

An approach to costs and energy consumption in private urban Spanish Mediterranean landscapes from a simplified model in sprinkle irrigation⁽¹⁾

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Abstract

The number of private gardens has increased in recent years, creating a more pleasant urban model, but not without having an environmental impact, including increased energy consumption, which is the focus of this study. The estimation of costs and energy consumption for the generic typology of private urban gardens is based on two simplifying assumptions: square geometry with surface areas from 25 to 500 m² and hydraulic design with a single pipe. In total, eight sprinkler models have been considered, along with their possible working pressures, and 31 pumping units grouped into 5 series that adequately cover the range of required flow rates and pressures, resulting in 495 hydraulic designs repeated for two climatically different locations in the Spanish Mediterranean area (Girona and Elche). Mean total irrigation costs for the locality with lower water needs (Girona) and greater needs (Elche) were € 2,974 ha⁻¹ yr⁻¹ and € 3,383 ha⁻¹ yr⁻¹, respectively. Energy costs accounted for 11.4% of the total cost for the first location, and 23.0% for the second. While a suitable choice of the hydraulic elements of the setup is essential, as it may provide average energy savings of 77%, due to the low energy cost in relation to the cost of installation, the potential energy savings do not constitute a significant incentive for the irrigation system design. The low efficiency of the pumping units used in this type of garden is the biggest obstacle and constraint to achieving a high quality energy solution.

Additional key words: hydraulic design; irrigation costs; pump efficiency; watering gardens.

Introduction

Nowadays, our society is more aware of the importance of the sustainable use of natural resources, among them water and energy, which are the essential inputs in irrigation systems. Saving these resources is of major importance for both environmental and economic reasons.

From an environmental point of view, a key aim is a reduction in gas emissions responsible for the greenhouse effect. In Europe, energy consumption accounts for 80% of emissions of gases related to the greenhouse effect (European Commission, 2010). To this end, the adoption of European Directive 2006/32/EC (OJ,

2006), on energy end-use efficiency and energy services, established the need to take measures to achieve energy savings of a minimum of 9% by 2016.

It is important to point out that the cost of energy has increased significantly in recent years. Until now, efforts in the irrigation sector have been focused primarily on reducing water consumption for crops, as agriculture is the largest user of water. In this respect, Corominas (2009) points out that, while water use per hectare was reduced by 21% from 1950 to 2007, the energy demand increased by 657%, from 206 to 1560 kWh ha⁻¹ year⁻¹. Several studies (Pulido-Calvo *et al.*, 2003; Vieira & Ramos, 2009; Daccache *et al.*, 2010; Rodríguez *et al.*, 2011; Rodríguez-Díaz *et al.*, 2011)

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⁽¹⁾ Any mention of trade or manufacturer names is for information only and does not imply any endorsement, recommendation, or exclusion by the authors of this paper.

have focused on improving energy efficiency by optimizing the two limiting resources for irrigation, *i.e.* water and energy.

On the other hand, the growing importance of the irrigation of parks and gardens should not be underestimated. This has been helped by the trend towards population concentration in urban and peri-urban areas, and by a change in the urban model leading to an increase in the number of single-family houses with gardens. For a number of years in Spain demographic and social patterns together with low interest rates have caused a housing boom that has produced a considerable increase in housing prices and the need to occupy land in the urban peripheries (Domene & Saurí, 2006), favouring the urban sprawl, or low density city, model. The resulting proliferation of gardens has had important positive effects at a territorial level besides its recreational function, beautifying the urban landscape and improving the individual well-being of their owners. On the one hand, they contribute to a local temperature reduction in hot climates (Beard & Green, 1994; Wong *et al.*, 2003) and in that respect, McPherson (1990) states that evapotranspirational cooling from strategically located turf areas could be cost-effective at current utility prices. Moreover, another beneficial aspect of gardens is greater rainwater infiltration in urban areas (Verbeeck *et al.*, 2011).

However, this urban-model change also has a greater environmental impact than that of the high density city based on population concentration (Rueda, 1995). These effects, detected in Anglo-Saxon countries, include an increase in energy consumption and emissions (Newman & Kenworthy, 1989; Anderson *et al.*, 1996; Crane, 1999; Lavière & Lafrance, 1999), as well as higher water consumption. On the other hand, in Spain, garden irrigation usually uses potable water, which costs more than water used for agricultural irrigation (Salvador *et al.*, 2011), and consumes a considerable amount of energy, related to the process of obtaining it.

Water consumption related to urban change has been studied by some authors. In the case of Spain, Domene & Saurí (2006) concluded that demographic and housing factors, especially family size and dwelling type, are significant variables that explain domestic water consumption: water consumption is higher in single-family houses, mainly due to outdoor uses, especially garden irrigation. St. Hilaire *et al.* (2008) pointed out that irrigation accounts for between 40% and 70% of the water used in houses with gardens in the USA, and in most cases the volume of water applied is greater

than necessary. In cities, in addition to domestic water consumption, municipal consumption is also important. There are few studies dealing with water consumption in private and public gardens, but those dealing with energy consumption are scarcer still and only provide predominantly qualitative generic recommendations. Domene & Saurí (2003) proposed several measures to save water and energy, such as grouping plant species according to their water needs, selecting species adapted to local climatic conditions, avoiding large lawn extensions, organizing irrigation depending on the plants' water needs, watering at the appropriate times according to the weather conditions, using mulching and using efficient irrigation systems.

The efficiency of a sprinkler irrigation system depends on its design and management. Regarding the design, an appropriate choice of system components (pipes, sprinklers and pumps) together with the applied hydraulic design criteria, are crucial in terms of energy consumption. In particular, the selection of the hydraulic pump must take into account the characteristic curves so that the operating point is close to maximum efficiency.

The objective of this paper is to analyze the different solutions derived from the hydraulic design of private gardens using products available on the market and relate these to their energy consumption. In addition, those cases that present the greatest energy savings will be studied and the extent to which the savings achieved are an economic incentive for the garden developer will be determined. Lastly, guidelines that contribute to technical and economic improvements in garden projects will be established.

