OPTIMISATION OF THE DISTRIBUTION OF POWER FROM A PHOTOVOLTAIC GENERATOR BETWEEN TWO PUMPS WORKING IN PARALLEL

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Abstract

In this work, a method for distributing the power generated in a photovoltaic pumping system equipped with two equal pumps, working in parallel is analysed.

For this purpose, a system equipped with two pumping groups 0.75kW each was investigated. Experimental tests at five different working frequencies (30 to 50 Hz), and at six pumping heads (18 to 48 m) were carried out.

The main objective of this paper is to establish a strategy for the distribution of the generated power that maximises the flow rate from the set of two pumps. This distribution depends both on the available electric power and on the pumping head.

The results show some differences between higher and lower pumping heads, but in both cases for lower power values, the strategy involves the operation of a single pump with the limitation that the power assigned to this pump cannot exceed the maximum value (P_{max}). However, if the available power exceeds a certain value, referred to as P_e, it must then be distributed at 50% between the two pumps. Thus, there is no power distribution ratio other than 0 and 50% that maximises the flow rate, except that required to limit the power assigned to one of the pumps to P_{max}.

It was proven that the optimal distribution strategy for the available power depends on whether $P_e>P_{max}$ (for higher pumping heads) or $P_e<P_{max}$ (in case of lower heads). In practice, it is easy to determine which case applies using a simple pumping test.

Keywords: pumping system; power optimisation; multi-pump system; parallel pumps

Nomenclature

H_{max} (m): Maximum pumping head at nominal speed

k: Distribution ratio of the available electric power between the two pumps

k_{min}: Minimum value of k in a given power range

k_{opt}: Optimal power distribution ratio between the two pumps.

P (kW): Electric power supplied to the motor-pump group

P_e (kW): Power value above which the two pumps operate with power distribution at 50%

P_h (kW): Hydraulic power

P_{max} (kW): Maximum motor-pump power

P_{min} (kW): Minimum power to start pumping

q(P) (L/s): Flow rate propelled by one pump

Q(P) (L/s): Flow rate propelled by the two pumps operating in parallel.

Greek symbol

η_{mp}: Efficiency of motor-pump group

1. Introduction

Photovoltaic (PV) pumping systems have proved to be an alternative method of supplying drinking water for human consumption. They also play an important role as a sustainable alternative for the agricultural sector. The applications of greatest interest are in remote rural areas of developing countries with high annual irradiance levels, where grid electricity is not easily available (Alonso, 2005; Meah et al., 2008; Aliyu et al., 2018; Wazed et al., 2018).

Solar pumping systems have also become widely used to supply electricity to the pumping facilities necessary for the irrigation of many crops e.g. in Latin America (Fedrizzi and Sauer, 2002; Espericueta et al., 2004; Guzmán et al., 2018), in Asia (Shoeb and Shafiullah, 2018), as well as in many countries of the Mediterranean region (López-Luque et al., 2015; García-Tejero and Durán-Zuazo, 2018; Narvarte et al., 2018; Todde et al., 2019).

In these facilities, the high variability of the incident solar radiation results in irregular electric power generation over time, meaning that the pump operates at variable flow rates (Hamrouni et al., 2009; Campana et al., 2013; Benghanem et al., 2018; Tiwari and Kalamkar, 2018).

In order to maximise the energy utilisation and to avoid to the extent as possible the effect of weather and irradiance fluctuations on the efficiency of pumping system, many solutions have been reported in the literature. It is worth noting some of them. Thus, Mérida García et al. (2018) developed an irrigation management model which enables synchronizing the PV energy production with the pumping power demand and also compensates occasional water supply lacks due to irradiance fluctuations. An optimisation approach based on the application of technical solutions to the design and implementation of a hybrid PV-diesel irrigation system was presented in Almeida et al. (2018a). These solutions were developed to overcome the PV peak power due to the passing clouds and to the imbalance between PV production and water needs. Almeida et al. (2018b) reduced power threshold to start pumping achieving longer periods of pumping. They proposed a pump selection method based on considering the efficiency in the whole range of operating frequencies. In Matam et al. (2018), a novel Reconfigurable PV Array based water pumping scheme is proposed to improve the response under various operating conditions. In the case of PV pumping systems based on a three phase induction motor without storage elements, Talbi et al. (2018) proposed an scheme which resulted in more pumped water under variable pumping heads, whereas Elkholy and Fathy (2016) developed an Artificial Neural Network model to obtain the optimal inverter voltage and frequency to extract maximum power from the PV array.

In conventional pumping stations, it is common to use various pumps working in parallel, which increases energy savings and enlarge the range of achieved flow rate with raised efficiency (Kaya et al., 2008; Pemberton and Bachmann, 2010; Koor et al., 2016). In this context, several researchers have developed different control methods and strategies which result very useful in optimising pumping efficiency (Shankar et al., 2016). In PV systems, this operating mode allows for the pumps to start at lower irradiance levels.

In PV facilities with several pumps working in parallel, it is possible to install an independent PV generator for each pump. Another option is to use a single PV generator to supply the entire facility, and to establish either a strategy of equal distribution of the generated power among the different pumps or a more efficient distribution strategy that allows for optimisation of the flow rate pumped by the facility at any time.

The aim of this work is to establish a strategy for the distribution of the power generated in a PV pumping system equipped with two equal submersible motor-pump groups, working in parallel, to maximise the flow rate pumped. The motor-pump groups are fed by means of a single PV generator through frequency converters. Both groups have the same dynamic water level, and work in parallel on the same hydraulic network.

In order to achieve this objective, laboratory trials were performed to determine the flow-head and flow-power characteristic curves at variable working frequencies and different pumping heads, thus establishing the flow rate propelled by the pumping group under each set of working conditions.

2. Materials and Methods

2.1. Experimental method

A system equipped with two pumping groups 0.75 kW each working in parallel on the same hydraulic network, was investigated. Experimental tests to determine the flow rate-pumping head (Q-H) and the flow rate-electric power (Q-P) curves of the pumping group at different working frequencies were performed in accordance with the international standard IEC 62253:2011.

In PV pumping systems, centrifugal and volumetric pumps are predominantly used, being centrifugal pumps the most common (Benlarbi et al., 2004). A type of pump manufactured by Bombas Ideal (SKI series) was selected for these experiments. This pump is capable of pumping at heads of between approximately 18 and 60 m. It is a multistage centrifugal radial-type submersible pump for boreholes of 4” in diameter. Activation is performed using a three-phase induction motor of 0.75 kW, at 230 V, 2870 rpm, and 50 Hz (Bombas Ideal catalogue). In practice, the selection of the pump of a photovoltaic pumping facility must be carried out taking into account that it works at a variable frequency. Almeida et al. (2018b) proposed a method for selecting pumps suitable for PV pumping applications based on considering not only the efficiency at the maximum operating frequency but in the whole range of operating frequencies.

Experimental setup

The experimental characterisation of the pumping group was carried out in the hydraulic laboratory at the Universitat Politècnica de València (Spain). Figure 1 shows a schematic view of the experimental facility.

An Altivar 61 (HU30M3 model) was used as a variable speed drive (VSD) to feed the motor-pump group, allowing modifying the electric power and the flow rate pumped. The VSD consists of a frequency converter (FC) for three-phase asynchronous motors at 200-240 V from 0.75 to 3 kW. The frequency of the FC was adjusted by means of a potentiometer (Alonso et al., 2003). Currently, the FCs used for PV pumping systems are standard equipment incorporating a solar kit which can operate as an MPPT (Maximun Power Point Tracker) to track the instantaneous MPP (Maximum Power Point) of the power array. The propulsion pipe of the hydraulic circuit was made of PVC PN10 DN63. The gate valve V1 allowed modifying and maintaining the head pressure of the pump at a constant value at each pumping frequency.

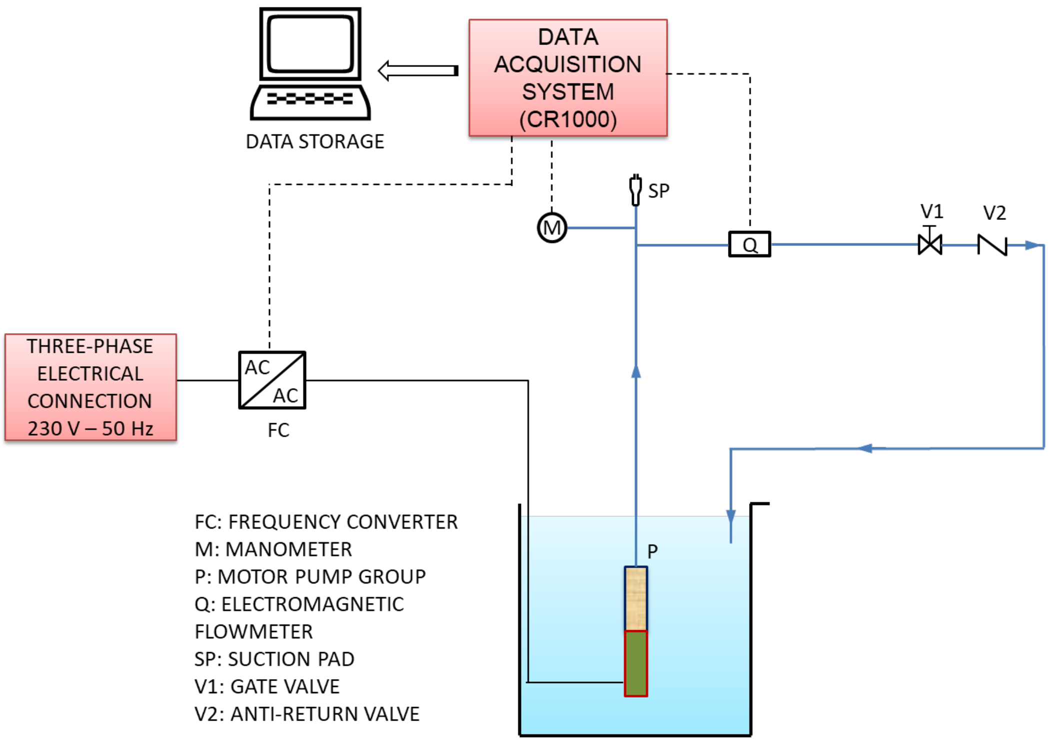


Figure 1. Schematic view of the experimental setup

In order to measure the flow rate, an ABB electromagnetic flowmeter was used (model FXE4000-DE43) with 50 Hz power supply between 100 and 230 V AC, 4-20 mA electric output (accuracy ±0.5 % of rate). A 0.6 bar Wica Eco-Tronic pressure transducer with 4-20 mA output (accuracy ≤0.5 % of span) was used to determine the pressure. The FC provided the data acquisition system with the functioning frequency and the electric power supply of the motor-pump group. Likewise, every 3 s, the data acquisition system (CR1000 data logger, Campbell Scientific) recorded the average values of the data taken from each sensor every 0.1 s.

