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ARTIGO TÉCNICO

ENERGY EFFICIENCY OF A CENTER PIVOT IRRIGATION SYSTEM

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KEYWORDS

energy performance, pumping unit, performance indicators.

ABSTRACT

This study aimed to evaluate the energy efficiency of a center pivot irrigation system operating in a terrain of variable topography. Values of Pumping Energy Efficiency (PEE), Supply Energy Efficiency (SEE), Global Energy Efficiency (GEE) and Specific Energy (Es in kWh m^{-3}) computed at 18 different angular positions of the lateral line were used as energy efficiency indicators. An ultrasonic flow meter, digital pressure transducers and a power quality analyzer were used in order to evaluate hydraulic (total system flow-Q and total dynamic head-TDH) and electrical parameters (active electrical power - AEP) of the center pivot pumping unit that were required for evaluating the selected energy efficiency indictors. Topographic elevations of the water source, the pumping unit and of the center lateral line were also determined. For the center pivot lateral line, it was necessary to determine, at the 18 angular positions considered, the altitude of the track of each center pivot support tower. Results indicated that currently, even after more than 10000h of use, the center pivot system operates with satisfactory energy efficiency, as indicated by an average GEE value equal to 42.5%, that is classified as "good". Statistical analysis indicated that the topographic disposition of the center pivot lateral line, as characterized by a uphill or downhill disposition, resulted on different PEE, SEE and GEE values, while the average Es value (0.42 kWh m^{-3}) was not affected by the lateral line disposition.

INTRODUCTION

In the near future due to water and energy constraints, production costs in agricultural areas tend to increase, and with this there will be the need to explore new technologies and methodologies for the management of irrigation systems (Evans & King, 2012).

In Brazil, the use of center pivot has been widely diffused on agricultural irrigated areas due to several advantages (automation, uniformity, reduction of manpower) that this equipment provides in relation to other types of irrigation system. Nowadays, there are 1.28 million hectares irrigated by center pivot system in Brazil. This represents an increase of 43.3% in relation to the 2006 center pivot irrigated area in Brazil (Guimaraes & Landau, 2016).

In this context of irrigated agriculture expansion and need of water and energy efficiency monitoring, different energy efficiency indicators were proposed (Rodríguez Díaz et al., 2011; Córcoles et al., 2010). According to Tarjuelo et al. (2015), it is important to implement an energy evaluation routine not only to determine the energy efficiency of an irrigation system, but also to assist in the decisions making process regarding improvements in the water distribution system, in order to optimize energy consumption and economic planning.

For the specific case of center pivot irrigation systems in Brazil, Cezar-de-Lima et al. (2008) and Schons et al. (2012) used a specific normalized energy consumption index that is expressed in $kWh.mm^{-1}.ha^{-1}.100m^{-1}$. This index represents the amount of active electrical energy (kWh) that is required in order to pump a normalized volume of water (mm.ha = $10m^3$) with an standart values of total dynamic head (100m).

For the case of pressurized irrigation systems, Abadia et al. (2008) proposed a procedure for calculation

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of a Global Energy Efficiency (GEE) indicator. This indicator is the result of the product of two other energy efficiency indicators: Pumping Energy Efficiency (PEE) and Supply Energy Efficiency (SEE). The Pumping Energy Efficiency (PEE) is related to the efficiency of the pumping unit (electric motor efficiency multiplied by centrifugal pump efficiency). Supply Energy Efficiency (SEE) is related to the design and management of the water distribution system.

The Specific Energy (Es in kWh m^{-3}) index is widely used to evaluate the energy performance of water distribution systems of different configurations (Córcoles et al., 2010; Abadia et al., 2010). The ES represents the amount of active electrical energy (kWh) that is required in order to pump a normalized volume of water (1,0 m^3). For practical proposes, the amount of electricity energy consumed by an irrigation system, that is measured in kWh, can be determined by multiplying the total volume of irrigated water pumped in the cropped area (m^3) by the Specific Energy value (Es, in kWh m^{-3}) of the pumping unit. According to Urrestarazu & Burt (2012) reduction on the amount of energy (kWh) consumed for pumping irrigation water in a irrigation system can be achieved by both methods: (i) reduction in the pumped water volume (m^3); and (ii) reduction on the pumping unit Specific Energy (kWh m^{-3}) value.

Cezar-de-Lima et al. (2008) pointed out that indicators of irrigation systems energy consumption must be in some way normalized, allowing the comparison of different irrigation systems, installed in areas of different topographic conditions. Abadia et al. (2010), Abadia et al. (2008) also warn that, for the particular case of irrigation systems operating in terrains with variable topographic conditions, energy efficiency indicators should be analyzed with caution, as this analysis may lead to errors of interpretation and, therefore, in non-representative GEE values.