This paper has the character of an approach to the analysis of the relationship between the installation and operating costs due to the numerous assumptions that it has been necessary to make to standardize the hydraulic cases studied, as well as the lack of previous quantitative studies on the topic.

Material and methods

Definition of the domestic garden type

Private gardens are highly variable in their characteristics, which makes it difficult to identify a representative garden type. Thus, particularities were avoided and the base garden considered had some general properties: flat topography, square geometry and turfgrass coverage. The occasional presence of shrubs or trees was not considered.

The garden surface area was taken to be variable. In defining values, reference was made to the results of Domene & Saurí (2003) who, after conducting 120 interviews with residents of single-family houses with gardens in six municipalities of the Metropolitan Area of Barcelona, found that average garden surface areas and their standard deviations were $235.5 \pm 148.6 \text{ m}^2$ for middle-income municipalities and $464.4 \pm 1,168.8 \text{ m}^2$ for high-income municipalities. Based on these data, for the present study different garden surface areas from 25 to 500 m^2 were analyzed, namely 25, 50, 100, 150, 200, 250, 300, 350, 400, 450 and 500 m^2 . This range covers all surface areas of the middle-income gardens and a significant portion of the high-income gardens described by Domene & Saurí (2003). It was not considered necessary to cover the whole range of garden surfaces for the high-income municipalities because they had very high standard deviations.

Sprinkler irrigation systems were considered because they are the predominant irrigation system and are technically sound. In the absence of more current data, in Catalonia, 63% of the surface area covered by parks and public gardens was irrigated by sprinklers (Arbat *et al.*, 2004). Also, it was assumed that a hydraulic pump would be needed, since the water could come from the potable water network with insufficient pressure for the proper operation of the irrigation system, a well or a rainwater storage tank, which is becoming increasingly common under resource sustainability criteria.

Irrigation equipment

The components of the irrigation system (sprinklers, pipes and hydraulic pumps) were chosen to be repre-

sentative of the domestic market, in order to reflect the typical commercially available options.

Thus, four sprinkler manufacturer brands with the highest share in the Spanish market were selected (Gardena, Ulm, Germany; Hunter, San Marcos, CA, USA; Rain Bird, Azusa, CA, USA; and Toro, Bloomington, MN, USA). For each of these four brands, the two sprinkler models most commonly used in home gardens were chosen. This selection was based on the opinions of several technicians within the gardening sector who were consulted. For each sprinkler model, all possible working pressures were considered, following the information supplied by the manufacturer.

The combination of the four sprinkler brands with the two models per brand, the different working pressures for each of the models (Table 1) and the 11 garden surface areas considered, allowed the analysis of a total of 495 irrigation system designs.

The nozzles, which are related to the sprinklers, were also considered. Each sprinkler can be combined with various nozzles, which can modify the wetted radius and flow rate to fit the geometry of the garden. Thus, for each combination of sprinkler/working pressure/nozzle, the wetted radius and supplied flow rate were collected.

Regarding the water distribution system, to calculate the head losses and costs, polyethylene pipes of commercial diameters and the accessories needed to connect these pipes to the sprinklers and pumping equipment were considered.

Design criteria for the irrigation system

The irrigation system was designed according to hydraulic criteria and widely accepted design recommen-

Table 1. Selected sprinklers and their working pressures

Manufacturer	Model	Σ Working pressure (kPa)	Flow rate range ($\text{m}^3 \text{h}^{-1}$)
Hunter	PGP	210, 280, 340, 410, 480	[0.11-3.27]
	PGJ	210, 280, 340	[0.15-1.20]
Rain Bird	RB-5000	170, 200, 250, 300, 350, 400, 450	[0.16-1.84]
	RB-3500	170, 240, 310, 380	[0.12-1.04]
Toro	Mini 8	200, 250, 300, 350	[0.18-0.69]
	V-1550	200, 250, 300, 350, 400, 450, 500	[0.21-2.99]
Gardena	200-1539	200, 300, 400, 500, 600	[0.16-0.96]
	380-1551	100, 200, 300, 400, 500, 600	[0.22-1.40]

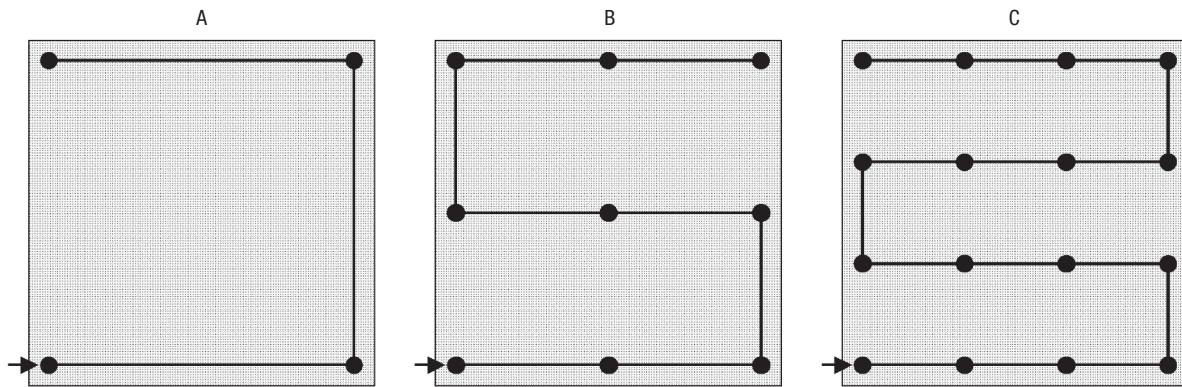


Figure 1. Possible arrangements for the sprinklers in a pipe (geometries A, B and C). The arrows show the water inlet.

dations together with the different manufacturers' additional technical standards.