Flow rate-pumping head characteristic curves (Q-H) at constant frequency

Five Q-H curves for the motor-pump group at frequency intervals of 5 Hz were obtained. The frequencies tested were 50, 45, 40, 35 and 30 Hz.

At each stage of the trials, the electric power supplied to the motor-pump group from the FC was also measured. In this way, the flow-power and flow-efficiency curves of the motor-pump group at constant frequency could also be obtained.

The efficiency of the motor-pump subsystem (η_{mp}) was determined as the ratio between the hydraulic power P_h (W) supplied to raise a certain flow rate of water Q (L/s) to a head H (m), and the electric power P (W) provided to the pumping group:

$$\eta_{mp} = \frac{P_h}{P} = \frac{\rho\, g\, Q\, H}{P} \qquad (1)$$

where g is the gravitational acceleration (m/s^2) and ρ is the water density (kg/m^3).

Measurements of P were obtained with the FC, while Q and H measurements were obtained by means of the electromagnetic flowmeter and the pressure transducer respectively.

Flow rate-electric power characteristic curves (Q-P) at constant head

The characteristic Q-P curves at constant head (H) are determined at heads H_1=0.3H_{max}; H_2=0.4H_{max}; H_3=0.5H_{max}; H_4=0.6H_{max}; H_5=0.7H_{max}; H_6=0.8H_{max}; and H_7=0.9H_{max} (IEC 62253). H_{max} is the maximum pumping head at nominal frequency (50 Hz), which for centrifugal pumps corresponds to a flow rate of Q=0.

The values of Q and P obtained in the experimental trials for each pumping head were adjusted by regression using a fourth-degree polynomial function:

$$q(P)=a_4 \cdot P^4+a_3 \cdot P^3+a_2 \cdot P^2+a_1 \cdot P+a_0 \qquad (2)$$

The adjusted equation allows obtaining the flow rate pumped under variable power conditions and determining the strategy of distribution of the available power P at each of the tested heads.

From these curves, the minimum power values required to start pumping (P_{min}) were also obtained at each of the heads tested.

In addition to the Q-P curves, the power-efficiency curves at constant head were also obtained by applying Equation (1).

2.2. Operation of a PV pumping system with two equal pumps in parallel

In the case of two equal pumps in parallel, two possible ways to design the required PV generator could be (Figure 2):

(a) Individually for each pump (Figure 2a.1). In this approach, two equal PV generators are available, and these transfer the electric power generated to their corresponding FC/motor-pump group. This case is similar to that of a single PV generator (double size of the required for a single group) where the generated power is distributed in equal amounts (50 %) between the two FC/motor-pump groups (Figure 2a.2).

(b) A single PV generator for both pumps. In this case, the power P_{PV} coming from the PV generator is applied to the pumps via their respective FCs, which can modulate the power supplied to each pump via the frequency/output voltage control (Figure 2b). This control is usually done through a PLC (programmable logic controller) which makes one of the FCs the *master* and the other the *slave*. The *master* is in charge of the MPPT control and the PLC determines how much power is transmitted to each motor-pump group as well as the power derived for other uses.

In PV pumping systems, there is a pumping threshold irradiance below which the minimum electric power P_{min} is not generated to start the pumping group (Bione et al., 2004). Its value basically depends on the nominal power of the PV generator and the pumping head. For this reason, the second operating mode can give more favourable results, since it allows a suitable power distribution strategy to be adopted, for example at lower solar irradiance levels. In this context, when less power is generated, all of it can be assigned to a single pump group, thus allowing its operation. In contrast, if the power were distributed at a ratio of 50 % between the two pumps, neither would not work at low solar irradiance levels, and this would cause an increase in the threshold irradiance for pumping.

Carrêlo et al. (2020) presented several configurations for large-power PV irrigation systems, some of them similar to those described here and shown in Figure 2.

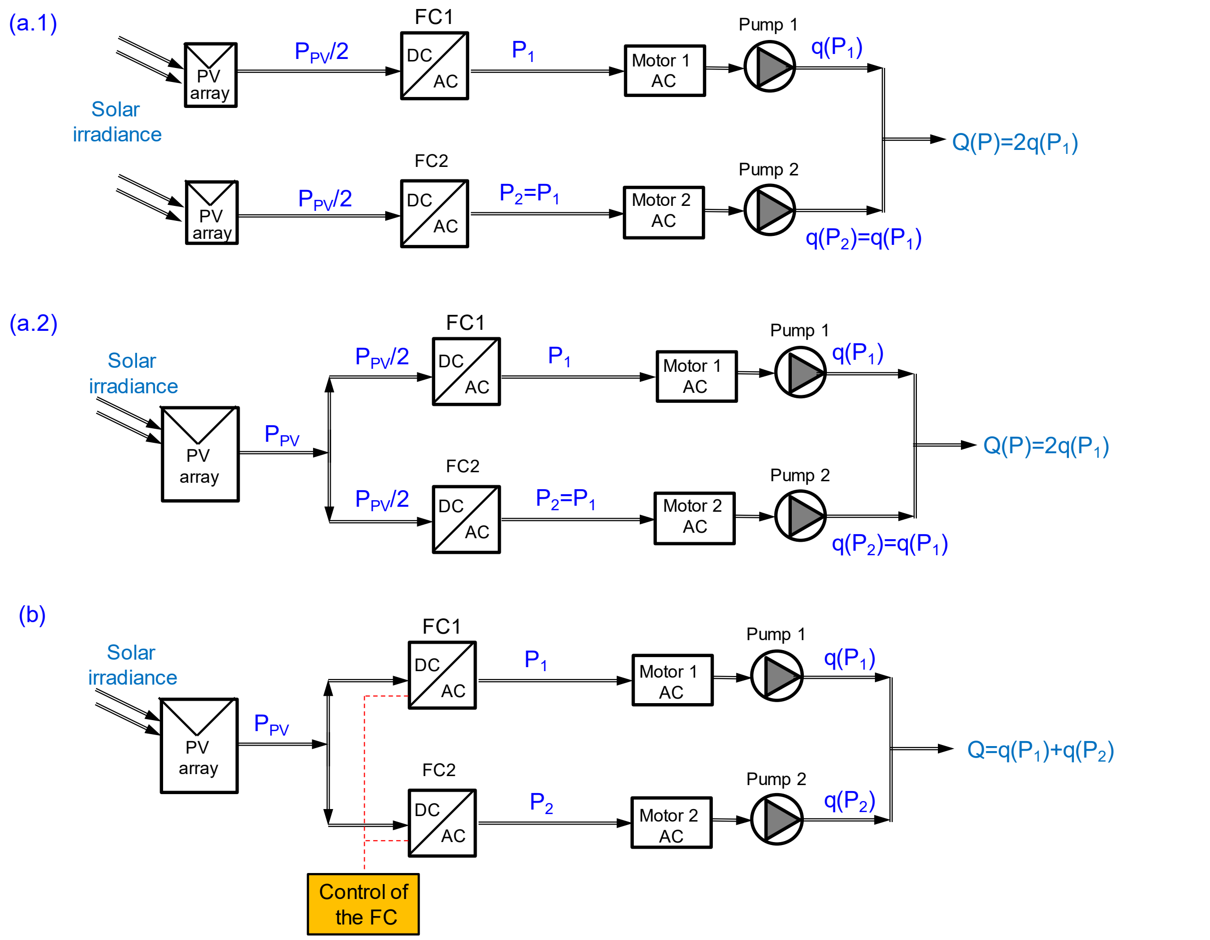


Figure 2. Design of a PV generator for two motor-pump groups with (a.1) an individual PV generator for each pump and (a.2) its equivalent with a single PV generator for both pumps, with power distribution ratio 50 %; and (b) a single PV generator for both pumps with the option to establish a power distribution strategy to maximise the flow rate.

In order to compare the flow rates pumped in the cases described above, the best power distribution strategy in case (b) must be previously investigated.

2.2.1. Pumping system with a single PV generator: Distribution of the generated power between the two pumps

In order to analyse the best distribution strategy for the generated power that allows for maximisation of the flow rate provided by the two pumps, a pumping system with two equal pumps working in parallel is considered. Equation (2) expresses the relationship between P and q (flow rate supplied by a single pump) at a certain pumping head, obtained from experimental tests.

When two pumps work in parallel, the power is distributed between them so that $P=P_1+P_2$ (neglecting the loss in the FC), where P_1 and P_2 represent the electric power feeding pumps 1 and 2 respectively. The flow rates of each pump are (Figure 2b):

$$q(P_1)=a_4 \cdot P_1^4+a_3 \cdot P_1^3+a_2 \cdot P_1^2+a_1 \cdot P_1+a_0$$

$$q(P_2)=a_4 \cdot P_2^4+a_3 \cdot P_2^3+a_2 \cdot P_2^2+a_1 \cdot P_2+a_0 \qquad (3)$$

For safety reasons, the values of P_1 and P_2 are limited so that they always remain below a maximum (P_{max},), the value of which only depends on the nominal power of the motor-pump group.

$$P_1 \leq P_{max} \qquad P_2 \leq P_{max} \qquad (4)$$

As consequence, the total power is limited to $P=P_1+P_2 \leq 2P_{max}$

In addition, for each pumping head, there is a minimum power threshold P_{min} below which the group does not pump. This condition can be expressed as:

$$\text{if} \quad P_1<P_{min} \quad q(P_1)=0 \qquad \text{if} \quad P_2<P_{min} \quad q(P_2)=0 \qquad (5)$$

The values of P_{min} for each pumping head and of P_{max} were obtained from the pumping tests.