The aim of this study was to evaluate the energy efficiency use of a center pivot irrigation system that operates in a terrain of varied topography by analyzing the behavior of different energy efficiency indicators (PEE, SEE, GEE, Es) that were adapted for this type of pressurized irrigation system.

MATERIAL AND METHODS

Characterization of the area

The study was carried out in a center pivot irrigation equipment located at the Fazenda Invernada in the municipality of Bom Sucesso-MG, with UTM coordinates of 23K 50940 2.45 m E, 7662306.20 m S.

Equipment Characteristics

The technical characteristics of the center pivot system used in this study, as described in the original design datasheet of the manufacturer's, are reproduced in Table 1.

TABLE 1. Characteristics of center pivot system as described at the original design datasheet.

ITEM	DESCRIPTION
1) Technical Data of the Pivot Brand	Valley
Model:	4871-8000-VSL/8-1.060-Hight: Standard – 2.74m
Structure:	4 long spans 6.5 /8"; 4 Medium spans of 6.5/8" With 20 m balance without final spray, without final cannon
Circular irrigated area:	58.78 ha
Total flow:	240.72 (m^3 h^{-1})
Radius of the last tower:	411.69 (m)
Pipe length:	432.57 (m)
Total irrigated radius:	432.57 (m)
2) Pipeline	
Total length:	840 (m)
Total dynamic height:	116 (m)
Centrifugal pump	
Brand:	KSB
Model:	WKL 125/3
Consumption:	113.31 (kWh)
Efficiency %	75.50%
Maximum power:	150.85 (cv)
Electric Motor	
Brand:	WEG
Model:	22 PLUS
Nominal Power:	150 (cv)
Efficiency %	95%

Along the center pivot lateral line, at the outlet end of ¾"flexible drop pipes that are regularly spaced by approximately 2,3, there are 189 Senninger R Iwob type emitters. The pressure head at the inlet section of each one of these emitters is controlled by a 10 psi nominal pressure regulating valve (PRV), that according to the manufacturer specifications (Senninger, 2017) operates adequately in pressure range from 69 kPa (hPRV = 7.02 m) up to 690 kPa (70.36 m).

Topography of the terrain

The planialtimetric survey of the irrigated area and the elevations of the pumping unit and the water supply level were determined with the aid of a GPS device of Topcom brand, Hyper Lite + model (accuracy of 5 mm). In order to generate topographic level curves on the irrigated area, the topographic data from this survey was submitted to an interpolation process provided by the QGIS software, 2.12 version. As indicated in Figure 1, the 18 different angular position of the center pivot lateral line, that were considered in this study represent different angular positions (α) assumed by the mobile lateral line along its rotation ($0^0 < \alpha \leq 360^0$) around the fixed pivot point, located at the center of the irrigated area. These angular positions were determined by the different positions assumed in the field by each one the 8 mobile towers (T1 to T8) used to move the lateral line around the pivot point.