The design criteria adopted to ensure good irrigation uniformity were:

1. The generally used criteria for pressure variation:

$$\Delta h_t \leq 0.20 p_n \quad [1]$$

where p_n is the nominal pressure (kPa) and Δh_t is the total head loss along the sprinkler pipe (kPa).

2. The generally used criteria for the pressure at the last sprinkler:

$$p_f = p_n - \frac{1}{4} \Delta h_t \quad [2]$$

where p_f is the pressure in the last sprinkler (kPa).

3. The separation between sprinklers was assumed to be equivalent to the wetted radius of a sprinkler.

4. The flow velocity limits inside the pipe (v):

$$0.4 \text{ m s}^{-1} < v < 2.5 \text{ m s}^{-1} \quad [3]$$

Although different layouts for the irrigation pipes are possible, in practice, a simple design is the most common in domestic irrigation sprinkler systems. For this reason, and to standardize the methodology used in all cases considered, a single irrigation pipe, fed at one end, and to which all the sprinklers were attached, was assumed for each garden. Three different types of layout were defined, hereafter identified as geometries A, B and C, having 4, 9 and 16 sprinklers, respectively (Fig. 1).

Determination of the optimal design for each case analyzed

The practical hydraulic design was determined individually for each combination of sprinkler/working pressure/garden surface area. For each case the most

suitable of the three sprinkler layouts (geometries A, B or C) was identified, taking into account the various possibilities offered by the available nozzles.

For each combination that met all of the adopted design criteria the solution requiring the fewest sprinklers was selected due to the lower cost of installation. Those cases where the wetted radius was greater than the length of the side of the garden were excluded from the study. The nozzles were selected by taking the sprinklers with a rotation angle of 90° then considering the optimum wetted radius of each nozzle (Fig. 2). For those sprinklers with other rotation angles (180° and 360°), the two nozzles selected were those that provide a flow approximately two to four times higher, respectively, for a given working pressure and that are included in the nozzle range available for each model of sprinkler. This design approach ensured that precipitation in the garden was as uniform as possible. The

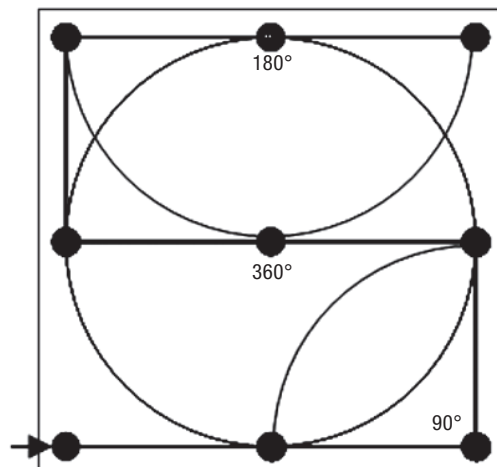


Figure 2. Types of sprinklers based on the rotation angle. The arrow shows the water inlet.

excess of wetted radius for those sprinklers located at positions of 180° and 360° could be corrected by modifying the regulation of the nozzle to reduce the sprinkler reach.

In the specific case of the Gardena sprinklers, there is no range of nozzle that allows for the modification of their performance, hence, the nozzles were selected exclusively according to their angle of rotation.

Pipeline sizing

Once the sprinklers and their positions were selected, the pipeline size was determined for each case.

Total pipeline pressure loss was obtained by adding the continuous pressure losses between sprinklers. The Hazen-Williams equation was used to obtain the pressure losses:

$$\Delta h = 104.18 C^{-1.85} L Q^{1.85} D^{-4.87} \quad [4]$$

where Δh is the continuous pressure loss (kPa), C is the material roughness coefficient (polyethylene) ($m^{0.37} s^{-1}$), L is the pipe section length (m), Q is the flow at the section ($m^3 s^{-1}$) and D is the inner pipe diameter (m).

Localized pressure losses were assumed to be 20% of continuous losses.

The pressure requirements at the irrigation system inlet were obtained using the design conditions given above and the following equation:

$$p_i = p_f + \Delta h_t \quad [5]$$

where p_i is the pressure at the pipeline inlet (kPa).

The minimum pipeline size that fulfils the established design criteria was chosen.

Moreover, the total flow rate needed at the irrigation system inlet was obtained by the addition of all the individual sprinkler flow rates. In this way, the flow rate and pressure requirements of the irrigation system were obtained for each case studied.

Pump selection

Pump selection was conducted by considering a wide range of models with the aim of fulfilling all the pressure and flow rate requirements of the cases analyzed. The pumps selected in this study were taken from the commercial catalogue of a Spanish manufacturer (ESPA, Banyoles, Spain), shown in Table 2, and correspond to the range of pumps used in garden irrigation systems by this manufacturer. The main conclusions of the paper would not differ

Table 2. Selected pumps

Range	Models
Prisma 15	15-2, 15-3, 14-4, 15-5
Prisma 25	25-2, 25-3, 25-4, 25-5, 25-6
Prisma 35	35-2, 35-3, 35-4, 35-5, 35-6
Prisma 45	45-2, 45-3, 45-4
XN 25	160/22, 200/30, 200/40, 250/55, 250/75

with the incorporation of pump models from other manufacturers since the different ranges have similar technical characteristics.

Using pumps with VFD (Variable Frequency Drives) is the best way to adjust the pump operating point to the irrigation system requirements; however, their use is very rare in small pumps such as those selected in this study due to their high cost. For this reason they were not considered.

Pump selection for each system was carried out by matching the characteristic curves of the pump and the irrigation system (resistance curve). Resistance curves for every irrigation system design were obtained from the Hazen-Williams equation, corrected by using the Christiansen reduction coefficient (F) to compensate for the water delivered along the pipeline. The F value depends on the number of uniformly spaced outlets along the pipeline. Pump characteristic curves, on the other hand, were supplied by the manufacturer.

