demand for animal proteins such as milk and meat products is growing around the world (Daniel et al., 2011). To respond this demand, intensification of livestock systems has been proposed as a solution. Intensification of these systems can be achieved by two major methods: input-based and output-based strategies (Herrero et al., 2016). In general, intensive dairy farming system, i.e. greater stocking rate, can be addressed by a number of indicators including milk per cow, milk per hectare, feed per cow, and cows per hectare (Álvarez et al., 2008). The strategy based on utilization of more inputs requires improvement of mechanization systems. This change has caused an increase in direct and indirect energy consumption on the farms. According to Lockeretz (2012), the direct energy refers to fossil fuel and electricity sources which are directly being used on the farm for different farm practices, while indirect energy refers to the energy depleted in the production process of inputs (feed ingredients, machinery, building, etc.). Thus, energy is of paramount importance in livestock production systems and should be managed effectively i.e. production with higher energy efficiency (Sefeedpari, 2012).

In Iran, dairy farming is an important part of agricultural sector. The dairy cow population in Iran was about 1.44 million animals in 2016. There was an estimated 4.09 million tonnes of milk production in 2015. The leading milk producing provinces in Iran are: Tehran (including Alburz and Qom), Isfahan and Fars with 26.6, 10.2 and 9.9 thousand tonnes in 2015 (Statistical Centre of Iran, 2016). The following figure (Fig. 1) contains information about the changes in milk production level and number of cattle based on different breeds during the last 22 years (1994-2016). This figure is showing the increasing trend both in milk production and capacity of dairy farms over the years. Milk production has increased with farm capacities (in terms of the number of cattle). Since 2010, milk production has shown a significant increase which can be related to the technological developments as well as the feed management.

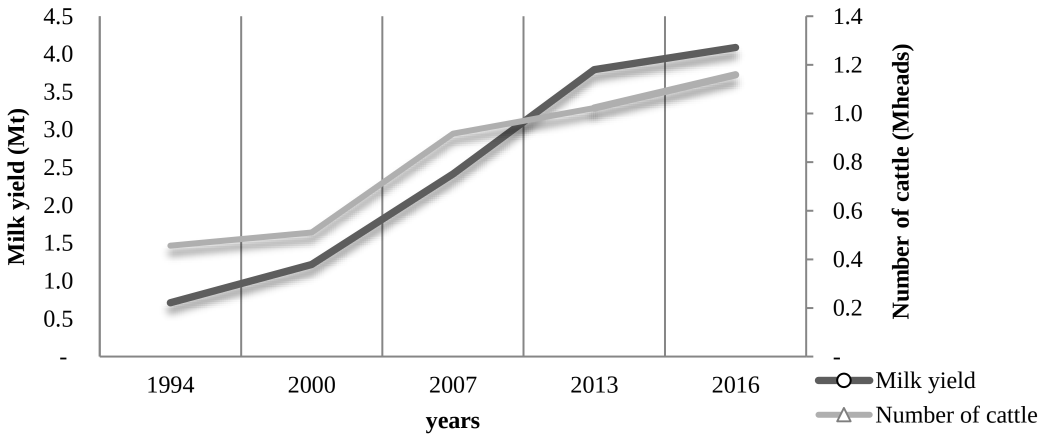

Fig. 1. Milk production and number of cows during 1994-2016. Source: Statistical Centre of Iran (2016)

The ambition of the dairy sector to increase the milk production per cow requires higher inputs which necessitates these farms to operate in a technically efficient way.

Assessing technical efficiency (TE) is one of the key indicators of resource use within agricultural production systems, which measures the output produced from specific amounts of input (Barnes et al., 2011). Data envelopment analysis (DEA) is considered as an operational method to quantify the relative efficiency of multiple entities (Cooper et al., 2007; Xie et al., 2019). These similar entities (e.g. provinces of Iran in this study) are generally called decision making units (DMUs). DEA has been widely applied in agricultural and horticultural sectors including peanut, rose cut-flower, rice, citrus, paddy, cotton, cranberry, cucumber, sugarcane and greenhouse products (Al-Mezeini et al., 2020; Alemdar and Işik, 2008; Aman and Haji, 2011; Balcombe et al., 2008; Beltrán-Esteve and Reig-Martínez, 2014; Chauhan et al., 2006; Clemente et al., 2015; Cobanoglu, 2013; Dong et al., 2015; Farrell, 1957; Heidari et al., 2012; Ullah et al., 2019). DEA has been used in livestock farming systems such as dairy cow, poultry, and pig farming. Much earlier, Fraser and Cordina (1999) applied DEA to examine the TE of input use in irrigated dairy farming system in Northern Victoria, Australia. In their research, DEA was found as a useful technique leading policy makers to benchmark units by finding the relationship among inputs and outputs simultaneously. DEA model was applied to analyse TE of a number of extensive livestock farms in Spain (Gaspar et al., 2009). In 17 districts of the East African countries, one- third of dairy farms had TE scores below 25% indicating the need to improve the output level by at least 75% without any increase in inputs use (Gelan and Muriithi, 2012). In 2011, DEA was coupled with life cycle assessment (LCA) to benchmark the operational and environmental performance of dairy farms (Iribarren et al., 2011). Level of TE was examined on Irish dairy farms by DEA. Based on this study, efficient farms had higher productivity (per cow and per hectare), higher milk quality standard and greater land quality (Kelly et al., 2012). DEA was also used to estimate the technical and environmental efficiency of dairy farming in Scotland. The farms with higher TE and greater milk production had lower negative impacts on environment (Shortall and Barnes, 2013).

In DEA, there are several methods for measuring efficiency changes over time, e.g. the window analysis and the Malmquist index (Al-Refaie et al., 2015; Lin and Ge, 2019; Pérez et al., 2017). To cope with the long-time courses, the dynamic DEA model (window analysis) enables to measure TE during a period of time. In this method, which is based on the moving average, a DMU is treated in each period (year) as if it is a different DMU. Therefore, the performance of each DMU can be compared with its performance in other periods; as far as it is compared with other DMUs in the same period (Ramanathan, 2003).

Application of window DEA (W-DEA) analysis model in agriculture was detected for sectorial studies over periods. Hemmasi et al. (2011) studied the wood panel manufacturing industry in Iran for a period of five years using W-DEA analysis. Malaysian aquaculture industry was investigated in different states (regional areas) during nine years (Mustapha et al., 2013). In another study, TE of agriculture in EU countries was assessed over 2003-2011 period. All member states of the EU have the potential to reach higher efficiency levels while the Eastern members (recently became EU members) are less efficient compared to older member states (Vlontzos and Niavis, 2014). In 2017, the impact of greenhouse gas emissions, as an undesirable output, was assessed in EU member countries during 2006-2012. A significant variation on efficiency score was observed among UE countries is spite of a stable policy framework (Vlontzos and Pardalos, 2017). Slack-Based Model (SBM) was incorporated to DEA and in addition to Life Cycle Analysis (LCA) to estimate the environmental efficiency and emission reduction potential of dairy farms in Italy (Cecchini et al., 2018). Moreover, the SBM was applied to compute the ecological energy efficiency of 30 regions in China during the period 2005–2009 (Li and Hu, 2012). Window analysis method was applied by Masuda (2018) to the 2005-2011 statistical data in order to examine the effect of increasing scale of rice farming on energy efficiency. From the reviewed studies, it can be found that the W-DEA model can effectively measure the TE of milk production as well as comparing the performance of dairy farming in Iran over time while each unit can be examined for its performance during one year.

As far as it is known, assessing productivity of the dairy sector at national-level and over time has not been widely studied in Iran. This research tries to partially fill the gaps found in existing literature by applying Window DEA (W-DEA) model to conduct a dynamic evaluation of TE of dairy farming in 25 provinces of Iran during the period 1994-2016, using statistical data collected in 1994, 2000, 2007, 2013 and 2016. Meanwhile, the provinces will be ranked by means of the calculated efficiency scores and the milk production in Iran during 22 years. To present the substantial amount of inefficiency and compare the radial and non-radial methods, SBM was coupled with W-DEA (SBM-W-DEA model). The rest of this paper is organized as follows: section 2 describes data collection, energy assessment and the DEA model and its variables. The results of efficiency assessment per province and during 1994 to 2016 and discussions over the findings are presented in sections 3 and 4. In the final section, the concluding remarks are presented.