The resulting flow rate propelled by the two pumps working in parallel Q(P) is:

$$Q(P)=q(P_1)+q(P_2)=a_4 \cdot (P_1^4+P_2^4)+a_3 \cdot (P_1^3+P_2^3)+a_2 \cdot (P_1^2+P_2^2)+a_1 \cdot (P_1+P_2)+2 \cdot a_0 \qquad (6)$$

It is evident that for each value of P there will be a power distribution ratio which maximises Q(P).

2.2.2. Distribution ratio k of the available power P between two pumps

If k is defined as the distribution ratio of P, the power assigned to each pump will be:

$$P_1=k \cdot P \quad (0 \leq k \leq 0.5)$$

$$P_2=(1-k) \cdot P \quad (0.5 \leq (1-k) \leq 1)$$

This means that if there is an unequal distribution of power, pump 1 will work at a lower power and pump 2 will receive a higher power, i.e. $P_1 \leq P_2$.

Based on Equation (6), the resulting flow rate will be:

$$Q(P)=a_4 \cdot [k^4 \cdot P^4+(1-k)^4 \cdot P^4]+a_3 \cdot [k^3 \cdot P^3+(1-k)^3 \cdot P^3]+a_2 \cdot [k^2 \cdot P^2+(1-k)^2 \cdot P^2]+a_1 \cdot [k \cdot P+(1-k) \cdot P]+2 \cdot a_0 \qquad (7)$$

Due to the conditions established in Equations (4) and (5), a range of variation for k of between 0 and 0.5 is only possible for certain values of P. On this basis, two restrictions can be established:

(1) Since pump 2 receives higher power, $P_2=(1-k)P \leq P_{max}$

(2) Since pump 1 receives lower power, if $P_1=k \cdot P<P_{min}$, $q(P_1)=0$

These restrictions affect the power distribution strategy, since if the power assigned to pump 1 is insufficient to produce flow rate, the total available power P must be assigned to pump 2, which implies k=0 and 1-k=1, provided that this does not violate restriction 1 (i.e. $P_2 \leq P_{max}$).

There will therefore be values of P for which the distribution ratio k will have a certain value, or will be limited to within a range of values. In view of this, the following cases can be considered:

(1) $P<P_{min}$. Power is below the minimum threshold, and neither of the pumps are able to work, thus Q(P)=0. In accordance with restrictions 1 and 2, all power should be assigned to pump 2, but as it is lower than P_{min}, it would constitute a loss and hence: k=0, (1-k)=1, $P_1=0$, $P_2=P$, $q(P_1)=q(P_2)=Q(P)=0$.

(2) $P_{min} \leq P<2P_{min}$. If the available power were distributed between the two pumps, pump 1 would not reach the minimum power for pumping under any conditions, and the power assigned to it would be wasted. In order to avoid this, the total power must be assigned to pump 2 and therefore k=0, (1-k)=1, $P_1=0$, $P_2=P$, $Q(P)=q(P_2)$.

(3) $2P_{min} \leq P<P_{max}$. In theory, k can take values of between 0 and 0.5. However, if the power assigned to pump 1 is lower than P_{min}, this does not generate flow rate, and therefore the total power must be assigned to pump 2. In other words, if $P_1=k \cdot P<P_{min}$, which is equal to the condition $k<(P_{min}/P)$, then k=0. Hence, the allowed values of k in this power range are k=0 and $(P_{min}/P) \leq k \leq 0.5$.

(4) $P_{max} \leq P \leq 2P_{max}$. Pump 2 cannot receive the total available power, since restriction 1 ($P_2 \leq P_{max}$) must be fulfilled. In other words, $(1-k)P \leq P_{max}$, and $k \geq 1-(P_{max}/P)$.

The distribution ratio k can therefore vary between $1-(P_{max}/P) \leq k \leq 0.5$.

The remaining available power may be lower than Pmin. In this case, it could not be assigned to pump 1 and it will therefore be a loss associated to PV pumping system design constraints since pump 2 cannot receive it.

(5) $P>2P_{max}$. The power supplied by the PV generator must be restricted to $2P_{max}$. This power must be equally distributed between the two pumps (k=0.5).

The five cases presented above apply whenever $2P_{min}<P_{max}$. If $2P_{min} \geq P_{max}$, these cases are all applicable except case 3 ($2P_{min} \leq P<P_{max}$), which becomes meaningless. Moreover, for certain values of P, conditions 2 and 4 can be fulfilled simultaneously, meaning that $P<2P_{min}$ and $P_{max} \leq P \leq 2P_{max}$. In these circumstances, k should be that presented in case 4, since for safety purposes it is essential that $P_2=(1-k)P \leq P_{max}$.

Figure 3 summarises the possible k-values allowed versus the available electric power when $2P_{min}<P_{max}$ (Figure 3a) and when $2P_{min} \geq P_{max}$ (Figure 3b).

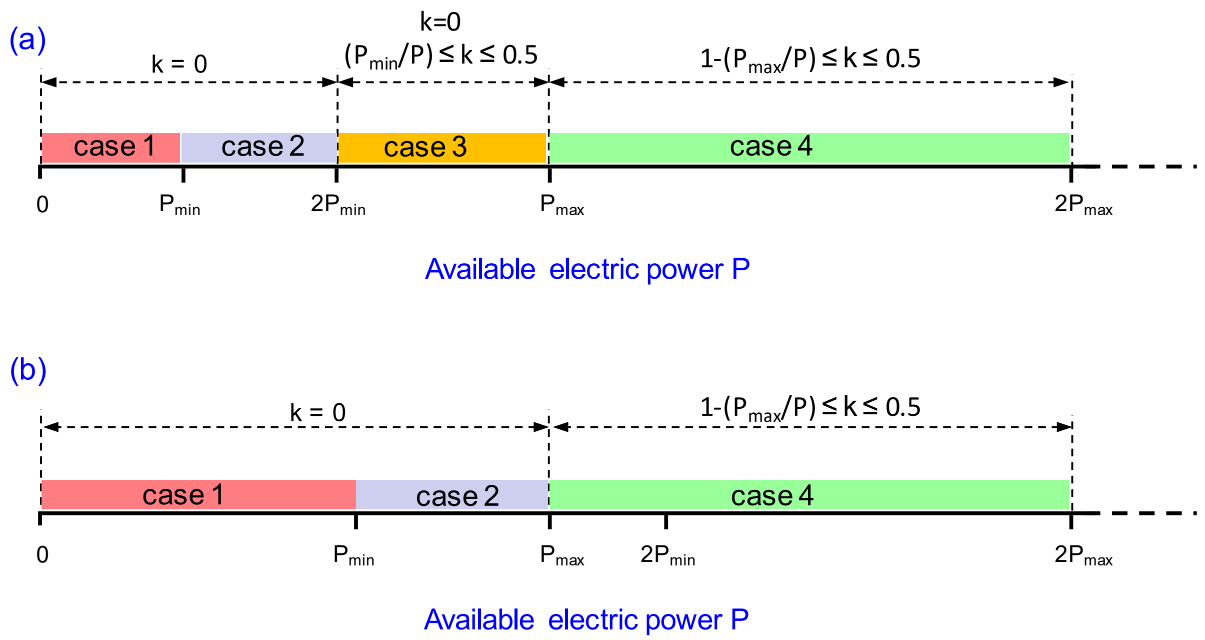


Figure 3. Possible values for the power distribution ratio k vs the available electric power when (a) $2P_{min} < P_{max}$; and (b) $2P_{min} \geq P_{max}$.

The value of the distribution ratio coefficient is k=0 for available powers lower than $2P_{min}$ in case $2P_{min}<P_{max}$ (Figure 3a) or than P_{max} in case $P_{max}<2P_{min}$ (Figure 3b). If the power is higher than the lower of these two values, k varies within a certain range, as indicated in Figure 3. Therefore, an optimal distribution ratio (k_{opt}) that maximises the resulting flow rate of the two pumps can be defined. Furthermore, the ranges of power over which k_{opt} can be sought, are determined.

3. Pumping group tests

3.1. Flow-head, flow-power and flow-efficiency curves of the motor-pump group at constant frequency

Figure 4a shows the Q-H and Q-P curves at frequencies of 50, 45, 40, 35 and 30 Hz for the pumping group. Power refers to the electric power assigned to the motor-pump group.

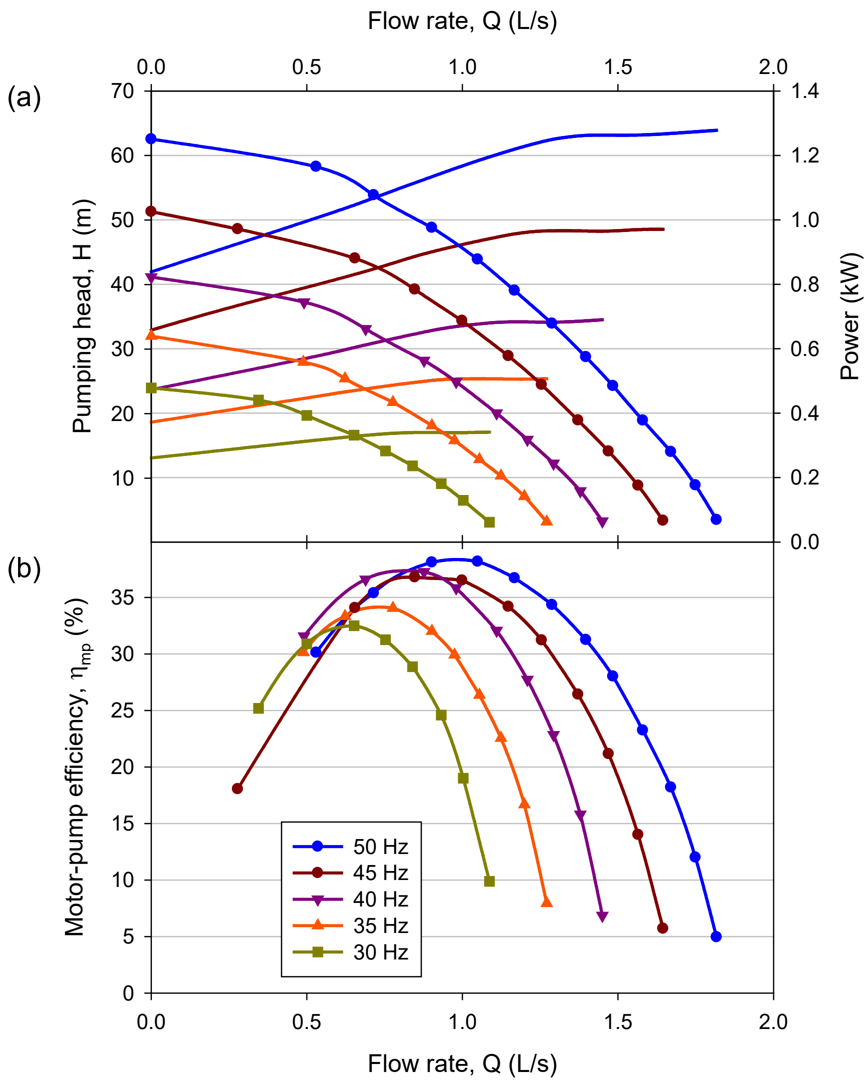


Figure 4. (a) Flow rate-head and flow rate-electric power curves, and (b) flow rate-efficiency curves of the pumping group at various frequencies between 30 and 50 Hz.