Pump selection for each case analyzed was carried out as follows: based on the pump equation, the working pressure was calculated using the required discharge as an independent variable. Pumps with inadequate discharges or insufficient pressure were excluded. The pump that was selected from all the possible options was the one that gave the required discharge with the smallest pressure, that is, the one that fitted the pressure design best.

Irrigation dose

The irrigation dose was calculated using the equation:

$$Ir = \frac{ET_L - P}{ef} \quad [6]$$

where Ir is the irrigation dose ($L m^{-2} yr^{-1}$), ET_L is the landscape evapotranspiration, P is the precipitation and ef is the characteristic efficiency of the irrigation system, assumed to be 0.85 for sprinkler irrigation in accordance with the high value of this system (Keller

& Bliesner, 1990), since it has been assumed that, for watering private gardens, the small size (relative to agricultural fields), in addition to their recreational and unproductive use, is such that it is not necessary to consider the quality of the installation.

The landscape evapotranspiration was obtained using the WUCOLS method (Costello *et al.*, 2000):

$$ET_L = K_L ET_o \quad [7]$$

where ET_o is the monthly average Penman-Monteith reference evapotranspiration, calculated for the period from 1994 to 2010. The data correspond to the two different climate regions (related to the potential evapotranspiration) of the Spanish Mediterranean coast (Estrela *et al.*, 1996). The selected locations were Cassà de la Selva-Girona (XEMA, 2012) and Elche (<http://estaciones.ivia.es/estacion/etoylluviamediam.php3?idprovincia=46>); K_L is the landscape coefficient, which was calculated from Costello *et al.* (2000):

$$K_L = k_s k_d k_{mc} \quad [8]$$

where k_s is the species factor, k_d is the density factor and k_{mc} is the microclimate factor. The values assumed for these factors were $k_s = 0.82$, corresponding to turf (Salvador *et al.*, 2011), $k_d = 1$ (average density) and $k_{mc} = 0.9$ (low, assuming that the garden is protected from the wind by nearby buildings and in most cases by perimeter fences, which will throw shadow onto the garden surface).

The value for the landscape coefficient was 0.738, and the irrigation water doses were 495.4 and 1,174.7 L m⁻² yr⁻¹ for Girona and Elche, respectively.

Annual pumping costs

Once the irrigation design components and the associated pump were defined, the annual cost was calculated using the following equation:

$$CT = CF + C_h h \quad [9]$$

where CT is the total annual pumping costs (€), CF is the annual fixed costs (€), C_h is the hourly costs (€ h⁻¹) and h is the annual irrigation time in hours.

The annual fixed costs correspond to the amortization of the irrigation material. Taken into consideration were the acquisition cost of the pump from catalogue prices, a 15-yr life span and linear amortization.

Annual variable costs correspond to the electricity consumption. For each one of the 495 cases considered, this value was calculated using the absorbed pump

power for a certain discharge and the time needed to apply the required irrigation dose. An energy price of € 0.172 kWh⁻¹ was assumed, in agreement with the regulated average price of electricity for domestic use in Spain, including taxes, for 2009 (Europe's Energy Portal, 2011). Water costs were not taken into account since all of the designs apply the same volume of water for each irrigation surface.

The optimal option, which allowed irrigation at the lowest cost for each sprinkler brand and irrigation surface, took into account the combination of the different possible working pressures, nozzles and pumps for each sprinkler. This optimal solution is the one that minimizes the total cost (installation costs plus energy costs), and it is computed for each one of the cases studied.

To evaluate the possible economic incentive that the potential energy saving would represent, four scenarios were studied. The first three considered different energy prices in order to analyze the incentive effect of savings deriving from this factor. The scenarios were: current situation (scenario 1), an increase in the energy price to twice the current value (scenario 2), and an increase in the energy price to five times the current value. Within these three scenarios the practical design was selected by minimizing total costs. For comparative purposes another scenario was investigated (scenario 4), using the current energy price but with the selection based on the minimization of energy consumption, independently of the costs.

Results

The results discussed here correspond to both of the locations studied; however the plots are illustrative of a particular location (Girona) to avoid duplicating information. Due to the fact that the hydraulic design is the same for both locations, with only the amount of water applied being different, and therefore the energy consumption, the plots for the other location (Elche) would be identical when the cost of this parameter was not included, while the points would be slightly displaced when it was.

Rationale for the selection of water pumps

Fig. 3 shows the pressure and the flow rate required for each of the designs analyzed, the characteristic curves of the water pumps considered, and their effi-

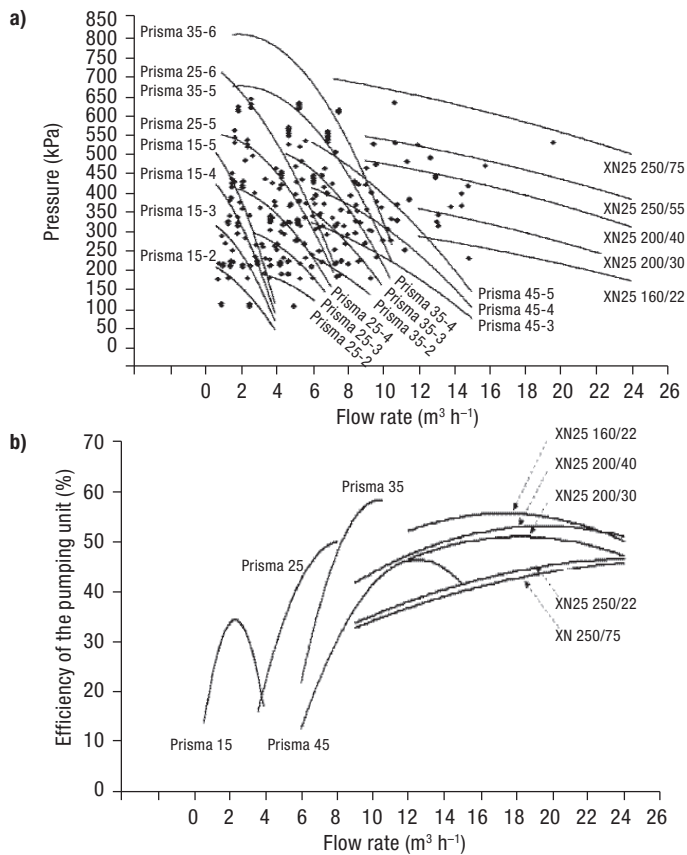


Figure 3. Characteristic curves of the water pumps (represented by lines) and pairs of pressure and flow values for each design analyzed (represented by dots) (a), and efficiency of these pumping units (b).