2. Material and methods

In this section, an input-oriented W-DEA model and incorporation of SBM are described to evaluate the TE of dairy farming based on energy consumption of inputs and milk production levels. Ultimately, the provinces in Iran will be compared based on the TE scores and milk production levels using statistical analysis (ANOVA and mean comparisons) during 1994 to 2016.

2.1. Description of the dairy system in Iran and data inventory

The study involved 25 provinces using the panel data collected by the National census program of the Statistics Centre in Iran during 1994 to 2016. The last report of this census was published in 2016. Main characteristics and management conditions of dairy farms are shown in Table 1. During the studied period, the total number of dairy farms has increased (55%) and reached to 13,193 units in 2016 while the milk production has quadrupled. It is seen that milk yield i.e. milk production per head, has increased over the years.

Table 1. Dairy farming characteristics in Iran during 1994-2016

Indicators ǀ Year	1994	2000	2007	2013	2016
Dairy farms (n)	8,464	9,345	10,644	12,334	13,193
Heads (n)	455,161	510,038	917,460	1,022,223	1,159,153
Total milk (kt)	799.4	1,215	2,414.9	8,268.3	4,086.7
Milk yield (kg head^{-1})	1756.3	2381.98	2632.05	2776.85	3537.82

2.2. DEA model

The DEA method is a non-parametric mathematical programming approach for evaluating a set of DMUs in a macro- economy level. Relative efficiency can be examined when a problem is dealing with multiple inputs and outputs (Wang et al., 2013). The objective of such mathematical programming technique is maximizing the TE that is the ratio of outputs over inputs with regard to the constraint of equal to and less than unity of TE (Mustapha et al., 2013). DEA model is classified into two well-known models, namely constant returns to scale (CRS) and variable return to scale (VRS) (Charnes et al., 1978; Liu et al., 2013).

The CRS model (also called CCR) considers that an increase in inputs leads to a proportional increase in outputs while the VRS model (also called BCC) assumes a variable change in outputs as a result of an increase in inputs. Another assumption is that in CRS model, no significant relationship between the scale of operations and efficiency is considered; i.e. under a controllable situation, input minimisation and output maximisation produce the same relative efficiency scores.

DEA model can be classified as input-oriented model and output-oriented model. The input-oriented model assumes a constant output level while the efficiency improvement is reducing the input use. Contrariwise, output-oriented model seeks the ways to improve efficiency while increasing the output and keeps the input level constant (Charnes et al., 1978). Using a linear programming (LP) problem, an input-oriented CCR DEA model is formulated in Eq. S1 in the SI. Likewise, the BCC model can be formulated as Eq. S2.

DEA model is based on radial efficiency measure, where the difference among inefficient DMUs and efficient ones are not taken into account (Morita et al., 2005). In this regard, slack-based model was developed to discover the impact on efficiency by a non-proportional reduction. Based on this model, the evaluated DMUs will be called as efficient if the optimal value (the slack value) is equal to zero. Otherwise, the positive and negative values (non-zero optimal) identifies the excess utilization of inputs or deficit in the outputs. The SBM efficiency score was obtained from the linear program presented in the Eqs. (S3-S5) of the SI.

Results of DEA models are mainly reported by the values calculated for technical efficiency (TE), pure technical efficiency (PTE) and scale efficiency (SE). TE is defined as an indicator of the efficiency of resource allocation to each DMU when CCR is used (Yan, 2019). PTE is a scale for relative farm performance by BCC model. Therefore, CCR measures inefficiencies due to size of operations (units) and the input/output level while BCC measures PTE by removing the effect of scale size (Avkiran, 2001). On the contrary, SE measures the impact of scale size changes on productivity of DMUs and demonstrates how efficiency scores vary between CCR and BCC models (Coelli et al., 2005). The relation between these three efficiency scales is expressed as (Eq. 1):

$$SE = TE/PTE \tag{1}$$

2.3. Window DEA analysis

Window analysis has shown to be an appropriate approach to evaluate the efficiency variations over specific time periods (Vlontzos and Pardalos, 2017; Wang et al., 2013). When W-DEA model is performed, efficiency scores are obtained for each *j* DMUs (*j*= 1,2,3,…,*n*) with *m* inputs and *s* outputs over T (*t*= 1,2,3,…,*T*) periods. The input vector X_n^t and output vector Y_n^t were assumed as follows (Jia and Yuan, 2017):

$$X_n^t = \begin{bmatrix} x_n^{1t} \\ \vdots \\ x_n^{mt} \end{bmatrix} \tag{2}$$

$$Y_n^t = \begin{bmatrix} y_n^{1t} \\ \vdots \\ y_n^{st} \end{bmatrix} \tag{3}$$

By assuming that the window analysis starts at time *k* ($1 \leq k \leq T$) and a window length (number of windows) is *w* ($1 \leq k \leq T\text{-}k$), the arrangement of inputs and outputs can be denoted as follows:

$$X^{k+w} = \begin{bmatrix} x_1^k & x_2^k & \dots & x_n^k \\ x_1^{k+1} & x_2^{k+1} & \dots & x_n^{k+1} \\ \vdots & \vdots & \ddots & \vdots \\ x_1^{k+w} & x_2^{k+w} & \dots & x_n^{k+w} \end{bmatrix} \text{ and } Y^{k+w} = \begin{bmatrix} y_1^k & y_2^k & \dots & y_n^k \\ y_1^{k+1} & y_2^{k+1} & \dots & y_n^{k+1} \\ \vdots & \vdots & \ddots & \vdots \\ y_1^{k+w} & y_2^{k+w} & \dots & y_n^{k+w} \end{bmatrix}$$

Applying these matrices to the inputs and outputs of a regular CCR (or BCC) model generates the results of the W-DEA model.

In this method, each province is considered as a different DMU in each year. The examined time period is from 1994 to 2016, covering 5 national census of dairy farming sector in Iran (*w*=5). Therefore, the total number of DMUs for this W-DEA analysis is 125 (25 provinces × 5 periods). It should be noted here that country divisions has been changed over the years in Iran. To have a consistent list of provinces over the years, the data of new provinces were aggregated by their corresponding previous division. Here, the DEA considers one output measure, i.e. milk yield and nine input measures. Since for a W-DEA model, efficiency scores can be interpreted via different width of windows (*w*), i.e. the number of years included in the analysis, the TE can be evaluated in different ways by modifying this parameter. Therefore, w was selected as five different values (w=1, 2, 3, 4 and 5) where w=1 evaluates a DMU per period (for the total 125 DMUs, each window consists of 25 DMUs) and w = 5, corresponds to an overall analysis through the entire period (22 years in 5 periods). In this paper where the term efficiency is used, the TE is aggregated by windows and over the years. To perform the DEA and SBM analysis, DEA-Solver Pro 15.0 was used and the statistical analysis were conducted by Genstat 19th edition.

2.4. Energy assessment

The inputs accounted in this study are fossil fuels, electricity, water, feed and labour. The fossil fuels were kerosene, diesel, petrol, liquid gas and natural gas. Machinery and equipment energy for activities within the farm were neglected due to complexity, lack of statistical data in dairy farming sector and the assumption of similarities among the farms. As outputs, this study considers the milk as the main product of dairy farms. The main energy equivalent coefficients used are presented in Table S1 of the Supplementary Information (SI). A careful attention was given to select the energy coefficients based on the characteristics of dairy farms in Iran.

3. Results and discussion

3.1. Energy consumption

Table 2 presents the average energy consumption of dairy farming per studied period. Among the inputs, electricity and diesel fuel were the highest contributors to energy consumption and were so variable during years whereas it can be seen that diesel fuel share has been substituted by electricity over time. The high share of fuel and electricity in total energy consumption was in consistence with previous studies (Koesling et al., 2017; Pagani et al., 2016; Uzal, 2013; Vigne et al., 2012). The indirect energy of feed (energy consumed during production of feed) had a significant increase over years and contributed to a large extent to the total energy use on dairy farms. Due to improvements in the level of mechanization and application of machinery, labour energy has dramatically decreased during the years.