Figure 4a suggests that the operating range for the pump used here is approximately 10 to 60 m at a nominal frequency of 50 Hz. It can be observed that for very high pumping heads, the possible margin for variation of the frequency is reduced; for example, at 50 m the frequency can only be reduced to 45 Hz.

The efficiencies of the motor-pump group were calculated from the experimental results as the ratio between the hydraulic power (P_h) and the feeding electric power (P).

Figure 4b represents the Q-η_{mp} curves at frequencies ranging from 30 to 50 Hz. The relation between Q and H for higher efficiencies at each frequency can be observed. The highest efficiency at a frequency of 50 Hz is 38.2 % with a flow rate of 1 L/s, while at 30 Hz, an efficiency of 32.5 % with a flow rate of 0.7 L/s is achieved.

3.2. Q-P characteristic curve at constant head: Efficiency of the motor-pump group

Since H_{max}=60 m, the heads used to obtain the Q-P curves were 18, 24, 30, 36, 42, 48 and 54 m. The Q-P curves were obtained with seven or eight experimental values for each H

(Figure 5). Using those values, adjustment to the fourth-degree polynomial function in Eq. (2) was carried out.

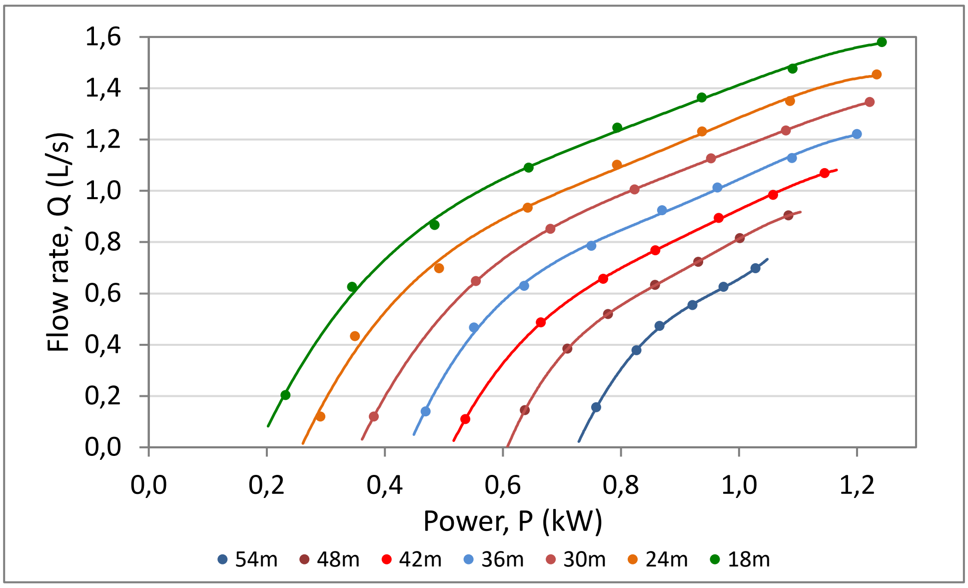


Figure 5. Relation between the flow rate and the electric power of the pumping group at heads of 18, 24, 30, 36, 42, 48 and 54 m: experimental values and adjusted curves.

The value of P_{max} can be obtained theoretically as $P_{nominal}/\eta_{electric\text{-}motor}$ being in this case 0.75/0.7≈1.1 kW. Nevertheless, it has been found experimentally (Figure 5) that P_{max} is approximately 1.2 kW for all pumping tests.

For each value of H, there is a certain minimum operating power (P_{min}), while the maximum power allowed (P_{max}) is around 1.2 kW in all cases (Table 1). It should be noted that P_{min} increases as the head increases.

Table 1. Minimum operating power (P_{min}) and maximum power allowed (P_{max}) for the pumping group for each pumping head tested

H (m)	P_{min} (kW)	P_{max} (kW)
18	0.20	1.20
24	0.26	
30	0.36	
36	0.45	
42	0.52	
48	0.61	
54	0.73	

Table 2 summarises the results of the regression adjustments of the Q-P curves and the corresponding regression coefficients (r^2) obtained for the heads tested.

Table 2. Adjusted equations q(P) and regression coefficients (r^2) for the pumping group for each head tested

H (m)	REGRESSION EQUATION $q(P)=a_4 \cdot P^4+a_3 \cdot P^3+a_2 \cdot P^2+a_1 \cdot P+a_0$	r^2
18	$q=-3.051 \cdot P_{mp}^4+10.737 \cdot P_{mp}^3-14.147 \cdot P_{mp}^2+9.146 \cdot P_{mp}-1.2721$	0.99871
24	$q=-4.582 \cdot P_{mp}^4+15.942 \cdot P_{mp}^3-20.625 \cdot P_{mp}^2+12.709 \cdot P_{mp}-2.1603$	0.99604
30	$q=-4.290 \cdot P_{mp}^4+16.530 \cdot P_{mp}^3-23.886 \cdot P_{mp}^2+16.236 \cdot P_{mp}- 3.4240$	0.99999
36	$q=-10.340 \cdot P_{mp}^4+38.341 \cdot P_{mp}^3-52.882 \cdot P_{mp}^2+33.152 \cdot P_{mp}-7.2259$	0.99900

42	$q=-10.605 \cdot P_{mp}^4+40.013 \cdot P_{mp}^3-56.678 \cdot P_{mp}^2+36.835 \cdot P_{mp}-8.6385$	0.99989
48	$q=-23.530 \cdot P_{mp}^4+89.984 \cdot P_{mp}^3-128.820 \cdot P_{mp}^2+83.039 \cdot P_{mp}-19.865$	0.99999
54	$q=23.563 \cdot P_{mp}^4-60.966 \cdot P_{mp}^3+45.190 \cdot P_{mp}^2-0.386 \cdot P_{mp}-6.746$	0.99980

From the experimental values for Q and P and from the adjusted curves, η_{mp} was determined for each H (Figure 6).

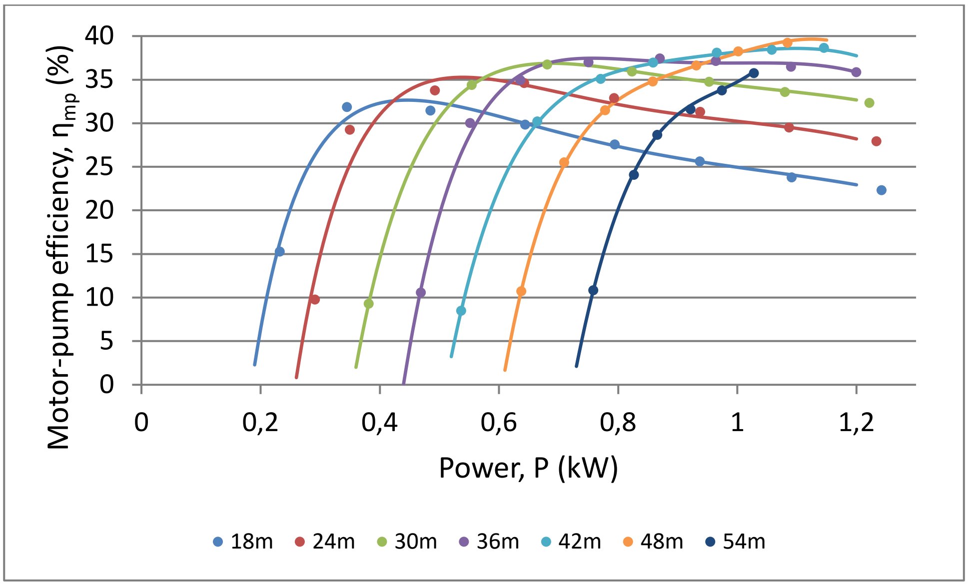


Figure 6. Relation between the efficiency and the power of the pumping group at heads of 18, 24, 30, 36, 42, 48 and 54 m: experimental values and adjusted curves.

In general, it is observed for all heads that the efficiencies increase rapidly with power, reaching a maximum after which a moderate decrease is seen. The maximum efficiencies achieved for heads of 48 and 18 m are 39.6 % and 32.6 %, respectively. At 54 m the pumping group works at low efficiencies at almost all power rates. Thus, this head is not considered in this study.

4. Results and Discussion

4.1. Optimal power distribution ratio between the two pumps

Since P_{min} and P_{max} are determined, it can be established at each pumping head whether $2P_{min}<P_{max}$ or $2P_{min} \geq P_{max}$. As shown in Section 2.2.2, the intervals of variation of k (Figure 3) and the ranges of power over which k_{opt} should be sought can be specified in each case. These results are summarised in Table 3. Two possible cases are presented since for heads of 18, 24, 30, 36 and 42 m it is $2P_{min}<P_{max}$, while at H=48 m it is $2P_{min} \geq P_{max}$.