ciency. It is noteworthy that the Prisma series covers the pressure and flow rate requirements for most of the

gardens. However, flow rates exceeding 12 m³ h⁻¹ require higher performance water pumps (in this case XN25), which would also be required for lower flow rates when the pressure demand is high. The set of water pumps considered satisfies the requirements of all the cases analyzed.

It is important to stress, as shown in Fig. 3, that water pumps of the higher series have efficiency curves with flatter shape than those of the lower series, because of his mechanical design, the XN-series have just one impeller while the Prisma-series are a multistage pumps with multiple impellers. This fact allows that the XN-series works close to optimal efficiency in a wide range of flow rates.

Pressure and flow rate requirements

Fig. 4 shows the energy consumption plotted against the pressure requirements for each geometry and water pump series in Girona. As expected, this figure shows a positive relationship between energy consumption and pressure requirements, even though, for a given pressure, the energy consumption values are widely scattered. For a given surface, the designs with more sprinklers (geometries B and C) tend to consume less because they have lower pressure requirements and are therefore associated with a less powerful water pump. It is noteworthy that, for a given pressure, lower consumption usually corresponds to the combinations of sprinkler, pressure and surface area where the water pump belongs to the higher series possible for that

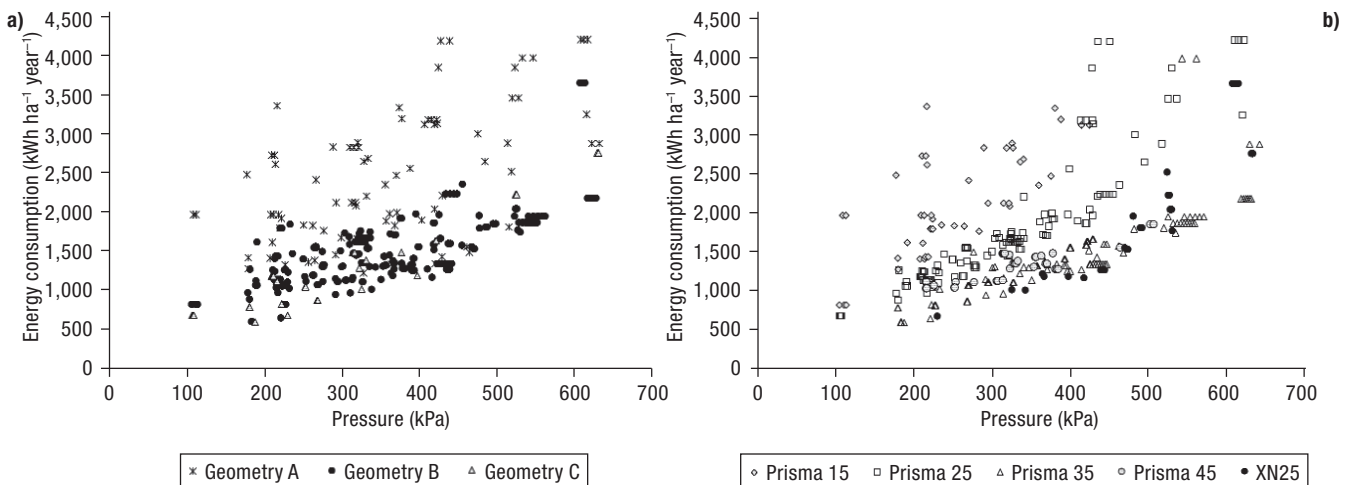


Figure 4. Relationship between the required pressure of the irrigation system and the energy consumption (kWh h⁻¹ yr⁻¹) in Girona, classified according to the selected geometry (a) and the water pump series (b).

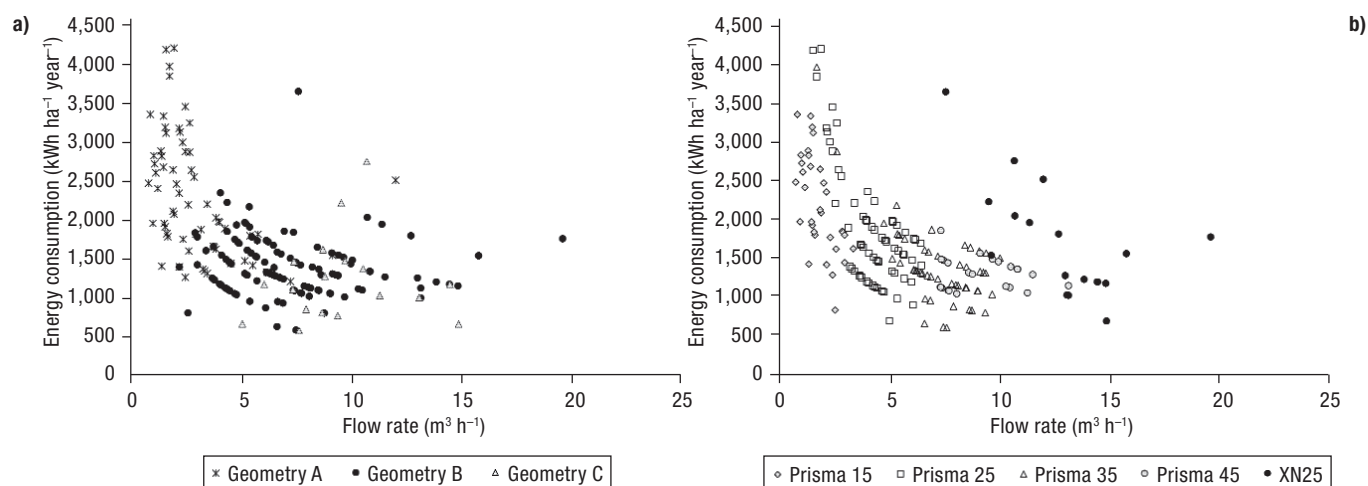


Figure 5. Relationship between the flow rate required by the irrigation system and the energy consumption ($\text{kWh ha}^{-1} \text{yr}^{-1}$) in Girona, classified according to the selected geometry (a) and water pump series (b).

pressure, due to their better performance compared to lower range pumps.