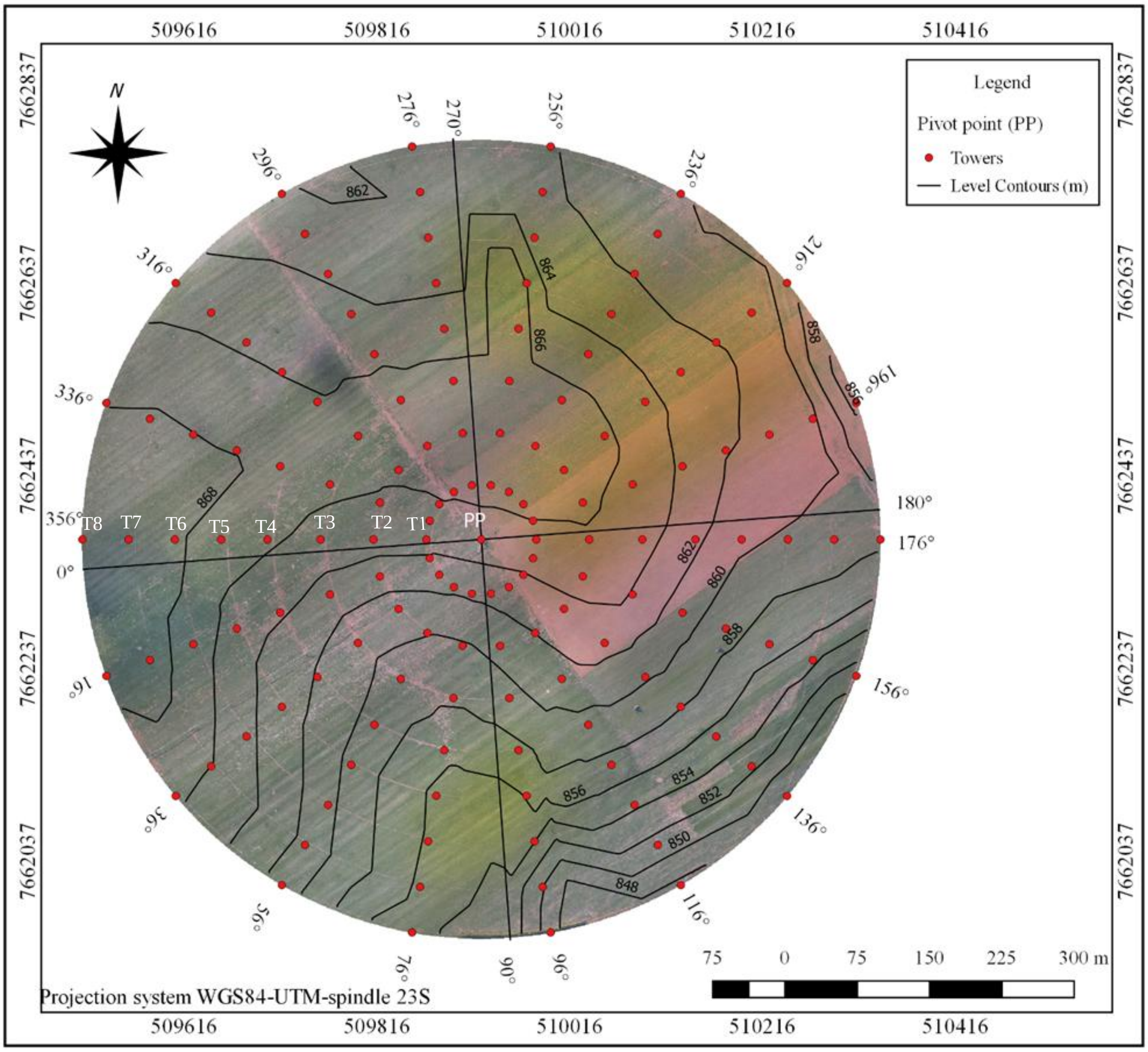

FIGURE 1. Angular positions of the center pivot movable lateral line.

Calculation of Global Energy Efficiency (GEE)

Abadia et al. (2008) define the overall energy efficiency of an irrigation system (GEE) as the ratio between the required energy (Er) for irrigation and the actual energy consumed (Ec) in the irrigation process. For each one of the 18 angular position (α) assumed by the moving lateral, the GEE values were computed as percentage (%), based on [eq. (1)] the product of two efficiency components: the supply energy efficiency (SEE) and the pumping energy efficiency (PEE).

$$GEE_{(\alpha)} = \frac{Er}{Ec}.100 = (SEE_{(\alpha)}.PEE_{(\alpha)}).100 \quad (1)$$

where,

$GEE_{(\alpha)}$ - global energy efficiency referring to the angular position (α),%;

$PEE_{(\alpha)}$ - pumping energy efficiency referring to the angular position (α), decimal,

$SEE_{(\alpha)}$ - supply energy efficiency referring to the angular position (α), decimal.

The energy efficiency of the pumping unit (PEE) is expressed by the ratio between the delivered hydraulic power (P_H) and the active electrical power (AEP), as expressed by [eq. (2)] (Abadia et al., 2008):

$$PEE_{(\alpha)} = \left(\frac{PH}{AEP}\right)_{(\alpha)} = \frac{\rho.g.Q_{(\alpha)}.TDH_{(\alpha)}}{AEP_{(\alpha)}} \quad (2)$$

where,

$PH_{(\alpha)}$ - hydraulic power, kW;

$AEP_{(\alpha)}$ - active electrical power referring to the angular position (α), kW;

$Q_{(\alpha)}$ – total system flow measured at the angular position (α), $m^3\ s^{-1}$;

ρ - water specific mass, kg m^{-3};

g - acceleration of gravity, 9.81m s^{-2},

TDH (α) - total dynamic head measured at the angular position (α), m.