Table 3. Relationship between the values P_{min} and P_{max}, intervals of variation of the power distribution coefficient k, and ranges of power in which k_{opt} (the value of k that maximises the resulting flow rate of the two pumps) should be sought, at each of the tested pumping heads.

H(m)	$2P_{min}$ (kW)	P_{max} (kW)	Relationship $2P_{min} \leftrightarrow P_{max}$	Intervals of variation of k	Ranges of power P for k_{opt}
18	0.4	1.2	$2P_{min}<P_{max}$	k=0 and $(P_{min}/P) \leq k \leq 0.5$	$2P_{min} \leq P \leq P_{max}$
24	0.52	1.2			
30	0.72	1.2			
36	0.9	1.2		$1-(P_{max}/P) \leq k \leq 0.5$	$P_{max}<P \leq 2P_{max}$
42	1.04	1.2			
48	1.22	1.2	$2P_{min} \geq P_{max}$	$1-(P_{max}/P) \leq k \leq 0.5$	$P_{max}<P \leq 2P_{max}$

The values of the coefficients a_0, a_1, a_2, a_3 and a_4 obtained from the adjustment by regression of the function q(P) (Table 2) allow applying Eq. (7) to determine the flow rate pumped by the two pumps, based on the value of k at each pumping head and the available power.

Next, the implementation of the distribution strategy set out in the Materials and Methods section is described in more detail for each case at the specific pumping heads.

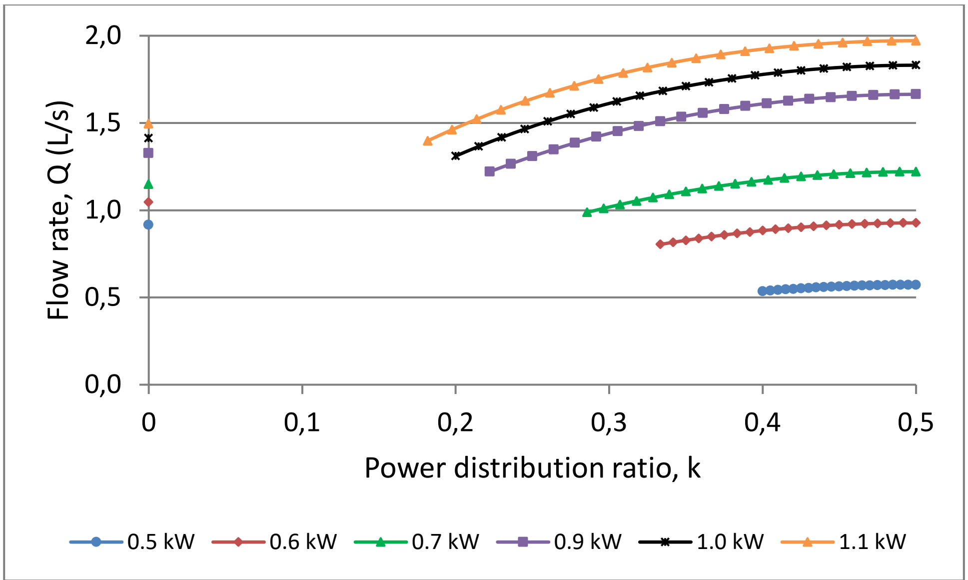
4.1.1. Pumping when $2P_{min}<P_{max}$

Considering H=18 m as an example, when $P<2P_{min}$, k=0 (Figure 3a), and the intervals of power in which the value of k_{opt} should be found are: $2P_{min} \leq P \leq P_{max}$ and $P_{max}<P \leq 2P_{max}$ (Table 3).

(1) Power in the range $2P_{min} \leq P \leq P_{max}$ (i.e. 0.40 kW≤P≤1.2 kW)

The values of the power distribution ratio are either k=0 or any value within the interval $(P_{min}/P) \leq k \leq 0.5$.

Figure 7 shows the flow rate resulting from the two pumps Q(P) based on k and for six values of available power within the range considered. The table attached to the figure gives the value of k_{opt} and the maximum resulting flow rate (Q_{max}) at each power.



P (kW)	0.5	0.6	0.7	0.9	1.0	1.1

(P_{min}/P)	0.400	0.333	0.286	0.222	0.200	0.182
k_{opt}	0.00	0.00	0.50	0.50	0.50	0.50
Q_{max} (L/s)	0.92	1.05	1.22	1.66	1.83	1.97

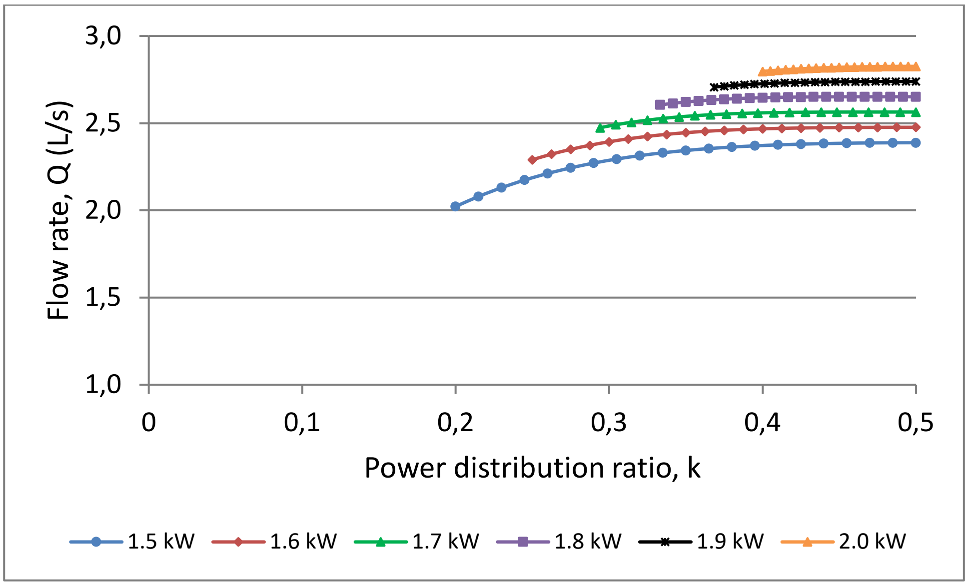
Figure 7. Flow rate resulting from the two pumps Q(P) at H=18 m vs power distribution ratio k, for six values of available power (0.5, 0.6, 0.7, 0.9, 1.0 and 1.1 kW) within the range $2P_{min} \leq P \leq P_{max}$. Only the flow rates for the accepted values of k: k=0 and $(P_{min}/P) \leq k \leq 0.5$ are shown. The attached table gives the values of k_{opt} and the corresponding maximum flow rates for each available power.

Within this range of values for the power, k_{opt} only takes the values 0 and 0.5. Furthermore, there is a value of the power defined as P_e (between 0.6 and 0.7 kW) below which k_{opt}=0, and above which k_{opt}=0.5. This value P_e therefore represents the power above which the two pumps should work in parallel with a power distribution at 50 %. The expression for its calculation is given below.

(2) Power in the range $P_{max}<P\leq 2P_{max}$ (i.e. 1.2 kW<P≤2.4 kW)

The parameter k can take any value in the interval $1-(P_{max}/P)\leq k\leq 0.5$ (in this case, $1-(1.2/P)\leq k\leq 0.5$), where $1-(P_{max}/P)$ denotes the minimum value of k, k_{min}, for all P in this interval.

Figure 8 shows the flow rate Q(P) in accordance with k, for six values of available power in the range 1.2 kW<P≤2.4 kW. The table attached to the figure gives the value of k_{opt} and the corresponding Q_{max} for each power.



P (kW)	1.5	1.6	1.7	1.8	1.9	2.0
$k_{min}=1-(P_{max}/P)$	0.200	0.250	0.294	0.333	0.368	0.400
k_{opt}	0.50	0.50	0.479	0.475	0.50	0.50
Q_{max} (L/s)	2.3879	2.4765	2.5640	2.6516	2.7391	2.8260
Q for k=0.5 (L/s)			2.5640	2.6515		

Figure 8. Flow rate resulting from the two pumps Q(P) at H=18 m vs power distribution ratio k, for six values of available power: 1.5, 1.6, 1.7, 1.8, 1.9 and 2.0 kW, within the range $P_{max} < P \leq 2P_{max}$. The attached table gives the

value of k_{opt} and the corresponding maximum flow rate for each power. In the cases where k_{opt}<0.5, the flow rate obtained at k=0.5 is also given.

It is observed that k_{opt}=0.5 for most of the P values analysed here; in cases where k_{opt} is not equal to 0.5 (i.e. at P=1.7 kW and 1.8 kW), it takes values close to 0.5 and Q_{max} is practically the same as that obtained for k=0.5. It can therefore be considered that k_{opt}=0.5 for all P within the studied interval.

Figure 9 summarises the results for H=18 m.

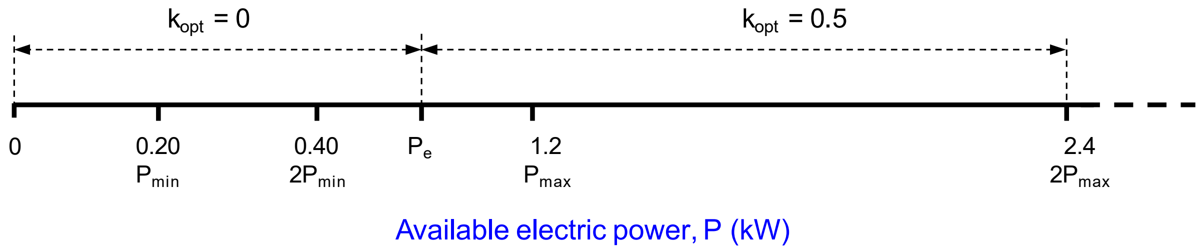


Figure 9. Values of the optimal power distribution ratio k_{opt} vs available electric power, for a pumping head H=18 m. The value of P_e is between 0.6 and 0.7 kW.

Pumping heads of 24, 30 36 and 42 m give the same behaviour as H=18 m, since $2P_{min}<P_{max}$ (Table 3).