Fig. 5 shows the energy consumption plotted against the flow rate required by the garden-pump system; this varies from 587 to $4,192 \text{ kWh ha}^{-1} \text{yr}^{-1}$. The trend shows a decrease in energy consumption per hectare as flow rate increases. Indeed, for a given surface area, a higher irrigation flow corresponds to a greater number of sprinklers, a smaller distance between sprinklers and therefore lower pressure requirements. It is observed that for a given flow rate, the choice of water pumps is limited, while for the same pressure (Figs. 4 and 5) there is a wider range of selectable pumps. In some cases where, due to the high pressure requirements, a superior series (XN 25) water pump is required, the energy consumption is very high.

In Elche, the results are similar. The distribution of points exhibited the same shape for both pressure and flow rate (results not shown), however the range of energy consumption varied from 1,131 to $9,982 \text{ kWh ha}^{-1} \text{yr}^{-1}$.

Power and efficiency of the selected pumps

Power consumption (P1) for the pumping units studied in each design varied from about 0.20 to 3.0 kW for the Prisma series and approximately 3.0 to 6.0 kW for the XN series (Fig. 6). The trend of an increase in power consumption for the higher pump series is clear, but shows a few ups and downs, probably due to the existence of boundary cases among the 495 analyzed, meaning, in other words, the adoption of commercial

diameters more or less different from those calculated, or singular cases in the pump range selection.

The analysis of the efficiency of the pumping units is interesting. Fig. 7 shows the ratio of the power consumption (P1) to the hydraulic effective power (P3), namely the efficiency of the pumping units at the operating point for all the cases considered. It can be seen that in all cases the efficiency value is below 50%, with most lying between 25% and 50% and some having an even lower value. These lower efficiency values are very common in small power units commonly used for watering gardens. Therefore, the low efficiency of these pumping units is a major obstacle to achieving energy efficient solutions. Among the majority of the cases considered, the choice of higher performance pumping units above the operating point, which could have slightly greater efficiencies, meant an increase in energy consumption and constitutes an unnecessary expense due to operating at a higher pressure than the required level. Consequently, this solution does not solve the problem.

System costs

Energy consumption is influenced by the selection of irrigation components (pipes, sprinklers and nozzles, water pumps). For this reason the relationship between the installation and operating costs are analyzed (Fig. 8).

According to the results in Girona, the location with lower irrigation requirements, the total cost of the different irrigation designs (depreciation of equipment plus operating costs) ranges from $\text{€}1,253$ and $\text{€}15,492 \text{ ha}^{-1} \text{yr}^{-1}$, with an average value of $\text{€}2,974 \text{ ha}^{-1} \text{yr}^{-1}$. The

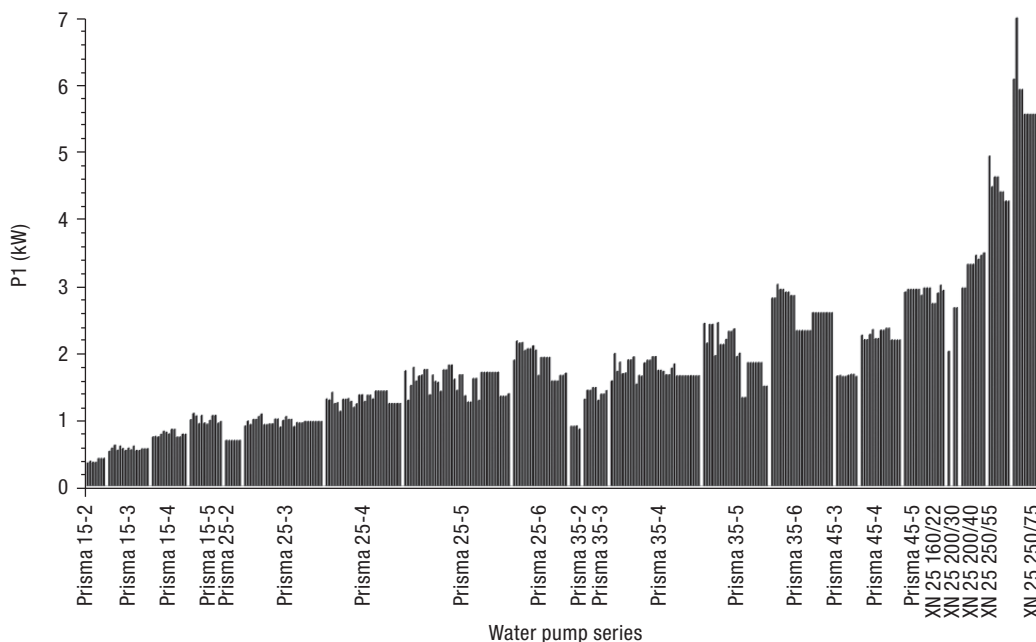


Figure 6. Power consumption (P_1) at the operating point for different water pump series.

component corresponding to the energy costs is on average 11.37% of the total irrigation cost (material plus energy), with a minimum value of 3.57% and a maximum of 22.80%. In Elche, the other location studied, which has higher irrigation requirements, the behaviour was very similar, but of course, the total annual costs were higher, with the values ranging from €1,500 and €16,258 $ha^{-1} yr^{-1}$, with an average value of €3,383 $ha^{-1} yr^{-1}$. In this case the percentage corresponding to the energy costs is about twice (23.01%) that of the location with lower irrigation needs.