Total system flow values ($Q_{(\alpha)}$) were determined using a portable FMS 175 brand ultrasonic flowmeter with built-in data logger. The flow meter was installed on the pump unit suction pipe, observing minimum values of straight-pipe runs upstream and downstream from sensitive flow elements. According to the manufacturer's specifications, for flow velocity above 0.18 m/s, the equipment used has an accuracy of 1%, with ± 0.5% linearity and ± 0.2% repeatability. Pressure values at inlet and outlet sections of the pump were measured. Absolute pressure values at the pump inlet section were measured with an Instrutherm pressurure transducer, VA-318 model, connected to a VDR-920 digital reader. A digital Instrutherm brand, PS100-20 BAR model, pressure head transducer, with a 20 bar maximum capacity, connected to a digital reader, Instrutherm MRV-87 model, was used for recording pressure head values at the inlet section of the pump. Both digital readers are equipped with a RS232 output that was used to store the measured pressure values in a computer file.

TDH values were obtained by correcting the difference between relative pressure head values taken at the pump outlet section (PL_{out}/γ) and at the pumping inlet section for differences on water velocity head values and elevation values in these sections [eq. (3)]. Relative pressure head values at the inlet pumping section were obtained by subtracting from the absolute pressure head values mensured at this section ($PL_{entrance}/\gamma$) the absolute value of the atmospheric pressure (P_{atm}/γ) observed at the same time in which the inlet pressure measurement were taken.

$$TDH_{(\alpha)} = \left[\left(\frac{PL_{outlet}}{\gamma}\right)_{(\alpha)} - \left(\left(\frac{PL_{inlet}}{\gamma}\right)_{(\alpha)} - \left(\frac{P_{atm}}{\gamma}\right)\right)\right] + \left(\frac{V_{outlet_{(\alpha)}}{}^2 + V_{inlet_{(\alpha)}}{}^2}{2_g}.\right) + (Z_{outlet} - Z_{inlet}) \quad (3)$$

where,

$PL_{outlet\ (\alpha)}$ - pressure at the outlet of the pump in the angular position (α), kPa;

$PL_{entrance\ (\alpha)}$ - absolute pressure at the pump entrance in the angular position (α), kPa;

P_{atm} - atmospheric pressure, 91.39 kPa;

$V_{outlet\ (\alpha)}$ -averange water flow velocity at the pump outlet section, $m.s^{-1}$;

$V_{inlet\ (\alpha)}$ - averange water flow velocity at the pump inlet section, $m.s^{-1}$;

$Z_{inlet\ (\alpha}$ - geometric elevation of the absolute pressure sensor at the pump inlet, m;

$Z_{outlet\ (\alpha)}$ - geometric elevation of the effective pressure sensor at the pump outlet, m,

γ – irrigation water specific weight, $kN.m^{-3}$.

Active electrical power values (AEP) were measured with a Fluke® power quality analyzer, 435-II model, with 0.5% accuracy, with built-in data logger. The power quality analyzer was installed in a three-phase three-wire connection at the starter protection system of the 110 kW nominal power asynchronous motor used to drive the center pivot pump.

Supply Energy Efficiency (SEE) values are directly related to the effects of topographic variations on the spatial distribution of the ratio of required pressure available pressure at the irrigated area. In order to apply the methodology proposed by Abadia et al. (2008) to compute SEE values based on the ratio of system water head balance (ΔWH) and TDH, each one of the 18 center pivot lateral line angular positions of the was considered as a different irrigation project. Further, it was considered that which one of these 18 "irrigation projects" is supposed to pump irrigation water to feed 189 different irrigated fields, that were identified by an J index in the range $1 \leq J \leq 189$. By attributing to each "irrigation project" a total number of irrigated fields equal to the total number of emitters installed along the center pivot lateral line, it was possible to estimate to each one of "irrigated field", that is part of an irrigation project, values of field irrigated area (Aj), field average topographic elevation (Zj), required inlet pressure head (hprv), equal to the ones corresponding to the emitter with the same J index value along the center pivot lateral line. This adaptation to the methodology proposed by Abadia et al. (2008) to compute SEE is shown in [eq.(4)]:

$$SEE_{(\alpha)} = \frac{\Delta WH_{(\alpha)}}{TDH_{(\alpha)}} = \frac{(WHD - WHI)_{(\alpha)}}{TDH_{(\alpha)}} = \frac{\dfrac{\sum_{j=1}^{j=189}(Z_{j(\alpha)} - Z_a + h_{PRV}).A_j}{\sum A_j}}{TDH_{(\alpha)}} \quad (4)$$

where,

$\Delta WH_{(\alpha)}$ - balance of water head in the system, m;

$WHD_{(\alpha)}$ - required water head in the irrigated area at the angular position (α), m;

$WHI_{(\alpha)}$ - water head injected into the system in the angular position (α), m;

Z_j - geometric elevation of each emitter (j) installed on the lateral line, m;

h_{PRV} - minimum pressure head required by the pressure regulating valve (PRV), 7.02 m;

A_j - area irrigated the emitter identified by the index j, m²,

Z_a - geometric elevation of the water supply level of the irrigation system, m.