Shine et al. (2020) have reported electricity and diesel use as the second greatest consumers of energy, followed by the indirect energy required for the production of fertilizer. It was reported that electrical energy made up on average 48% of direct usage across all studies (conventional and organic farms) while other liquid fuels were responsible for the remaining 52%. Upton et al. (2013) found that electricity energy was the largest source of total direct energy use (60%), which is the third largest contributor to total energy use behind fertilizer application (57%) and concentrates feed (21%) (Upton et al., 2013). Meul et al. (2007) utilized a representative set of Flemish farms to analyze the energy use efficiency between 1989–1990 and 2000–2001 periods. It was shown that electricity use contributed to 9.5% of the overall energy use on dairy farms in 2000-2001.

Table 2. Average energy consumption, total energy input and the milk yield during 1994 to 2016

Inputs	Unit	1994	2000	2007	2013	2016
Kerosene	MJ (kg milk)$^{-1}$	258.63	1136.77	890.32	402.54	504.02
	%	*0.86*	*1.36*	*3.82*	*2.12*	*3.10*
Diesel	MJ (kg milk)$^{-1}$	784.43	7168.30	2296.94	4373.89	3343.85
	%	*2.59*	*8.60*	*9.86*	*23.07*	*20.55*
Petrol	MJ (kg milk)$^{-1}$	336.41	113.96	770.75	648.50	961.66
	%	*1.11*	*0.14*	*3.31*	*3.42*	*5.91*
Liquid gas	MJ (kg milk)$^{-1}$	251.98	47.74	1114.25	160.09	142.49
	%	*0.83*	*0.06*	*4.78*	*0.84*	*0.88*
Natural gas	MJ (kg milk)$^{-1}$	8.41	12029.47	137.20	504.11	744.11
	%	*0.03*	*14.44*	*0.59*	*2.66*	*4.57*
Electricity	MJ (kg milk)$^{-1}$	23471.47	44934.75	10744.80	1611.40	2248.97
	%	*77.62*	*53.93*	*46.11*	*8.50*	*13.82*
Water	MJ (kg milk)$^{-1}$	29.66	255.87	187.61	549.22	82.03
	%	*0.10*	*0.31*	*0.81*	*2.90*	*0.50*
Feed	MJ (kg milk)$^{-1}$	4919.09	17208.84	7092.48	10643.55	8182.55
	%	*16.27*	*20.65*	*30.44*	*56.15*	*50.29*
Labour	MJ (kg milk)$^{-1}$	179.76	423.26	65.80	61.83	61.10
	%	*0.59*	*0.51*	*0.28*	*0.33*	*0.38*
Total input energy	MJ (kg milk)$^{-1}$	30239.83	83318.97	23300.15	18955.14	16270.79
Milk yield	t (head)$^{-1}$	1.7	1.8	3.18	3.18	3.10

3.2. Results of DEA window analysis

By the inventory executed for energy consumption on dairy farms in 25 provinces of Iran, the input-oriented CCR model (window-I- C model) and the input-oriented BCC (or window-I-V) were applied to compute the TE, PTE and SE of dairy units. This dynamic analysis generated a DEA matrix including the data in Table 2 as DEA inputs and milk yield as the output of DEA model. Results of the analysis are summarised in Table 3. The corresponding disaggregated results are presented in the Excel Supplementary Information file (E-SI) file.

By comparing provinces, it was shown that in three provinces including Bushehr, Zanjan, and Hormozgan, TE was higher. Dairy farming in these provinces can be characterized as intensive. Intensive dairy production systems are characterized by the use of higher stocking rate (animal per hectare) and milk production per cow. This result is in a good agreement with similar studies assessed the production efficiency of intensive dairy farming systems (Álvarez et al., 2008; Gonzalez-Mejia et al., 2018) and would suggest future studies to investigate the impact of intensification on efficiency of these systems.

Table 3. Average TE, PTE and SE scores aggregated by years and obtained by W-DEA model

	TE					PTE					SE				
	W1	W2	W3	W4	W5	W1	W2	W3	W4	W5	W1	W2	W3	W4	W5
Bushehr	1	0.96	0.93	0.92	0.89	1	1	1	1	1	1	0.96	0.93	0.92	0.89
Zanjan	1	1	0.99	0.99	0.99	1	1	1	1	0.99	1	1	0.99	0.99	1
Hormozgan	1	1	0.99	0.98	0.97	1	1	1	1	1	1	1	0.99	0.98	0.97
Ardabil	0.99	0.99	0.99	0.98	0.98	1	1	1	1	1	0.99	0.99	0.99	0.98	0.98
Tehran	0.97	0.95	0.94	0.94	0.95	1	0.98	0.98	0.97	0.96	0.97	0.97	0.96	0.96	0.99
Yazd	0.94	0.93	0.90	0.92	0.93	0.96	0.95	0.93	0.94	0.95	0.98	0.98	0.97	0.97	0.98
Kohgiluyeh and …	0.94	0.91	0.88	0.88	0.87	0.99	0.96	0.93	0.94	0.94	0.95	0.95	0.94	0.94	0.93
Isfahan	0.91	0.87	0.84	0.82	0.85	0.96	0.93	0.91	0.91	0.90	0.95	0.94	0.92	0.91	0.95
Kurdestan	0.91	0.93	0.93	0.92	0.86	0.95	0.97	0.96	0.96	0.92	0.96	0.96	0.96	0.95	0.94
Charmahal and Bakhtiari	0.91	0.88	0.87	0.87	0.89	0.98	0.95	0.94	0.93	0.92	0.93	0.92	0.92	0.93	0.97
Sistan and Baluchestan	0.90	0.87	0.87	0.83	0.81	0.99	1	0.99	0.99	0.97	0.91	0.87	0.87	0.84	0.83
Khorasan Razavi	0.87	0.83	0.81	0.82	0.83	0.92	0.88	0.85	0.86	0.86	0.94	0.95	0.95	0.96	0.97
Hamedan	0.86	0.86	0.87	0.86	0.85	0.99	0.98	0.97	0.96	0.95	0.87	0.88	0.90	0.89	0.90
Gilan	0.86	0.81	0.76	0.80	0.81	0.91	0.88	0.83	0.86	0.86	0.94	0.92	0.91	0.93	0.94
Fars	0.85	0.85	0.81	0.84	0.81	0.95	0.94	0.91	0.92	0.92	0.89	0.90	0.90	0.90	0.88
Markazi	0.85	0.85	0.81	0.83	0.83	0.92	0.90	0.86	0.89	0.90	0.92	0.94	0.94	0.94	0.92
Kermanshah	0.85	0.83	0.80	0.80	0.80	0.91	0.90	0.88	0.86	0.83	0.93	0.92	0.91	0.93	0.96
Semnan	0.84	0.83	0.79	0.81	0.81	0.90	0.90	0.88	0.89	0.89	0.93	0.92	0.90	0.91	0.91
Mazandaran	0.83	0.79	0.77	0.75	0.74	0.90	0.86	0.84	0.82	0.81	0.91	0.92	0.92	0.91	0.92
Khuzastan	0.82	0.83	0.80	0.79	0.73	0.91	0.89	0.85	0.86	0.81	0.91	0.93	0.93	0.92	0.90
East Azerbaijan	0.80	0.78	0.76	0.75	0.74	0.93	0.90	0.87	0.87	0.85	0.85	0.86	0.88	0.87	0.87
Ilam	0.79	0.80	0.74	0.78	0.78	0.87	0.86	0.80	0.83	0.84	0.91	0.93	0.93	0.94	0.93
Kerman	0.77	0.75	0.73	0.74	0.75	0.93	0.91	0.87	0.88	0.85	0.84	0.82	0.83	0.84	0.89
West Azerbaijan	0.73	0.68	0.65	0.68	0.70	0.96	0.96	0.93	0.94	0.92	0.75	0.71	0.70	0.72	0.76
Luristan	0.62	0.60	0.63	0.58	0.56	0.94	0.92	0.93	0.92	0.91	0.66	0.65	0.68	0.63	0.62

The single most remarkable result to emerge from Table 3 is that PTE scores are greater than TE scores as the effect of scale size are removed in the BCC model. On the contrary, SE scores demonstrated the higher efficiency scores while varying between TE and PTE scores and indicating the impact of scale size changes on productivity of DMUs . The results of the study by Hosseinzadeh-Bandbafha et al. (2018) indicated the average score of TE, PTE and SE of dairy farmers in Qazvin province of Iran as 0.9, 0.94 and 0.95, respectively .