Thus, the energy cost is a small part of total costs, and therefore the margin for energy savings does not

act as an economic incentive in the selection of irrigation material. Obviously, as water requirements increase there is a corresponding increase in the energy cost since, for a given design, the irrigation time increases and, therefore, the power consumption rises; however, even in this case the energy cost was less than one quarter of the total irrigation cost.

Fig. 8 shows that the region with the highest concentration of points exhibits a moderate dispersion of total costs (in Girona from €1,300 $ha^{-1} yr^{-1}$ to €3,800 $ha^{-1} yr^{-1}$ and in Elche from €1,500 $ha^{-1} yr^{-1}$ to €4,000 $ha^{-1} yr^{-1}$), and a higher dispersion of energy costs (in Girona from €100 $ha^{-1} yr^{-1}$ to €400 $ha^{-1} yr^{-1}$ and in Elche from €200 $ha^{-1} yr^{-1}$ to 800 $ha^{-1} yr^{-1}$). For both locations almost all the small gardens (surface areas from 25 m^2 to 100 m^2) lie outside of this region, representing greater total costs and greater energy costs per hectare. The gardens with small surface areas are commonly associated with designs using four sprinklers (Geometry A) and a less powerful pump (mainly Prisma 15 and 25).

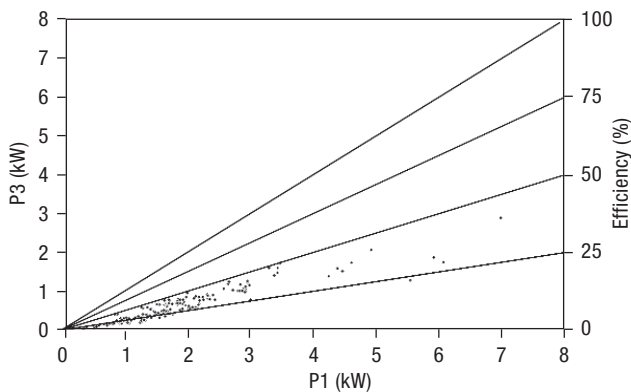


Figure 7. Power consumption (P_1), hydraulic effective power (P_3), and efficiency of the pumping units. The dots indicate P_1 and P_3 , and black lines point out efficiency ranges.

Potential for energy savings: analysis of scenarios

Table 3 shows the maximum and minimum energy consumption values for each of the locations and surface areas analyzed, as well as the results of the analy-

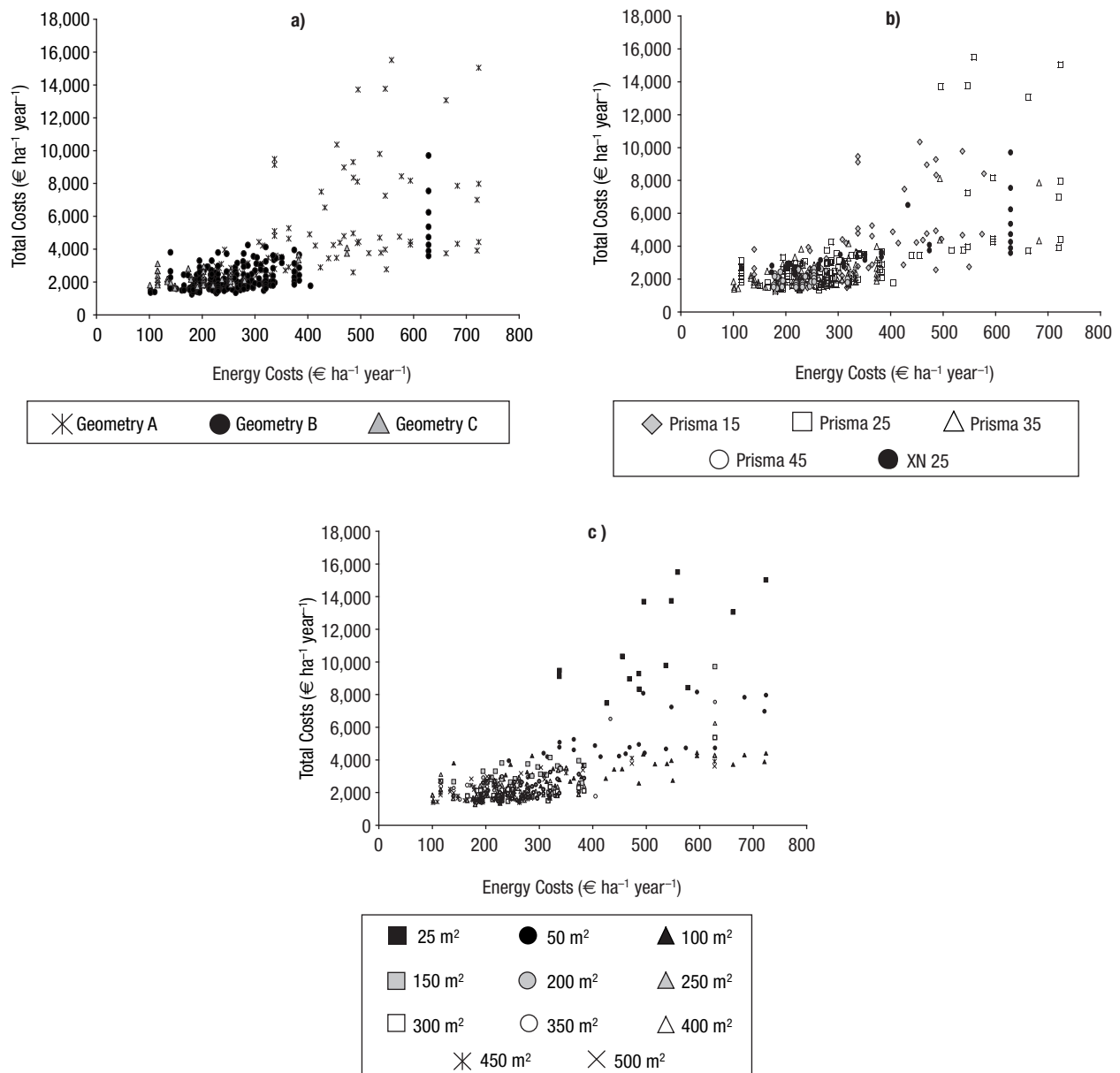


Figure 8. Relationship between energy costs and total costs (€ ha⁻¹ yr⁻¹) in Girona, classified according to the chosen geometry (a), the selected water pump series (b) and the garden surface area (c).