ΔWH (α) values were computed considering the geometric elevation of water source level (Za = 806 m) and the minimum pressure head value (hPRV = 7.02 m) required by the pressure regulator valve model (10psi or 69kPa) used on the emitters installed along the lateral line length. For each angular position (α), emitter elevation values (Zj, α) were computed based on the topographic elevation of each one of the eight A- framed mobile towers (T1 to T8) and on the distance among then:

$$Z_{J(\alpha)} = \left((Zt_{i-1})_{(\alpha)} + 2.15\,m\right) + (rg_j - rt_{i-1}).\left(\left((Zt_i)_{(\alpha)} - (Zt_{i-1})_{(\alpha)}\right) \Big/ (rt_i - rt_{i-1})\right) \quad (5)$$

where,

$Z_{e\,j,i\,(\alpha)}$ - elevation of the emitter (j) in the tower (i), m;

$(Zt_{i-1})_{(\alpha)}$ - wheel track elevation, at angular position α of the tower demarking the inlet end of the i^{th} span, m;

rg_j - distance from center pivot inlet to the inlet point of index j emitter's drop pipe, m;

rt_{i-1} - wheel track radius of the tower demarking the inlet end of the index i span, m;

In [eq. (5)] the constant 2.15 m represents the height of the water entrance point in the pressure regulating valves installed in each emitter.

Es calculation

At each angular position (α), simultaneous measured values of active electric power (AEP in kW) and total flow system flow (Q in m3s-1) were used to determine specific energy consumption values (Es in kWh m-3) as indicated in In [Eq. (5)] (Viholainen et al. 2012, Urrestarazu & Burt (2012), and Schons et al. (2012)).

$$Es_{(\alpha)} = \frac{1h}{3600s}.\frac{AEP_{(\alpha)}}{Q_{(\alpha)}} \quad (6)$$

where,

$Es_{(\alpha)}$ - specific consumption referring to angular position (α), kW h m^{-3}.

RESULTS AND DISCUSSION

Table 2 shows the values of Q, TDH, AEP and the energy efficiency indicators (PEE, SEE, GEE and Es) calculated for each angular position of the lateral line.

TABLE 2. Computed values of the energy efficiency indicators PEE, SEE, GEE and Es.

Position α (°)	Q (m^3 h^{-1})	AEP (kW)	PH (kW)	TDH (m)	WHD (m)	WHI (m)	ΔWH (m)	PEE %	SEE %	GEE %	Es (kWh m^{-3})
16	229.02	97.30	71.66	115.03	875.58	806.03	69.55	73.65	60.47	44.53	0.43
36	232.44	97.86	71.91	113.73	873.38	806.03	67.35	73.48	59.22	43.51	0.42
56	237.49	99.28	71.95	111.37	869.84	806.03	63.81	72.47	57.30	41.52	0.42
76	237.45	99.52	70.45	109.08	861.60	806.03	55.57	70.79	50.95	36.07	0.42
96	238.72	99.44	71.80	110.58	862.13	806.03	56.10	72.21	50.74	36.64	0.42
116	236.54	99.32	71.26	110.75	864.52	806.03	58.49	71.74	52.82	37.89	0.42
136	238.17	99.10	72.05	111.22	865.44	806.03	59.41	72.71	53.41	38.84	0.42
156	235.63	99.10	72.05	112.17	866.70	806.03	60.67	72.71	54.09	39.32	0.42
176	232.13	98.78	71.54	111.41	870.35	806.03	64.32	72.43	57.73	41.81	0.43
196	231.91	98.54	70.35	113.35	870.57	806.03	64.54	71.39	56.94	40.65	0.43
216	232.06	98.32	71.50	113.39	871.86	806.03	65.83	72.73	58.05	42.22	0.42
236	229.10	98.16	71.58	113.97	872.03	806.03	66.00	72.92	57.92	42.23	0.43
256	227.00	97.84	71.02	114.36	873.54	806.03	67.51	72.59	59.04	42.85	0.43
276	231.34	97.92	70.61	114.07	873.48	806.03	67.45	72.11	59.13	42.64	0.42
296	229.37	98.02	71.78	114.56	873.48	806.03	67.45	73.23	58.88	43.12	0.42
316	230.13	97.62	71.47	115.35	875.09	806.03	69.06	73.22	59.87	43.83	0.42
336	223.06	96.92	70.32	115.90	876.88	806.03	70.85	72.56	61.13	44.35	0.43
356	227.13	97.26	71.40	115.57	877.29	806.03	71.26	73.41	61.66	45.26	0.43