The W-DEA model for *w*=1 was run in order to identify significant differences between provinces while years were constant. An alternative of this approach is to expand the window width that is being assessed to consider not only the entire set of DMUs for one course of time but also the whole observations for the entire covered years (Lorenzo-Toja et al., 2018). Fig. 2 illustrates the temporal changes identified over time and windows (w=1,2,…,5). The distinction between *w*=1 and *w*=5 was significant as the latter has estimated the efficiencies inclusively.

Detailed results are represented in the Tables (S2-S4) of the SI file and the E-SI file. The average TE and PTE scores for *w*=5 were lower in comparison with *w*=1. In this case, the TE of each DMU was not only computed considering the performance of all other units but also its own performance during different courses of time. Hence, it can be concluded that W-DEA may contribute to compute a more accurate TE score.

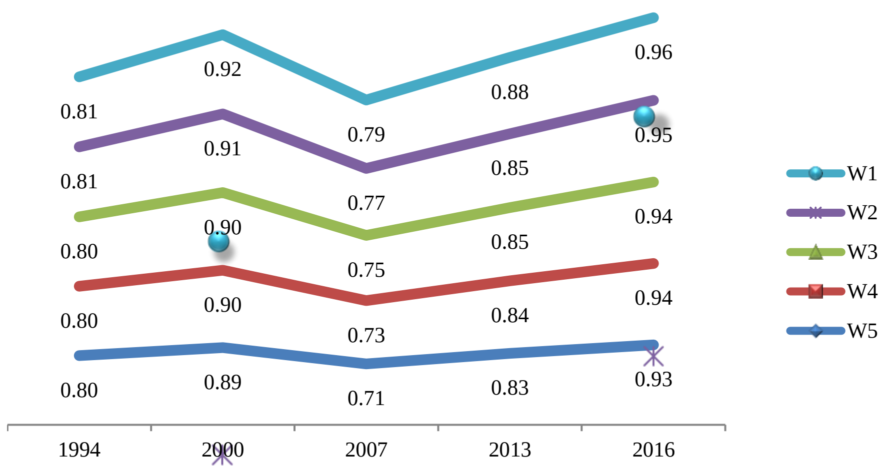

Fig. 2. Temporal changes of TE over different window states and time (W1 is for *w*=1, …, W5 is for *w*=5).

Table 4 presents the term-efficiency scores of dairy farming for the covered years and different provinces in Iran. Regarding individual periods, 2007 was, on average, the year with the lowest efficiency (0.75), followed by the year 1994 (0.81). The years 2016 and 2000 were found to have the highest number of term-efficient provinces (18 and 14, respectively). By comparing the whole 125 TE scores over provinces and years, it was concluded that all values (except for DMU20 in 2000) were more than 0.3. Moreover, more than 79% of the cases had term-efficiency of above 0.7.

The most remarkable result to emerge from Table 4 is that there were variation among dairy farming of different provinces. The fluctuations of TE reflect the instable policy framework, prices and the corresponding effect on resource consumption during 1994–2016. Looking at provinces with higher TE scores, it can be understood that provinces are distinctive in terms of the structural characteristics such as milk production, herd size and stocking rate. Therefore, it is obvious that there is a substantial space for resource management and improving structure of dairy farms in order to minimize energy consumption.

Hosseinzadeh-Bandbafha et al. (2018) reported that 42.5% and 53.2% of farms were efficient based on CCR and BCC models, respectively in dairy farms of Iran. In another study, the TE, PTE and SE were 44.6%, 74.48% and 53% in the 44 industrial dairy farms of Gilan province in Iran (Soltanali et al., 2016).

Table 4. Term TE scores of provinces aggregated by windows and obtained by W-DEA model

Provinces	1994	2000	2007	2013	2016	Average
Zanjan	1	1	0.98	1	1	1
Ardabil	1	1	1	0.93	1	0.99
Hormozgan	0.92	1	1	1	1	0.98
Tehran	1	1	0.92	0.87	1	0.96
Bushehr	1	0.77	1	1	0.96	0.94
Yazd	1	1	0.69	1	1	0.94
Kohgiluyeh and Boyer-Ahmad	0.85	0.99	0.68	1	1	0.90
Charmahal and Bakhtiari	1	1	0.81	0.69	1	0.90
Kurdestan	0.71	1	1	0.93	0.81	0.89
Isfahan	1	0.87	0.71	0.83	1	0.88
Hamedan	0.72	0.87	1	0.70	1	0.86

Khorasan Razavi	1	1	0.69	0.75	0.78	0.84
Sistan and Baluchestan	0.52	1	1	0.69	1	0.84
Markazi	0.70	0.94	0.56	1	1	0.84
Gilan	0.88	1	0.38	0.91	1	0.83
Kermanshah	0.84	1	0.72	0.59	1	0.83
Fars	0.67	1	0.60	1	0.86	0.83
Semnan	0.64	0.92	0.54	1	1	0.82
Mazandaran	0.77	0.83	0.75	0.60	1	0.79
Ilam	0.54	1	0.38	1	1	0.78
Khuzastan	0.31	1	0.72	0.86	1	0.78
East Azerbaijan	0.85	0.69	0.75	0.80	0.78	0.77
Kerman	1	0.76	0.57	0.83	0.65	0.76
West Azerbaijan	0.69	0.74	0.39	0.76	1	0.71
Luristan	0.51	0.21	0.96	0.56	0.72	0.59
Average	0.81	0.90	0.75	0.85	0.94	0.85

On national scale, the average TE of dairy farming was 0.85 over the whole studied period (Table 4). Zanjan, Ardabil and Hormozgan provinces were the highest efficient provinces while Luristan province showed the lowest TE. Considering the intensification level of production (milk production per cow and head of cattle per ha), it can be concluded that the efficient provinces are among provinces with intensive farming system. These high efficient provinces have mainly dairy farming as a small business, i.e. small scale dairy farms for livelihood of rural farmers. This is pertained to the low level of mechanization, energy consumption and hence the smaller scale of production. These results showed that small scale dairy farms with intensive system were closer to their energy frontier than large ones, suggesting a positive relationship between intensification and efficiency. A detailed review of dairy farming in Luristan province indicates that animal husbandry in the western mountainous areas of the country is not only aimed at milk production but also for meat production. This reveals that meat production efficiency needs to be considered along with their dairy farming system. To better demonstrate the detailed results of window analysis, the TE scores of all window widths are presented in the E-SI file. The results obviously showed that how the computed efficiency scores were influenced by the window DEA model.

Term efficiency changes against energy use is depicted in Fig. 3. Tehran province contributed most to energy use on dairy farms while this province was appeared to be fully efficient in 2000 and 2016. This graph also illustrates the energy use status associated with the TE. Provinces adjacent to the vertical axis consumed less energy while those located on the upper end of the vertical axis indicated higher TE scores. One major outcome of this finding is that for improving the performance of dairy sector, limiting energy consumption leading to improvements in energy efficiency is essential. Any reduction of inputs pertaining to increasing energy efficiency needs to be managed so that milk productivity remains at its highest level. For this purpose, Iranian livestock farming policies need to be reformed by applying mechanized systems, optimal strategies for water, electricity and fossil fuel consumption, feed management and improving herd characteristics. In general, the energy efficiency of Iranian dairy sector has increased during our study period, and this increase associated to a series of energy policies issued and carried out by the Iranian government in order to alleviate fuel consumption since 2010. Fuel subsidy removal and its effect on energy demand and potential energy savings have been found to be an efficient policy mechanism. However, further investigations are strongly recommended because a long-term review is required (Al-Mezeini et al., 2020). In the literature, no study has been published on assessing the efficiency of dairy farming sector in Iran in relation to energy consumption over the years; therefore, no comparison can be made between our results and previous studies.