The cases H=24 m and H =30 m (results not shown) differ from the case H=18 m only in terms of the value of P_e, which is between 0.8 and 0.9 kW (H=24 m), and between 1.05 and 1.1 kW (H=30 m). Note that in all three cases (18, 24 and 30 m) $P_e<P_{max}$.

However, for both H=36 m and H=42 m (results not presented), it is verified that $P_e>P_{max}$. This means that in the interval of power between P_{max} and P_e, a value of k=0 would mean that the power assigned to the pump 2 would be higher than P_{max}. Hence, $k_{opt}=1-(P_{max}/P)$, meaning that $P(1-k)=P_{max}$. The remaining available power only could be assigned to pump 1 if it is higher than P_{min}. Otherwise it would be a lost. Figure 10 illustrates the conclusions in these cases (H=36 m and H=42 m). It is found that the value of P_e is between 1.23 and 1.3 kW for H=36 m, whereas for H=42 m is between 1.3 and 1.4 kW.

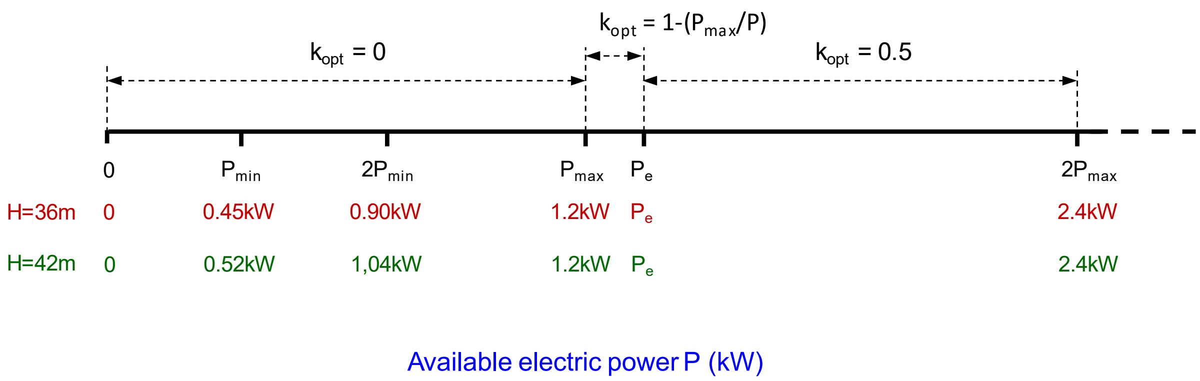


Figure 10. Values of optimal power distribution ratio k_{opt} vs available electric power, for pumping heads H=36 m (P_e between 1.23 and 1.3 kW) and H=42 m (P_e between 1.3 and 1.4 kW).

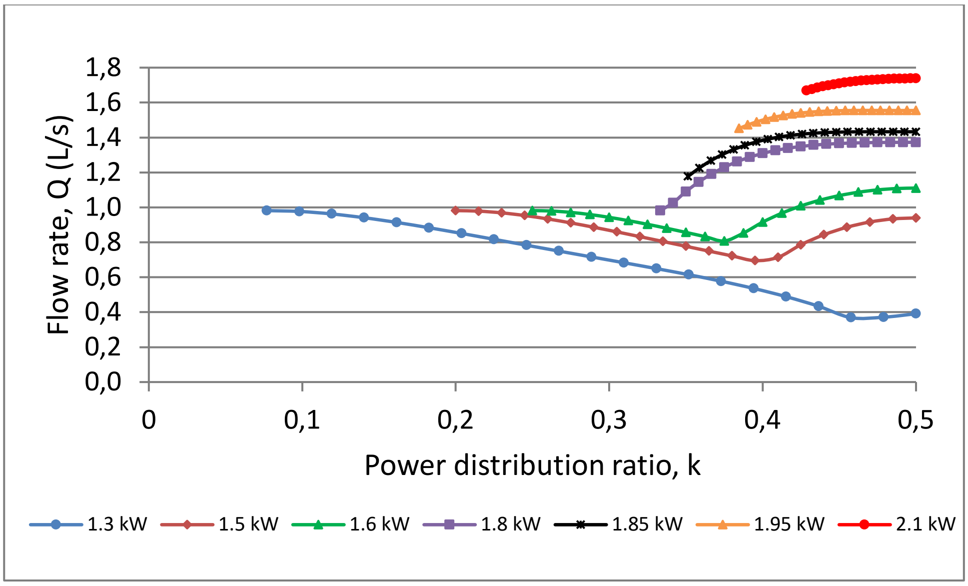
4.1.2. Pumping when $2P_{min} \geq P_{max}$

It should be noted that the condition $2P_{min}<P_{max}$ occurs under the normal operating conditions of the motor-pump groups. The case $2P_{min}\geq P_{max}$ occurs only for high pumping heads within the application range of the selected pump (e.g. the case of a pumping system in which there is a significant decrease in the water table; the pump is selected so that these are not the normal operating conditions). In the present study the condition $2P_{min}\geq P_{max}$ only occurs for the highest pumping head, H=48 m.

Considering then H=48 m as an example of this case, the range of powers in which in which k_{opt} should be sought is $P_{max}<P\leq 2P_{max}$ (Table 3). For $P\leq P_{max}$ (i.e. P≤1.2 kW), $k_{opt}=0$ and all the power is assigned to pump 2 (Figure 3b).

If power is in the range $P_{max}<P\leq 2P_{max}$ (i.e. 1.2 kW<P≤2.4 kW), k can take any value within the interval 1-(1.2/P)≤k≤0.5.

Figure 11 presents the resulting flow rate Q(P) vs k, for seven values of available power within the range 1.2 kW<P≤ 2.4 kW. The attached table shows the values of k_{min}, k_{opt}, and Q_{max} at each considered power.



P (kW)	1.3	1.5	1.6	1.8	1.85	1.95	2.1
$k_{min}=1-(P_{max}/P)$	0.077	0.200	0.250	0.333	0.351	0.385	0.429
k_{opt}	0.077	0.200	0.500	0.500	0.478	0.471	0.500
Q_{max} (L/s)	0.9815	0.9815	1.1106	1.3724	1.4330	1.5551	1.7375
Q for k=0.5 (L/s)					1.4328	1.5545	

Figure 11. Flow rate resulting from the two pumps Q(P) at H=48 m vs power distribution ratio k, for seven values of available power: 1.3, 1.5, 1.6, 1.8, 1.85, 1.95 and 2.1 kW, within the range $P_{max} \leq P \leq 2P_{max}$. The attached table gives the values of k_{opt} and the corresponding maximum flow rate for each value of available power.

It should be noted that there is a value of power P_e (between 1.5 and 1.6 kW) below which $k_{opt}=k_{min}$. For $P\geq P_e$, the Q_{max} occurs when k=0.5, except when P is around 1.85-1.95 kW. In these cases, k_{opt} is slightly less than 0.5 although the resulting Q_{max} is practically the same as that obtained at a distribution ratio k=0.5.

In fact, for $P<P_e$, it should be $k_{opt}=0$, but this would mean that the power assigned to pump 2 would be $P(1-k)>P_{max}$. Thus, $k_{opt}=1-(P_{max}/P)$, meaning that $P(1-k)=P_{max}$. It is possible that the power assigned to pump 1 may be insufficient for pumping.

Therefore, over the whole interval of powers (1.2 kW<P≤2.4 kW), $k_{opt}=1-(P_{max}/P)$ when $P<P_e$ and $k_{opt}=0.5$ when $P>P_e$.

Figure 12 illustrates the results of this case (H=48 m).

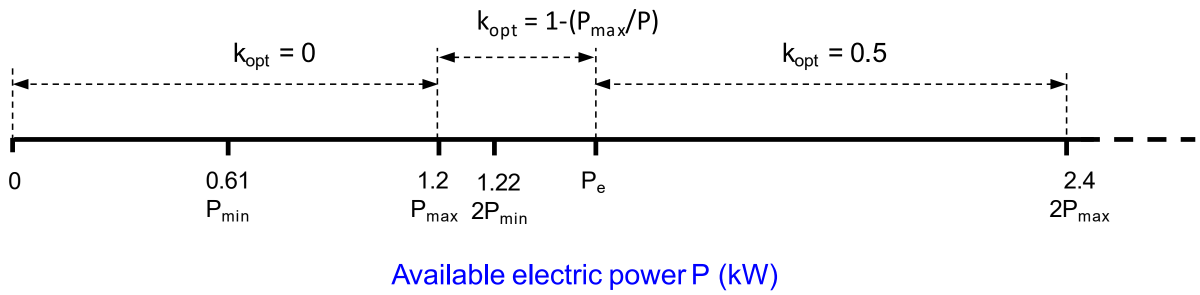


Figure 12. Values of optimal power distribution ratio k_{opt} vs available electric power, for pumping head H=48 m. P_e is a value between 1.5 and 1.6 kW.

Note that at heads of 36, 42, and 48 m, the condition $P_e>P_{max}$ is fulfilled and the same conclusions can be drawn for the calculation of k_{opt} (Figures 10 and 12).

There is therefore no power distribution ratio other than 0 and 0.5 which maximises the flow rate, except that indicated to limit the power assigned to one of the pumps up to P_{max}.

These experimental tests were also carried out for 1.5 kW pumps, with similar results (not reported here), and this confirms the applicability of these conclusions to pumps of different powers.

4.2. Power P_e and determination of its value

This section explains how the value of P_e is determined.

In all cases, it is found that when $P>P_e$, the two pumps must work at a power distribution of 50 % ($k_{opt}=0.5$).

The flow rate propelled by both pumps in parallel, each of which receives half of the available power (k=0.5), is:

$$Q(P)=q(P/2)+q(P/2)=2\cdot q(P/2)=2\cdot[a_4\cdot(P/2)^4+a_3\cdot(P/2)^3+a_2\cdot(P/2)^2+a_1\cdot P/2+a_0] \qquad (8)$$

The flow rate from a single pump can be compared with that from two pumps in parallel with k=0.5. Figure 13 shows the curves for the flow rate-power of a single pump q(P) and for two pumps in parallel Q(P) with a power distribution of 50 % (k=0.5). Two cases can be considered:

(a) The curves Q(P) and q(p) intersect at a value of power $P<P_{max}$ (Figure 13a).