According to the data flow described in Table 2, it is possible to note that in the regions where the uphill regions was is determined when the elevation of last tower is greater than the elevation of pivot point (865 m), which comprises the angular positions (α) of 316 ° ≤ α ≤ 36 ° (Figure 3), the flow values are smaller than the downhill regions (angular positions (α) of 56 ° ≤ α ≤ 296 °), where the elevation of the last tower was less than the pivot point elevation (865 m).

Pumping Energy efficiency (PEE)

The observed PEE values vary in the 18 angular positions studied (Table 2). The average value found during the lateral rotation was 72.57% (classified as excellent according to Abadia et al. (2008)), with a maximum value recorded of 73.65%, referring to the position of 16° (uphill) and the lower value of 70.79%, referring to the angular position of 76° (downhill), according to Table 1.

The PEE values have this behavior due to alterations in the relief (downhill and uphill) and also due to oscillation in the flow values in function of the topography and probably the flow are altered by the wear of the pressure regulating valves due to the time of use. Such changes in the flow values reflect in the efficiency of the centrifugal pump according to its performance characteristic curve (Figure 2).

When analyzing the average PEE value observed with the PEE project value obtained by the product of the pump efficiency and electric motor values reported in the catalogs, the value of 72.46% is obtained. Due to the wear time, it was expected that the PEE value would be reduced due to wear of equipment. This behavior was not observed because the observed flow values were lower than the project value (240.72 m^3 h^{-1}) as shown in Figure 2 and, according to the performance curve of the pump, the values of catalog efficiency in function of the observed flow are higher than the project value (Figure 2), thus raising the PEE values.

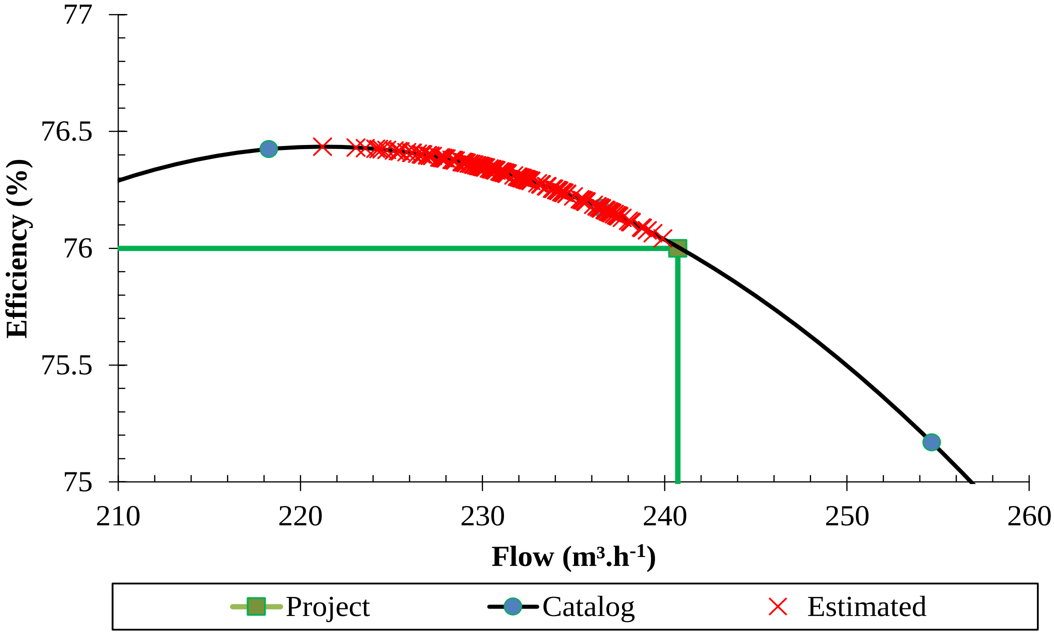

FIGURE 2. Performance characteristic curve of the centrifugal pump KSB WKL 125/3.

Abadia et al. (2008) in their study found a PEE value equal to 63.8%. These authors attributed this values to the capacity of the pumping unit to provide a flow and pressure head constant. This study, it observed that the values of Q showed a maximum variation of 7% and a maximum of 6% for TDH, and according to the characteristic curve of the centrifugal pump in studing (Figure 2), these pairs of points are close to the highest efficiency points, corroborating with the information described above by Abadia et al. (2010).