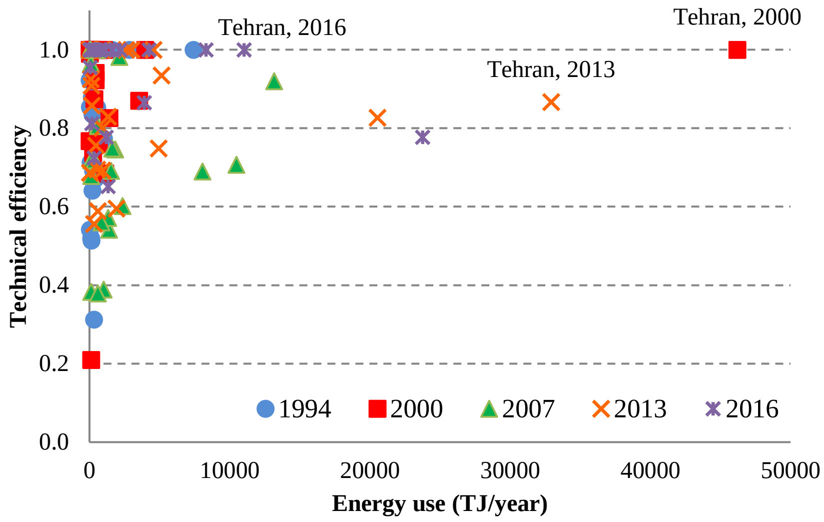

Fig. 3. Term efficiency versus energy use in dairy farms (1994-2016)

3.3. Results of SBM-W-DEA model

Table 5 presents the term-efficiency scores for the covered years and different provinces in Iran computed by the slack-based method. More results can be found in the SI file (Table S5 and S6). Regarding individual periods, 2007 and 2016 werethe years with, on average, the lowest (0.57) and highest (0.87) TE scores. Average TE of 0.83 was estimated by Cecchini et al. (2018) using SBM model to assess the TE of dairy farms in Umbria (Italy).

Table 5. Term TE scores aggregated by windows and obtained by SBM-W-DEA model

Provinces	1994	2000	2007	2013	2016	Average
Zanjan	1	1	0.88	1	1	0.98
Hormozgan	0.70	1	1	1	1	0.94
Ardabil	1	1	1	0.54	1	0.91
Tehran	1	1	0.72	0.60	1	0.86
Yazd	1	0.90	0.39	1	1	0.86
Bushehr	1	0.35	1	1	0.88	0.84
Charmahal and Bakhtiari	1	1	0.54	0.42	1	0.79
Sistan and Baluchestan	0.40	1	1	0.53	1	0.79
Hamedan	0.53	0.62	1	0.52	1	0.73
Isfahan	1	0.66	0.43	0.54	1	0.73
Ilam	0.34	1	0.28	1	1	0.73
Gilan	0.60	1	0.21	0.78	1	0.72
Kohgiluyeh and Boyer-Ahmad	0.21	0.91	0.45	1	1	0.71
Markazi	0.43	0.82	0.27	1	1	0.70
Khorasan Razavi	1	1	0.42	0.51	0.49	0.68
Fars	0.43	1	0.29	1	0.68	0.68
Semnan	0.44	0.60	0.33	1	1	0.67
Kurdestan	0.34	1	1	0.53	0.41	0.66

Kermanshah	0.33	1	0.40	0.49	1	0.64
Khuzastan	0.15	1	0.37	0.63	1	0.63
Mazandaran	0.63	0.65	0.45	0.45	0.96	0.63
Kerman	1	0.59	0.41	0.61	0.42	0.61
East Azerbaijan	0.69	0.47	0.43	0.56	0.54	0.54
West Azerbaijan	0.42	0.55	0.18	0.47	1.0	0.52
Luristan	0.30	0.21	0.85	0.33	0.41	0.42
Average	0.64	0.81	0.57	0.70	0.87	0.72

By analysing the results for a single years (Table 5), it was concluded that in 2016, there were 17 provinces with maximum SBM efficiency score, equal to 1, indicating the achievement of full efficiency. These provinces are therefore positioned along the efficient frontier, as demonstrated by the null values of inputs and output slacks, and have no margins to improve their performances, neither by reducing the inputs use nor by increasing the milk production. Besides, it can be derived from Table 5 that Luristan and West Azarbaijan provinces can be ranked as the least efficient provinces of Iran in this study while West Azarbaijan is ranked as the sixth highest milk producing city in Iran. As far as it is known, no study has integrated SBM-DEA model in the context of window analysis to estimate the TE of dairy cattle farms. Thus, comparisons could not be made with the results of this study.

A comparison of calculated efficiency scores using SBM-W-DEA model indicated smaller TE values compared to W-DEA results. According to Li et al. (2016), since the SBM model computed TE scores by considering input and output slacks simultaneously, they are not easy to interpret, although they provide an indication of overall efficiency. The difference between the estimated TE scores using these two models are reported in Table 6. In general, the efficiency scores of SBM were less than CCR efficiency scores for all windows and DMUs, in the sense that a CCR inefficient DMU never becomes SBM efficient. This is due to the fact that SBM considers not only the proportional reduction but also the slacks in the variables. The lower efficiency scores from the SBM model also put forward the capability of DEA models in comparing and evaluating the DMUs better (with less changes) than the radial models (You and Yan, 2011). Given that the highest difference was found in window 5, this may reflect the function of window analysis whereas in *w*=5, the TE of each DMU was computed in respect to not only the performance of all other units but also its own performance during different courses of time. The average TE scores from the radial model in assessing the TE of winter wheat production in Poland were also higher than the non-radial SBM model as reported by Pishgar-Komleh et al. (2020).

Table 6. The difference between TE_{CCR} and TE_{SBM} for different windows, DE (%)=(TE_{CCR}-TE_{SBM})*100

DMU	W1	W2	W3	W4	W5
Kurdestan	25%	28%	27%	26%	21%
East Azerbaijan	25%	23%	22%	22%	22%
West Azerbaijan	20%	16%	13%	16%	18%
Kermanshah	20%	18%	15%	16%	16%
Kohgiluyeh and Boyer-Ahmad	19%	17%	15%	16%	24%
Khorasan Razavi	17%	15%	13%	14%	16%
Luristan	17%	15%	21%	17%	19%
Isfahan	17%	14%	11%	11%	15%
Mazandaran	16%	14%	13%	12%	18%
Semnan	16%	15%	11%	14%	14%
Fars	16%	17%	14%	16%	14%
Kerman	16%	14%	12%	14%	15%
Markazi	14%	14%	10%	13%	13%
Bushehr	13%	9%	6%	5%	14%
Hamedan	13%	13%	14%	12%	12%
Khuzastan	12%	20%	18%	18%	14%
Charmahal and Bakhtiari	11%	9%	8%	8%	10%
Gilan	9%	9%	4%	8%	13%
Ardabil	8%	8%	8%	7%	8%
Tehran	8%	8%	8%	9%	10%
Ilam	7%	7%	2%	6%	5%
Yazd	6%	5%	2%	7%	12%
Sistan and Baluchestan	2%	8%	10%	8%	7%
Zanjan	0%	0%	2%	3%	6%
Hormozgan	0%	0%	9%	8%	7%
Average	**13%**	**13%**	**11%**	**12%**	**14%**

To better demonstrate the results obtained, the mean TE scores (derived from both models) were compared for three different groups of provinces with different milk production levels by conducting statistical ANOVA (Table 7). The ANOVA results indicated that the TE was significantly different between the lowest and highest milk producing provinces. Over the time, lower milk producing provinces have improved their TE however in general higher milk producing provinces have had declining efficiencies.

Table 7. Mean comparison of TE scores from two models based on different levels of milk production

Levels	Milk yield (kt)	1994	2000	2007	2013	2016
			W-DEA model			
Low	<20	0.77 [a]	0.90 [a]	0.72 [a]	0.92 [a]	0.97 [a]
Medium	20-100	0.82 [a]	0.90 [a]	0.77 [b]	0.76 [b]	0.92 [b]
High	>100	1 [b]	0.96 [b]	0.77 [b]	0.88 [c]	0.95 [a]
			SBM-W-DEA model			
Low	<20	0.57 [a]	0.80 [a]	0.57 [a]	0.81 [b]	0.90 [a]
Medium	20-100	0.69 [ab]	0.80 [a]	0.58 [a]	0.55 [a]	0.84 [a]
High	>100	1 [b]	0.89 [a]	0.52 [a]	0.76 [b]	0.89 [a]

[a, b, c] Means in the same column with different superscripts are significantly different ($P \leq 0.05$).