It should be noted that for values of power higher than the intersection point, the flow rate for two pumps in parallel with k=0.5 is higher than that for a single pump fed with all the available power. Thus, if $P>P_e$, then $Q(P)>q(P)$. The power at the intersection point is precisely the value of P_e for heads of 18, 24 and 30 m, all of which have a similar power distribution.

(b) The curves Q(P) and q(p) do not intersect for values of power $P<P_{max}$ (Figure 13b).

In this case, when $P<P_{max}$, the flow rate for a single pump q(P) is higher than that for two pumps Q(P) with k=0.5. However, even if the value of P_{max} is exceeded, only a single pump can work, although it cannot be fed with all the available power. The maximum power assigned to this pump must be kept equal to P_{max}, and the excess cannot be assigned to the other pump, (given that this may be insufficient for pumping). Then it would be a loss if it could not be allocated for other uses. This is equivalent to a power distribution ratio of $k=1-(P_{max}/P)$.

When the available power exceeds a certain value, it is verified that Q(P)>q(P), meaning that the two pumps must work in parallel with k=0.5. This value corresponds to the value of P_e obtained for pumping at heads of 36, 42 and 48 m, in which, as stated above, the power distribution is similar.

In order to establish an adequate working strategy and the values of k_{opt} for each H, it is required to determine which case applies, i.e. (a) or (b) (Figure 13), and to obtain the value of P_e.

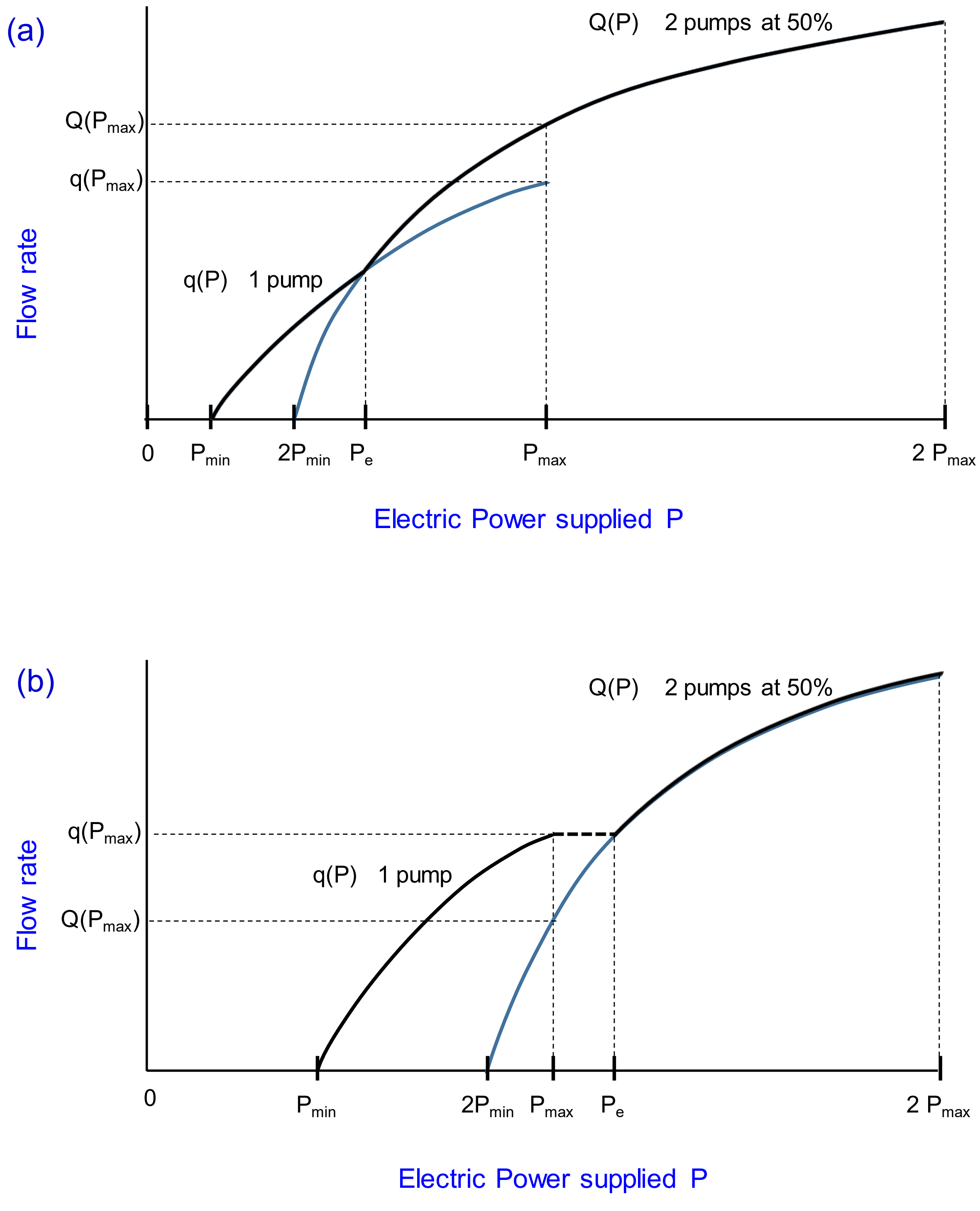


Figure 13. Flow rate-power curves for a single pump (q(P)) and for two pumps in parallel with a power distribution ratio of 50 % (Q(P)), for (a) $P_e<P_{max}$; (b) $P_e>P_{max}$.

In order to determine whether pumping at a certain head corresponds to case (a) or (b), as shown in Figure 13, the flow rates q(p) and Q(P) at $P=P_{max}$ are compared. Thus, if $q(P_{max})<Q(P_{max})$ it is case (a), while if $q(P_{max})>Q(P_{max})$ it is case (b). In practice, it is simple to verify this fact at any facility. Since $Q(P_{max})=2q(P_{max}/2)$, it is sufficient to perform a pumping test with a single pump and to check whether $q(P_{max})$ is lower (case (a)), or higher (case (b)), than $2q(P_{max}/2)$.

In case (a), $P_e<P_{max}$ and the value of P_e is obtained by equating Equations (2) and (8), giving:

$$(7/8)\cdot a_4\cdot P^4+(3/4)\cdot a_3\cdot P^3+(1/2)\cdot a_2\cdot P^2-a_0=0 \qquad (9)$$

To solve Equation (9) and obtain the value of P_e, numerical methods can be used. The optimal distribution strategy for the available power is as follows: if $P\leq P_e$, all the power must be assigned to one of the pumps (k=0), and if $P>P_e$, the power must be distributed at 50 % between the two pumps (k=0.5).

In case (b), $P_e>P_{max}$, and the value of P_e above which both pumps function can be obtained from the solution of the equation:

$$Q(P)=q(P_{max})$$

$q(P_{max})$ is expressed as:

$$q(P_{max})=a_4\cdot P_{max}^4+a_3\cdot P_{max}^3+a_2\cdot P_{max}^2+a_1\cdot P_{max}+a_0 \qquad (10)$$

Equating Equations (8) and (10) gives:

$$(a_4/8)\cdot P^4+(a_3/4)\cdot P^3+(a_2/2)\cdot P^2+a_1\cdot P+2\cdot a_0=q(P_{max}) \qquad (11)$$

The solution to the above equation leads to obtain the value of P_e. In this case, the optimal distribution strategy for the available power is as follows: when $P\leq P_{max}$, all the power must be assigned to one of the pumps (pump 2), and k=0. When P is in the range $P_{max}<P\leq P_e$, pump 2 must operate with P_{max} and the excess power is transferred to pump 1, ($k=1-(P_{max}/P)$), only in case that the power received ($P-P_{max}$) is higher than P_{min}. Finally, if $P>P_e$, the power must be distributed at 50 % between the two pumps (k=0.5).

Figure 14 shows the optimal distribution strategy (k_{opt}) vs P in cases (a) ($P_e<P_{max}$) and (b) ($P_e>P_{max}$). The different operating modes in each case (ON/OFF status of each pump) have also been included.

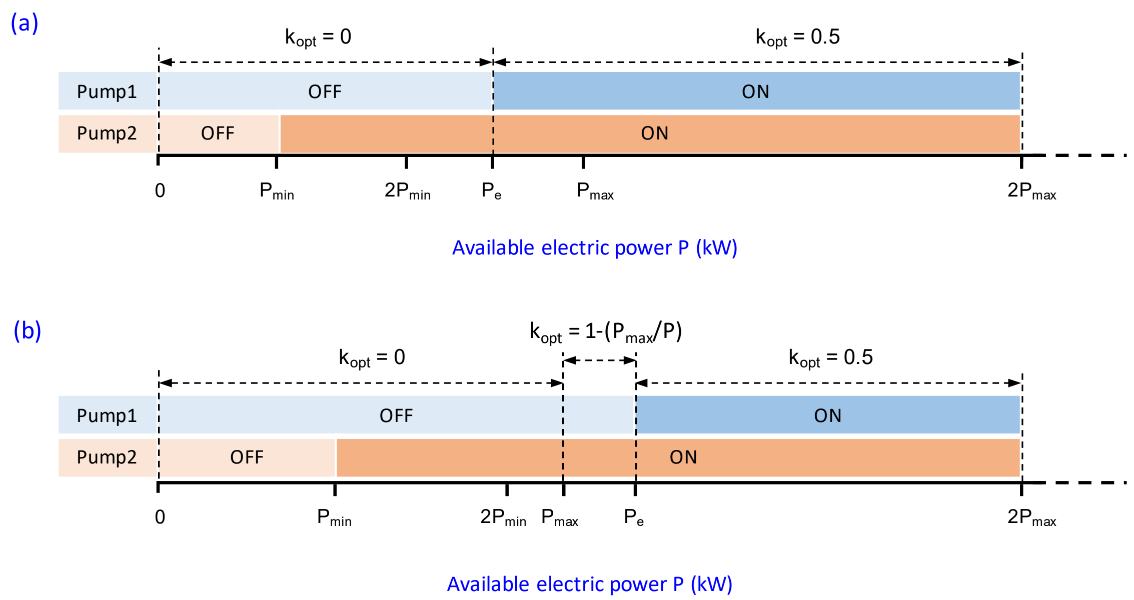


Figure 14. Optimal distribution strategy for the available power for (a) $P_e<P_{max}$; (b) $P_e>P_{max}$. Operating mode (ON/OFF status) of both pumps in each case.