The analysis of the PEE adequacy value is relatively simple and when there is no equipment installed in the pumping unit such as frequency inverters and cable efficiency values, the PEE can be expressed by the product of efficiency of the pump and the electric motor, in which "theoretical" PEE values can be calculated from pump and motor performance data taken from commercial catalogs (Moreno et al., 2010). However, Urrestarazu & Burt (2012) emphasize the importance of verifying in the field the validity of such "theoretical" values.

Thus, the analysis of the adequacy of specific energy consumption values must necessarily consider the adequacy of the observed value of active electric power (kW) required to the activation of the pumping unit operating at the desired flow rate. For a same pumped flow value, the active electrical power required for activation of a pumping unit (kW) it's affected by both the total TDH value supplied by the pump and the PEE value.

Therefore, for the same pump value, any analysis of the reduction possibility in the observed value of specific energy consumption (Es in kWh m^{-3}) is necessarily conditioned: (i) to the analysis of the adequacy of the observed value of TDH provided by the pump; (ii) to the analysis of the adequacy of the PEE value of the motor-pump set used.

Luc et al. (2006) report that the PEE may have a deviation in its values due to the interference of other factors such as TDH or motor and pump efficiency, which corroborates with the data obtained here in this study where TDH (Table 2) and the pump and motor efficiency (Figure 2) have their values changed in function of the angular position of the lateral line in the area (Table 2). This behavior is also observed in this study through a quadratic polynomial regression analysis of the data described in Table 1 of TDH correlated with PEE, resulting in a R^2 value of 0.49. Urrestarazu & Burt, (2012) report that for operating conditions of pumping units in California the factor that most correlates with PEE is TDH. When the PEE is correlated with Q values, the obtained value of R^2 is only 0.25.

The PEE can be classified according to the methodology proposed by Abadia et al. (2008) adapted from Pelli & Hitz (2000), which varies from unacceptable efficiency (PEE <45%) up to excellent (PEE> 65%).

Supply Energy Efficiency (SEE)

The average value of SEE in all the tested positions was 57%, registering a maximum value of 61.66%, referring to the angular position of 356° (uphill) (Figure 3), region with the highest WHD value due to greater geometric elevation in irrigated area (Figure 2).The lowest value of SEE was 50.7% for angular position of 96° (downhill) (Figure 3), position with lower WHD value due to the lower geometric elevation.

Abadia et al. (2012) report that SEE values are influenced by a pumping of water with excessive pressure head to regions downhill slopes, thus generating a waste of energy. The verification of leaks in lateral and mainline pipe should also be verified, as it influences the SEE of system.

An alternative to improve SEE and PEE is the installation of frequency inverters in pumping unit the center pivot when this system operates in irregular areas. According to Dos Santos Lima et al. (2015) the use of frequency inverters reduces energy consumption due to the use of the resulting TDH from the difference in level between the center of the pivot and its end the lateral line. However, the implementation of a frequency inverter is conditioned a previous economic feasibility study that varies in each case study (Campana et al., 2000).