4. Implications of the results and recommendations

This study is the first step towards enhancing our understanding of the performance of dairy farming in different provinces of Iran related to the TE of energy use. The obtained results may have several implications for 1) policy makers in decision making into efficient allocation of resources to dairy farms as well as 2) for dairy farmers and stakeholders in their management decisions to enhance the milk production. Given the increasing milk production over the time (Table 2), a key to enhancing the TE of dairy farming in Iran could be improving the performance of dairy farming in terms of energy use. Our research suggests that there are two approaches for producing milk while increasing the TE followed by optimizing the energy consumption as follows:

- Coupling strategies for allocation of inputs to dairy farms aligned with their performance (TE) in terms of energy use and environmental indicators. Currently, there is no parameter to evaluate the productivity of energy use and environmental impacts of dairy farms in Iran and thus these units are merely evaluated based on their milk production without considering the sustainability aspects of their production. Innovative approaches to increase the use of renewable sources, optimum application of fossil fuels and fossil-based electricity, and expand the development of mechanization are recommended to be considered by policy makers. In this respect, policies should encourage farmers to use less inputs and maintain their production at reasonable levels using proper management practices.

- Allocation of public subsidies in both agriculture and livestock sectors needs to be modified in Iran. Currently, subsidies are allocated to regions and farms based on the farm size. Most large scale dairy farms are located in larger (most populated) cities such as Tehran, Isfahan and East Azerbaijan. However, this study showed that these provinces were ranked lower compared to provinces with small scale farms.

For optimum resource use in relation to the subsidies allocated to the farmers, the following recommendations are proposed:

- Subsidies to fossil fuels and electricity charges could be levied on farmers whose technical efficiency is higher. This will encourage farmers to improve their milk yield while keeping their resource use optimized.
- Subsidies allocation could be levied on farms which have improved their efficiency in two successive years while keeping their milk production constant.
- In respect to the fact that energy use in livestock production systems is directly related to environmental impacts and sustainability aspects, subsidies and resources can be allocated based on new established indicators. This would put forward the necessity to initiate renewable energy use on dairy farms.
- Lastly, an integrated data collection system would help further monitoring of dairy farming system.

Although parts of the objectives discussed above have been achieved, there are big gaps between the results obtained from this research and the practical application of these results by the users. This is primarily because there has been little interaction between scientists, extension agents, and farmers for practical application of the latest findings in Iran. In addition, the existing gaps can be due to the complexity of these systems in terms of the various factors affecting TE.

5. Conclusions

This study assessed the technical efficiency of milk production in Iran by applying the dynamic data envelopment analysis model (W-DEA). The application of this approach to different provinces of Iran showed its suitability to measure the technical efficiency of entities over a period of time (from 1994 till 2016), identifying the efficient and inefficient provinces in terms of energy use. The obtained results were compared with slack based model coupled with W-DEA model. By comparing the performance of different provinces grouped by the milk production, it was found that the technical efficiency of dairy farming in high milk producing regions is not as high as those with lower milk production. With these results, it is suggested to adjust dairy farming policies according to the production efficiency of milk production on farm level and/or on regional level. In conclusions, the diverse results of this study indicates the necessity to regular monitoring of the efficiency improvements during formulation of strategies, application of technology and allocation of subsidies to dairy farmers.

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Supplementary Information file

Dynamic energy efficiency assessment of dairy farming system in Iran: application of Window Data Envelopment Analysis (W-DEA)

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S1. DEA model

The radial DEA model (Eq. S1 and Eq. S2) concerns the proportionate change of input or output values without considering the slacks. The CCR and BCC models are formulated as a linear programing model as follows:

$$
\begin{aligned}
&\max \sum_{r=1}^{s} u_r y_{rj} \\
&\textit{s.t.:} \\
&\sum_{i=1}^{m} v_i x_{ij} = 1 \\
&\sum_{r=1}^{s} u_r y_{rj} - \sum_{i=1}^{m} v_i x_{ij} \le 0 \qquad \forall j, \\
&u_r, v_i \ge 0 \qquad \forall i, r.
\end{aligned}
\tag{S1}
$$

$$
\begin{aligned}
&\max \sum_{r=1}^{s} u_r y_{rj} \\
&\textit{s.t. :} \\
&\sum_{r=1}^{s} u_r y_{rj} - \sum_{i=1}^{m} v_i x_{ij} \le 0 \qquad \forall j, \\
&u_r, v_i \ge 0 \qquad \forall i, r.
\end{aligned}
\tag{S2}
$$

S2. Slack-Based Model (SBM)

SBM was first introduced and developed by (Tone, 2001). Efficiency score of a SBM problem expressed as follows:

$$
\begin{aligned}
&min_{\lambda, s^-, s^+} \quad \rho = \frac{1 - (1/m) \sum_{i=1}^{m} s_i^- / x_{i0}}{1 + (1/s) \sum_{r=1}^{s} s_r^+ / y_{r0}} \\
&\textit{s.t.:} \\
&x_0 = X\lambda + s^- \quad ; \quad y_0 = Y\lambda - s^+ \quad ; \quad \lambda \ge 0 \ , \quad s^- \ge 0 \ , \quad s^+ \ge 0
\end{aligned}
\tag{S3}
$$

where *x* and *y* are vectors of inputs and outputs; *i* and *r* indicate indices for inputs and outputs; *j* defines the firms; λ denotes a nonnegative vector; s^- and s^+ are the input excess and output shortfall, respectively.

The above equation can easily be formulated in the similar way of CCR model as follows:

$$min_{t,\lambda,s^-,s^+} \quad \tau = t - \frac{1}{m}\sum_{i=1}^{m} ts_i^- / x_{i0} \qquad \text{S4}$$

S.t.:

$$1 = t + \frac{1}{s}\sum_{r=1}^{s} ts_r^+ / y_{r0} \;\; ; \; x_0 = X\lambda + s^- \; ; \;\; y_0 = Y\lambda - s^+ \; ; \; \lambda \geq 0 \, , \; s^- \geq 0 \, , \; s^+ \geq 0 \, , \; t > 0$$

The above problem can be transformed into the following linear programing problem (Tone, 2001):

$$\max \sum_{r=1}^{s} u_r^- y_{rj}^- + \sum_{i=1}^{m} v_i^+ x_{ij}^+$$

s.t. :

$$\begin{aligned} &\sum_{j=1}^{n} \lambda_j \, x_{ij} + s_i^- = x_{io} \qquad i = 1,2, \ldots, m; \\ &\sum_{j=1}^{n} \lambda_j y_{rj} - s_r^+ = y_{ro} \qquad r = 1,2, \ldots, s; \\ &\lambda_j, s_i^-, s_r^+ \geq 0 \end{aligned} \qquad \text{S5}$$

Where j represents *jth* DMUs ($j=1,2,.., n$). The above model denotes the input-oriented SBM model.

Table 2. Embodied energy used in energy assessment

Input (unit)	Energy (MJ unit^{-1})	Reference
Kerosene (l)	36.7	(Kitani and Jungbluth, 1999)
Diesel (l)	47.8	(Kitani and Jungbluth, 1999)
Gasoline (l)	46.3	(Kitani and Jungbluth, 1999)
Liquid gas (l)	32.3	(Kitani and Jungbluth, 1999)
Natural gas (m^3)	49.5	(Kitani and Jungbluth, 1999)
Electricity (kWh)	11.93	(Ozkan et al., 2004)
Water (m^3)	1.02	(Acaroglu, 1998)
Labour (h)	1.96	(Kitani and Jungbluth, 1999)
Feed (kg)		
Barely	3.81	(Sainz, 2003)
Wheat bran	0.32	(Sainz, 2003)
Beet pulp	12.12	(Sainz, 2003)
Molasses	5.81	(Sainz, 2003)
Soybean meal	5.61	(Sainz, 2003)
Concentrate	6.3	(Meul et al., 2007)
Hay	2.77	(Sainz, 2003)
Clover	2.26	(Nasrollahi-Sarvaghaji et al., 2014)
Corn silage	2.33	(Sainz, 2003)
Maize	5.13	(Sainz, 2003)
Alfalfa	1.59	(Sainz, 2003)

Table S2. Technical Efficiency scores (TE) and standard deviations (SD) per individual province (Window 1) by W-DEA model