Table 4 gives the ranges in which the value of P_e is found for each H (previously obtained) and its relationship with P_{max}. It should be noted that the power distribution strategy for the lower pumping heads (18, 24 and 30 m) corresponds to case (a) with $P_e<P_{max}$, while that for the higher pumping heads (36, 42 and 48 m) corresponds to case (b) with $P_e>P_{max}$.

Table 4. Range of values of P for which the value of P_e is found and relationship between P_e and P_{max} for all pumping heads

H(m)	P_e Rank (kW)	P_{max} (kW)	Relationship $P_e \leftrightarrow P_{max}$
18	0.6-0.7		
24	0.8-0.9	1.2	$P_e<P_{max}$
30	1.05-1.1		
36	1.23-1.3		
42	1.3-1.4	1.2	$P_e>P_{max}$
48	1.5-1.6		

Based on the previous considerations, the value of P_e is determined below for the different pumping heads. The conclusion drawn here can be used to define the strategy for pumping heads H=18 m and H=42 m, as representative examples of the two possible cases (Table 4).

P_e and power distribution strategy at H=18 m

Firstly, the values of $q(P_{max})$ and $Q(P_{max})=2\cdot q(P_{max}/2)$ are compared. Substituting the corresponding values, since $q(P_{max})<Q(P_{max})$, it is case (a), i.e. $P_e<P_{max}$. By substituting and solving Equation (9), the value of P_e is determined (table 5).

Figure 15 shows the optimal distribution strategy for the available power at H=18 m.

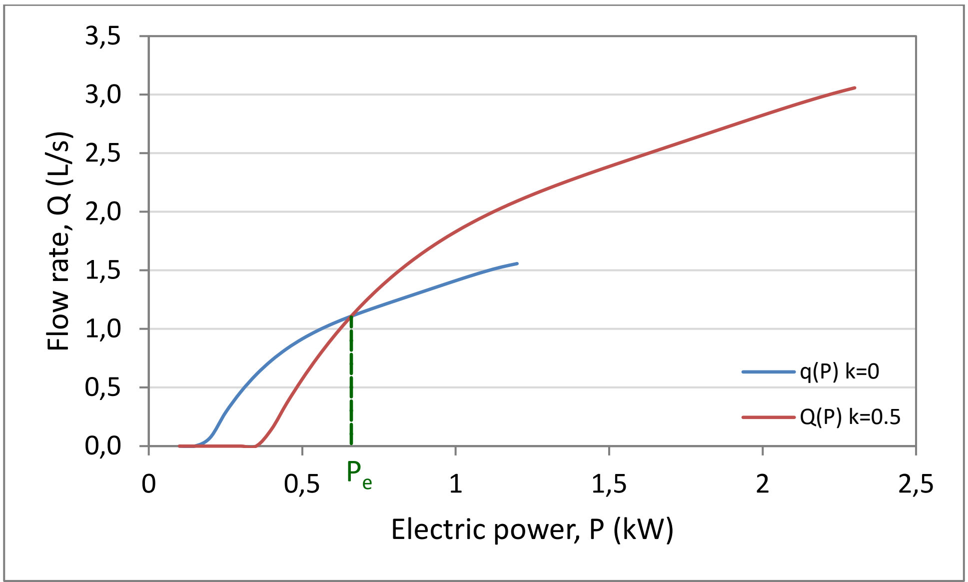


Figure 15. Flow rate-power curves for a single pump of 0.75 kW (k=0), and for two pumps of 0.75 kW working in parallel with ratio of power distribution of 50 % (k=0.5), pumping at H=18 m. P_e = 0.660 kW.

P_e and power distribution strategy at H=42 m

As in the case of H=18 m, the values for $q(P_{max})$ and $Q(P_{max})=2\cdot q(P_{max}/2)$ are first compared. Since $q(P_{max})>Q(P_{max})$, it is case (b), i.e. $P_e>P_{max}$. By substituting and solving Equation (11), the value for the power P_e can be obtained (Table 5).

Figure 16 shows the optimal available power distribution strategy at H=42 m.

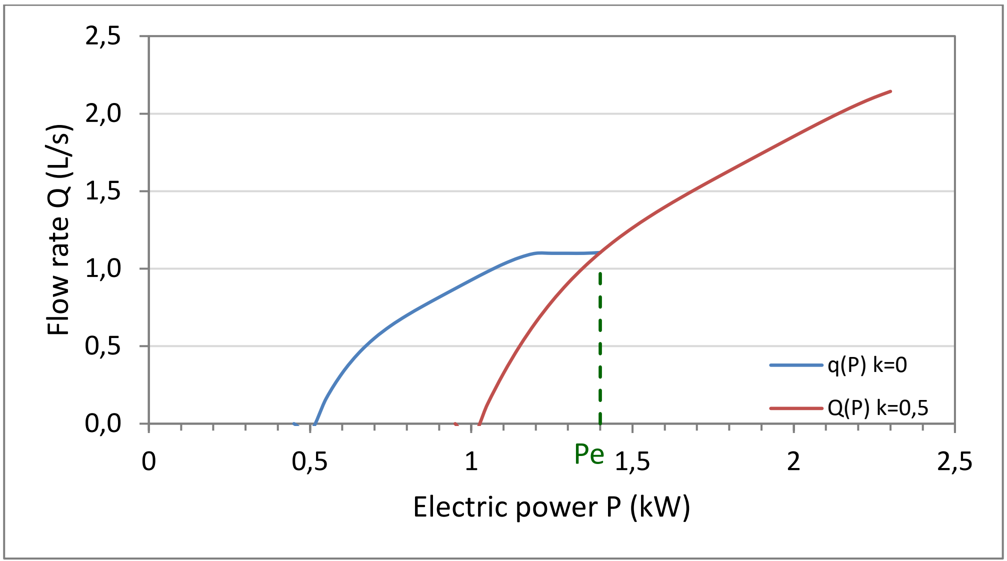


Figure 16. Flow rate-power curves for a single pump 0.75 kW (k=0), and for two pumps of 0.75 kW in parallel with power distribution at 50 % (k=0.5), pumping at H=42 m. P_e = 1.40 kW.

Table 5 summarises the results of determining P_e for all pumping heads tested in this work, and shows that the calculated value for P_e is within the previously estimated range.

Table 5. Calculated P_e values for all pumping heads tested

H(m)	$q(P_{max})$ (L/s)	$Q(P_{max})$ (L/s)	case	P_e (kW)
18	1.558	2.092		0.660
24	1.437	1.78	(a) $P_e<P_{max}$	0.824
30	1.332	1.466		1.083
36	1.219	1.139		1.243
42	1.099	0.654	(b) $P_e>P_{max}$	1.400
48	0.982	0.000		1.522

5. Conclusions

In this paper, a method of distributing the power generated in a photovoltaic pumping system equipped with two equal 0.75 kW pumps working in parallel is investigated.

The pumps were experimentally characterised by the determination of the Q-H and Q-P curves at five different working frequencies (30-50 Hz), and at six pumping heads (18-48 m).

A strategy for the distribution of the generated power is established which maximises the flow rate pumped by the set of both pumps. For this purpose, a distribution ratio of the available power between the two pumps, k, is defined.

The possible values that k can take are analysed based on the available power P. These can be grouped into two cases, depending on whether $2P_{min}<P_{max}$ or $2P_{min}\geq P_{max}$, where P_{min} is the minimum power required to start the pumping at a certain head, and P_{max} is the maximum power allowed for the pumping group.

An optimal distribution ratio (k_{opt}) of the power between the two pumps can be defined. The power ranges in which k_{opt} can be found and its possible values can be specified in each case.

The results for the different pumping heads show differences between higher and lower heads. However, there is a power value P_e above which $k_{opt}=0.5$ and the power should be distributed at 50 % between the two pumps; conversely, if the power is lower than P_e, $k_{opt}=0$ and all the available power must be assigned to only one of the pumps. But if it exceeds P_{max}, the power assigned to the pump that is receiving higher power is limited to the value of P_{max} and $k_{opt} = 1-(P_{max}/P)$. This condition occurs only if $P_e>P_{max}$ (heads 36, 42 and 48 m).

Consequently, there is no power distribution ratio other than 0 and 0.5 that maximises the flow rate, except that required to limit the power assigned to one of the pumps to P_{max}.

The determination of the value of P_e can be established analytically from the curves representing the flow rate-power relationship of a single pump (q(P)), and for the two pumps in parallel (Q(P)) with power distribution of 50 %. Two possibilities can be considered:

(a) The curves q(P) and Q(P) intersect at a value $P<P_{max}$.

(b) The curves q(P) and Q(P) do not intersect for values of power $P<P_{max}$.

In order to establish the most suitable working strategy for a given set of pumps and a specific pumping head, it is necessary to determine previously which case applies.

In practice, it is possible to determine whether the pumping at a certain head corresponds to case (a) or (b) using a simple pumping test. Since $Q(P_{max})=2q(P_{max}/2)$, it is sufficient to carry out a pumping test with a single pump and to check whether $q(P_{max})$ is lower (case a) or higher (case b) than $2q(P_{max}/2)$.

When applying these conclusions to the pumping heads considered in this work, the power distribution strategy for the lower pumping heads (18, 24 and 30 m) corresponds to case (a) with $P_e<P_{max}$, while for the higher pumping heads (36, 42 and 48 m) this corresponds to case (b) with $P_e>P_{max}$.

In order to confirm that the conclusions derived from this work can be extrapolated to pumps of different powers, the same study was conducted with pumps of 1.5 kW, and identical results were obtained.

The proposed methodology can probably be generalised to pumping groups with higher numbers of pumps in parallel.

Further work is in progress related to the application of the method for distributing the power generated in the PV system proposed in this paper from the modelling of the facility during a whole year.

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