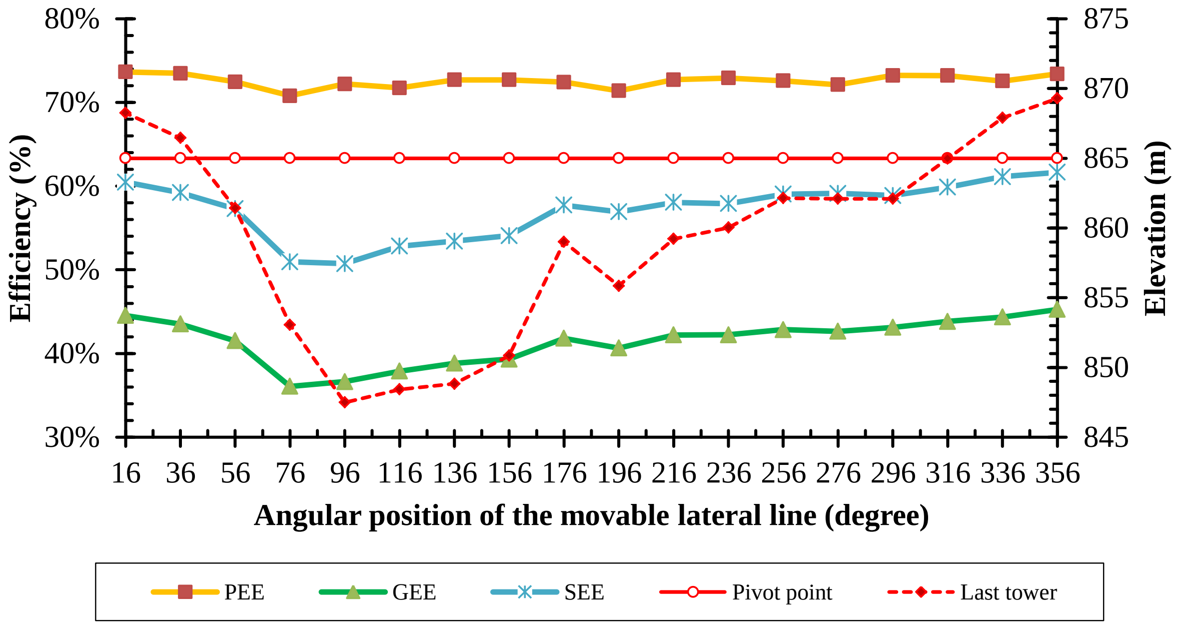

FIGURE 3. PEE, SEE and GEE values in function of the terrain topography.

Global Energy Efficiency (GEE)

For the GEE values, according to the data in Table 2 and Figure 3, there was a variation between maximum and minimum values of 7%, with the maximum value being 45% for uphill region (356°) and minimum of 36 % for the angular position 76° (downhill). According to the GEE qualification proposed by Abadia et al. (2008) adapted from Pelli & Hitz (2000) the average value of 42.52% is classified as "excellent". This behavior of the GEE (Figure 3) follows the PEE and SEE behaviors computed during lateral line rotation, since the energy excess applied in the region where is downhill causes the efficiency of the system to reduce.

Specific consumption (Es)

The specific consumption data (Es) of the center pivot pumping unit studied here presented an average value of 0.42 kWh m^{-3} (Table 2).Comparing the positions of the lateral line in area irrigated by center pivot, we can see higher values of Es for areas of higher elevation in the last tower (maximum value equal 0.43 kWh m^{-3} for the 336° position) and smaller Es values for lower altitude area (0.416 kWh m^{-3} referring to the 96° position). Schons et al. (2012) find an estimated value of 0.41 kWh m^{-3} for a center pivot in the state of Rio Grande do Sul. These authors also report that Es can be used to compare projects within the same irrigation system, and to evaluate the efficiency and depreciation of equipment.

Plappally & Lienhard, (2012) found Es values in water pumping stations. For the specific case of irrigation, these authors present values varying from 0.32 to 1.1 kWh m^{-3} for the localized irrigation system, and from 0.6 to 1.3 kWh m^{-3} for sprinkler irrigation system, for the case of the center pivot system to Australia conditions operating at a pressure head of approximately 400 kPa, the approximate Es value was 0.18 kWh m^{-3}. However, the comparison of specific energy consumption values for referring to different pumping stations should be made with caution.

Energy indicators x Topography of the terrain

The PEE, SEE, GEE and Es indicators were submitted to the statistical Student t test at significance level of 5%, as described in Table 3, in function of the angular position (uphill and downhill) of the lateral line.

TABLE 3. Values of statistical Student test applied to the energy efficiency indicators PEE, SEE, GEE and Es.

Indicators	Average	Variance	Calculated T	T critical
PEE(uphill)	0.73	0.000018	-3.60*	2.18
PEE(downhill)	0.72	0.000045		
SEE(uphill)	0.60	0.000095	-4.74*	2.12
SEE(downhill)	0.56	0.000953		
GEE (uphill)	0.44	0.000046	-5.21*	2.13
GEE(downhill)	0.40	0.000594		
Es(uphill)	0.43	0.000026	-1.48	2.36
Es(downhill)	0.42	0.000022		

* Significant at a 5% probability level.

It was observed the average values of PEE, SEE and GEE differ statistically for uphill and downhill lateral line positions.

The average values of Es it was considerate statistically equal for the angular positions in uphill and downhill. This observation differs from that made by Schons et al. (2012) where these authors relate values of Es only in function of the topography. Thus, the Es values may be more related to other factors, and according to Luc et al. (2006) who analyzed a group of 115 pumping units with a capacity greater than 80 m³.h^{-1}, and found that there is a linear relation with determination index (R^2) equal to 0.98 of the Es values with the TDH values.

CONCLUSIONS

It was possible to estimate the energy efficiency through the indicators adapted to the center pivot irrigation system.

The periodic monitoring of the center pivot irrigation system is essential for maintaining the energy efficiency levels as appropriate.

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