Province	DMU	TE					PTE					SE				
		1994	2000	2007	2013	2016	1994	2000	2007	2013	2016	1994	2000	2007	2013	2016
East Azerbaijan	DMU1	0.85	0.72	0.81	0.80	0.80	1	0.96	0.82	1	0.89	0.85	0.75	0.99	0.80	0.90
West Azerbaijan	DMU2	0.69	0.74	0.39	0.82	1	0.94	1	0.88	1	1	0.74	0.74	0.44	0.82	1
Ardabil	DMU3	1	1	1	0.94	1	1	1	1	1	1	1	1	1	0.94	1
Isfahan	DMU4	1	0.93	0.81	0.83	1	1	0.95	0.90	0.97	1	1	0.97	0.90	0.86	1
Ilam	DMU5	0.57	1	0.40	1	1	0.83	1	0.52	1	1	0.69	1	0.76	1	1
Bushehr	DMU6	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Tehran	DMU7	1	1	0.99	0.87	1	1	1	1	1	1	1	1	0.99	0.87	1
Charmahal and Bakhtiari	DMU8	1	1	0.86	0.69	1	1	1	0.95	0.95	1	1	1	0.90	0.73	1
Khorasan Razavi	DMU9	1	1	0.73	0.76	0.85	1	1	0.80	0.94	0.89	1	1	0.91	0.81	0.95
Khuzastan	DMU10	0.33	1	0.79	1	1	0.73	1	0.80	1	1	0.45	1	0.99	1	1
Zanjan	DMU11	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Semnan	DMU12	0.65	0.95	0.59	1	1	0.76	1	0.75	1	1	0.86	0.95	0.79	1	1
Sistan and Baluchestan	DMU13	0.52	1	1	1	1	0.96	1	1	1	1	0.54	1	1	1	1
Fars	DMU14	0.67	1	0.64	1	0.95	1	1	0.78	1	0.99	0.67	1	0.82	1	0.95
Kurdestan	DMU15	0.71	1	1	0.97	0.87	0.85	1	1	1	0.91	0.83	1	1	0.97	0.95
Kerman	DMU16	1	0.76	0.57	0.88	0.66	1	1	0.85	1	0.79	1	0.76	0.68	0.88	0.84
Kermanshah	DMU17	0.84	1	0.80	0.60	1	0.84	1	1	0.73	1	1	1	0.80	0.83	1
Kohgiluyeh and Boyer-Ahmad	DMU18	0.86	1	0.83	1	1	1	1	0.94	1	1	0.86	1	0.89	1	1
Gilan	DMU19	0.88	1	0.41	1	1	1	1	0.57	1	1	0.88	1	0.72	1	1
Luristan	DMU20	0.51	0.21	1	0.57	0.79	0.92	0.95	1	0.81	1	0.56	0.22	1	0.71	0.79
Mazandaran	DMU21	0.77	0.87	0.86	0.62	1	0.90	0.88	0.93	0.81	1	0.86	0.99	0.93	0.77	1
Markazi	DMU22	0.70	0.94	0.60	1	1	1	1	0.60	1	1	0.70	0.94	0.99	1	1
Hormozgan	DMU23	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Hamedan	DMU24	0.72	0.87	1	0.72	1	0.93	1	1	1	1	0.77	0.87	1	0.72	1
Yazd	DMU25	1	1	0.72	1	1	1	1	0.80	1	1	1	1	0.90	1	1
Average		**0.81**	**0.92**	**0.79**	**0.88**	**0.96**	**0.95**	**0.99**	**0.88**	**0.97**	**0.98**	**0.85**	**0.93**	**0.90**	**0.91**	**0.98**

Table S3. Technical Efficiency scores (TE) and standard deviations (SD) per individual province (Window 5) by W-DEA model

Province	DMU	TE					PTE					SE				
		1994	2000	2007	2013	2016	1994	2000	2007	2013	2016	1994	2000	2007	2013	2016
East Azerbaijan	DMU1	0.85	0.65	0.65	0.80	0.75	1	0.79	0.65	0.97	0.84	0.85	0.83	1	0.82	0.90
West Azerbaijan	DMU2	0.69	0.74	0.39	0.70	1	0.94	1	0.73	0.96	1	0.74	0.74	0.53	0.73	1
Ardabil	DMU3	1	1	1	0.92	1	1	1	1	1	1	1	1	1	0.92	1
Isfahan	DMU4	1	0.81	0.62	0.83	1	1	0.94	0.69	0.87	1	1	0.87	0.89	0.95	1
Ilam	DMU5	0.52	1	0.36	1	1	0.77	1	0.41	1	1	0.68	1	0.87	1	1
Bushehr	DMU6	1	0.67	1	1	0.78	1	1	1	1	1	1	0.67	1	1	0.78
Tehran	DMU7	1	1	0.88	0.86	1	1	1	0.92	0.87	1	1	1	0.95	1	1
Charmahal and Bakhtiari	DMU8	1	1	0.77	0.69	1	1	1	0.80	0.79	1	1	1	0.96	0.88	1
Khorasan Razavi	DMU9	1	1	0.67	0.74	0.75	1	1	0.67	0.79	0.82	1	1	1	0.94	0.91
Khuzastan	DMU10	0.30	1	0.59	0.78	1	0.68	1	0.61	0.78	1	0.45	1	0.97	0.99	1
Zanjan	DMU11	1	1	0.95	1	1	1	1	0.95	1	1	1	1	1	1	1
Semnan	DMU12	0.64	0.91	0.50	1	1	0.75	1	0.68	1	1	0.85	0.91	0.74	1	1
Sistan and Baluchestan	DMU13	0.52	1	1	0.51	1	0.96	1	1	0.91	1	0.54	1	1	0.56	1
Fars	DMU14	0.67	1	0.55	1	0.84	1	1	0.64	1	0.97	0.67	1	0.85	1	0.87
Kurdestan	DMU15	0.71	1	1	0.88	0.72	0.85	1	1	1	0.72	0.83	1	1	0.88	1
Kerman	DMU16	1	0.76	0.57	0.80	0.65	1	1	0.67	0.82	0.78	1	0.76	0.85	0.98	0.83
Kermanshah	DMU17	0.84	1	0.58	0.58	1	0.84	1	0.68	0.65	1	1	1	0.85	0.88	1
Kohgiluyeh and Boyer-Ahmad	DMU18	0.85	0.95	0.56	1	1	1	1	0.69	1	1	0.85	0.95	0.82	1	1
Gilan	DMU19	0.88	1	0.35	0.80	1	1	1	0.47	0.84	1	0.88	1	0.75	0.96	1
Luristan	DMU20	0.51	0.21	0.90	0.54	0.64	0.92	0.95	1	0.77	0.88	0.56	0.22	0.90	0.70	0.73
Mazandaran	DMU21	0.77	0.79	0.58	0.57	0.99	0.90	0.83	0.64	0.67	1	0.86	0.96	0.90	0.85	0.99
Markazi	DMU22	0.70	0.94	0.50	1	1	1	1	0.50	1	1	0.70	0.94	1	1	1
Hormozgan	DMU23	0.87	1	1	1	1	1	1	1	1	1	0.87	1	1	1	1
Hamedan	DMU24	0.72	0.87	1	0.66	1	0.93	1	1	0.80	1	0.77	0.87	1	0.82	1
Yazd	DMU25	1	1	0.67	1	1	1	1	0.76	1	1	1	1	0.88	1	1
Average		**0.80**	**0.89**	**0.71**	**0.83**	**0.93**	**0.94**	**0.98**	**0.77**	**0.90**	**0.96**	**0.84**	**0.91**	**0.91**	**0.91**	**0.96**

Table S4. Average TE scores through window 3 (*w*=3) by W-DEA model

Province	DMU	1994-2000-2007	2000-2007-2013	2007-2013-2016
East Azerbaijan	DMU1	0.76	0.76	0.77
West Azerbaijan	DMU2	0.61	0.64	0.70
Ardabil	DMU3	1	0.98	0.98
Isfahan	DMU4	0.90	0.78	0.83
Ilam	DMU5	0.63	0.80	0.80
Bushehr	DMU6	0.89	0.89	1
Tehran	DMU7	1	0.92	0.92
Charmahal and Bakhtiari	DMU8	0.95	0.83	0.82
Khorasan Razavi	DMU9	0.91	0.80	0.72
Khuzastan	DMU10	0.64	0.89	0.86
Zanjan	DMU11	1	1	0.98
Semnan	DMU12	0.71	0.81	0.84
Sistan and Baluchestan	DMU13	0.84	0.88	0.88
Fars	DMU14	0.74	0.88	0.82
Kurdestan	DMU15	0.90	0.98	0.90
Kerman	DMU16	0.78	0.73	0.67
Kermanshah	DMU17	0.80	0.80	0.79
Kohgiluyeh and Boyer-Ahmad	DMU18	0.88	0.88	0.88
Gilan	DMU19	0.76	0.79	0.73
Luristan	DMU20	0.54	0.59	0.76
Mazandaran	DMU21	0.78	0.74	0.78
Markazi	DMU22	0.72	0.84	0.86
Hormozgan	DMU23	0.96	1	1
Hamedan	DMU24	0.86	0.86	0.90
Yazd	DMU25	0.91	0.90	0.89

Table S5. Average TE, PTE and SE scores of provinces aggregated by year and obtained by SBM-W-DEA model

	TE					PTE					SE				
	W1	W2	W3	W4	W5	W1	W2	W3	W4	W5	W1	W2	W3	W4	W5
Zanjan	1	1	0.98	0.97	0.93	1	1.11	1	1	0.93	1	0.90	0.98	0.97	1
Hormozgan	1	1	0.90	0.90	0.90	1	1.28	1	1	1	1	0.78	0.90	0.90	0.90
Ardabil	0.91	0.91	0.91	0.91	0.91	1	1.77	1	1	1	0.91	0.51	0.91	0.91	0.91
Tehran	0.89	0.87	0.86	0.84	0.84	1	0.96	0.95	0.92	0.86	0.89	0.90	0.91	0.92	0.99
Sistan and Baluchestan	0.88	0.79	0.77	0.75	0.74	0.93	1.06	0.91	0.91	0.88	0.95	0.74	0.84	0.82	0.84
Yazd	0.88	0.88	0.88	0.85	0.81	0.88	1.03	0.88	0.88	0.88	1	0.86	1	0.96	0.92
Bushehr	0.87	0.87	0.87	0.87	0.75	1	1.52	1	1	1	0.87	0.57	0.87	0.87	0.75
Charmahal and Bakhtiari	0.80	0.79	0.79	0.79	0.79	0.89	1.01	0.86	0.85	0.81	0.89	0.79	0.92	0.93	0.97
Gilan	0.77	0.72	0.72	0.72	0.67	0.86	0.84	0.82	0.82	0.76	0.89	0.86	0.88	0.88	0.88
Kohgiluyeh and Boyer-Ahmad	0.75	0.74	0.73	0.73	0.63	0.94	1.03	0.91	0.90	0.89	0.80	0.72	0.80	0.81	0.72
Isfahan	0.74	0.74	0.73	0.71	0.70	0.82	0.80	0.79	0.79	0.76	0.90	0.92	0.92	0.91	0.93
Hamedan	0.74	0.73	0.73	0.73	0.73	0.95	0.97	0.89	0.88	0.86	0.77	0.75	0.82	0.83	0.85
Ilam	0.73	0.73	0.73	0.73	0.73	0.76	0.82	0.76	0.76	0.76	0.96	0.88	0.96	0.96	0.96
Khuzastan	0.71	0.62	0.62	0.61	0.60	0.75	0.74	0.71	0.70	0.65	0.94	0.84	0.88	0.86	0.92
Markazi	0.70	0.70	0.70	0.70	0.70	0.86	0.86	0.86	0.86	0.85	0.82	0.82	0.82	0.82	0.82
Khorasan Razavi	0.70	0.68	0.68	0.68	0.68	0.77	0.84	0.73	0.72	0.71	0.91	0.81	0.94	0.94	0.96
Fars	0.69	0.68	0.68	0.68	0.67	0.85	0.86	0.84	0.83	0.82	0.81	0.79	0.81	0.81	0.82
Semnan	0.68	0.67	0.67	0.67	0.67	0.78	0.79	0.78	0.78	0.78	0.86	0.86	0.86	0.86	0.86
Mazandaran	0.66	0.65	0.64	0.62	0.56	0.75	0.73	0.72	0.70	0.66	0.89	0.89	0.89	0.89	0.85
Kurdestan	0.66	0.66	0.66	0.65	0.65	0.78	1.42	0.78	0.78	0.77	0.85	0.46	0.84	0.84	0.84
Kermanshah	0.65	0.65	0.65	0.64	0.63	0.79	0.80	0.74	0.72	0.65	0.82	0.81	0.87	0.89	0.97
Kerman	0.62	0.61	0.60	0.60	0.60	0.80	0.79	0.75	0.75	0.73	0.78	0.76	0.81	0.81	0.82
East Azerbaijan	0.55	0.54	0.54	0.53	0.52	0.75	0.72	0.71	0.71	0.68	0.74	0.76	0.76	0.75	0.77
West Azerbaijan	0.52	0.52	0.52	0.52	0.52	0.84	0.85	0.80	0.79	0.73	0.62	0.62	0.66	0.67	0.71
Luristan	0.45	0.45	0.42	0.41	0.37	0.74	0.79	0.65	0.65	0.62	0.60	0.56	0.65	0.63	0.60

Table S6. Average SBM efficiency scores over the years (1994-2016) and for all windows

DMU	W1		W2		W3		W4		W5	
	CCR	BCC	CCR	BCC	CCR	BCC	CCR	BCC	CCR	BCC
DMU1	0.55	0.75	0.54	0.72	0.54	0.71	0.53	0.71	0.52	0.68
DMU2	0.52	0.84	0.52	0.85	0.52	0.80	0.52	0.79	0.52	0.73
DMU3	0.91	1	0.91	1.77	0.91	1	0.91	1	0.91	1
DMU4	0.74	0.82	0.74	0.80	0.73	0.79	0.71	0.79	0.70	0.76
DMU5	0.73	0.76	0.73	0.82	0.73	0.76	0.73	0.76	0.73	0.76
DMU6	0.87	1	0.87	1.52	0.87	1	0.87	1	0.75	1
DMU7	0.89	1	0.87	0.96	0.86	0.95	0.84	0.92	0.84	0.86
DMU8	0.80	0.89	0.79	1.01	0.79	0.86	0.79	0.85	0.79	0.81
DMU9	0.70	0.77	0.68	0.84	0.68	0.73	0.68	0.72	0.68	0.71
DMU10	0.71	0.75	0.62	0.74	0.62	0.71	0.61	0.70	0.60	0.65
DMU11	1	1	1	1.11	0.98	1	0.97	1	0.93	0.93
DMU12	0.68	0.78	0.67	0.79	0.67	0.78	0.67	0.78	0.67	0.78
DMU13	0.88	0.93	0.79	1.06	0.77	0.91	0.75	0.91	0.74	0.88
DMU14	0.69	0.85	0.68	0.86	0.68	0.84	0.68	0.83	0.67	0.82
DMU15	0.66	0.78	0.66	1.42	0.66	0.78	0.65	0.78	0.65	0.77
DMU16	0.62	0.80	0.61	0.79	0.60	0.75	0.60	0.75	0.60	0.73
DMU17	0.65	0.79	0.65	0.80	0.65	0.74	0.64	0.72	0.63	0.65
DMU18	0.75	0.94	0.74	1.03	0.73	0.91	0.73	0.90	0.63	0.89
DMU19	0.77	0.86	0.72	0.84	0.72	0.82	0.72	0.82	0.67	0.76
DMU20	0.45	0.74	0.45	0.79	0.42	0.65	0.41	0.65	0.37	0.62
DMU21	0.66	0.75	0.65	0.73	0.64	0.72	0.62	0.70	0.56	0.66
DMU22	0.70	0.86	0.70	0.86	0.70	0.86	0.70	0.86	0.70	0.85
DMU23	1	1	1	1.28	0.90	1	0.90	1	0.90	1
DMU24	0.74	0.95	0.73	0.97	0.73	0.89	0.73	0.88	0.73	0.86
DMU25	0.88	0.88	0.88	1.03	0.88	0.88	0.85	0.88	0.81	0.88
Average	**0.74**	**0.86**	**0.73**	**0.98**	**0.72**	**0.83**	**0.71**	**0.83**	**0.69**	**0.80**

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