sis of each of the scenarios. The different surface areas are analyzed separately to show the potential margin for savings in each case.

The results detailed in the second column (Table 3) show that there is considerable margin for saving when the design with minimal energy consumption is selected. The potential energy savings ranged from 53% to 84% depending on the case, with an average value of 77%. The smaller areas (from 25 to 100 m²) have higher

consumption per hectare usually because the sprinklers do not exploit their full potential and use inferior pump models, which are generally less efficient than superior models. These results demonstrate the importance of the irrigation system design and material selection on energy consumption.

Obviously, combinations of sprinklers and pressure that allow minimum energy consumption are those that employ sprinklers working at low pressures (and there-

Table 3. Energy consumption for each of the scenarios analyzed

Surface area (m ²)	Consumption range (including all designs, kWh ha ⁻¹ year ⁻¹)	Scenario 1	Scenario 2	Scenario 3	Scenario 4
		Consumption of the optimal design (kWh ha ⁻¹ year ⁻¹)	Energy savings compared with scenario 1 (%)		
<i>Girona</i>					
25	[1,963.2-4,209.7]	2,477.8	0.0	0.0	20.8
50	[1,413.3-4,209.7]	1,413.3	0.0	0.0	0.0
100	[814.4-4,209.7]	1,271.7	0.0	0.0	36.0
150	[814.4-3,654.1]	1,883.2	0.0	56.8	56.8
200	[814.4-3,654.1]	1,059.7	0.0	0.0	23.2
250	[673.8-3,654.1]	1,059.7	0.0	0.0	36.4
300	[673.8-3,654.1]	1,404.4	0.0	24.4	52.0
350	[673.8-3,654.1]	1,049.1	0.0	0.0	35.8
400	[586.6-3,654.1]	1,049.1	0.0	43.4	44.1
450	[593.7-3,654.1]	1,321.2	55.1	55.1	55.1
500	[671.4-3,654.1]	1,065.5	0.0	0.0	37.0
<i>Elche</i>					
25	[4,655.4-9,982.4]	5,875.6	0.0	0.0	20.8
50	[3,351.2-9,982.4]	3,351.2	0.0	0.0	0.0
100	[1,131.1-9,982.4]	3,015.6	0.0	0.0	36.0
150	[1,931.1-8,664.8]	3,436.9	43.8	43.8	43.8
200	[1,931.1-8,664.8]	2,512.9	0.0	23.2	23.2
250	[1,597.7-8,664.8]	2,512.9	0.0	0.0	36.4
300	[1,597.7-8,664.8]	2,516.7	0.0	0.0	36.5
350	[1,597.7-8,664.8]	2,487.7	0.0	16.2	35.8
400	[1,391.0-8,664.8]	2,487.7	43.4	43.4	44.1
450	[1,407.9-8,664.8]	1,407.9	0.0	0.0	0.0
500	[1,592.1-8,664.8]	2,526.7	0.0	36.8	37.0

In scenarios 1-3 the selection criterion of the optimal design was the minimization of total costs; in scenario 1 the current energy price was assumed, in scenario 2 the price was double the current value, and in scenario 3 it was five times the current value. In scenario 4 the current price was assumed but the selection criterion of the optimal design was the minimization of energy consumption.

fore have a reduced spray distance between sprinklers and a larger number of them), while the minimum cost is achieved through using the minimum number of sprinklers, associated with the lowest possible range of pumps. This discrepancy between minimum energy consumption and minimum material cost, together with the low weight of the energy costs with respect to total cost, means that developers who base their choice on cost minimization do not take into account maximum energy efficiency. One of the most important aspects of this study is the analysis of scenarios, which compares the energy consumption of optimal designs to the criterion of minimizing costs for different energy prices (scenarios 1-3) and of minimizing energy consumption (scenario 4). The scenarios considered produce different effects in the 22 cases of surface area and

location considered (Table 3). To perform the analysis it is necessary to compare the energy saving columns corresponding to the two price-increase scenarios (scenarios 2 and 3) with the maximum potential energy saving column (scenario 4). When scenario 2 is considered (double the current energy price), in the majority of cases (16 values corresponding to an energy saving of 0 in scenario 2 coinciding with values different from 0 in scenario 4), the energy price is not a sufficient incentive to change the design. On the other hand there are three cases (when the value of the energy saving is 0 in scenarios 2 and 4) where the initial design corresponds to the maximum energy savings. In 1 other case (when the value of the energy saving in scenario 2 is different from 0 and different from the maximum potential saving); the price changes the design, although

there is still potential for making energy savings. Only in two cases (when the energy saving in scenario 2 coincides with the maximum potential saving in scenario 4) does the price act as an incentive to choosing the design that leads to maximum savings. When the energy price is taken to be five times the current price (scenario 3), which is an extreme situation far from reality but interesting in order to obtain effects, in approximately 45% of cases the price has no influence and there is still the possibility of increasing savings. In 23% of cases, the chosen design achieves some savings, although not the maximum potential, and in only 18% of cases does the increase lead to choosing the design with the maximum savings.

Although the results do not show specific trends, the conclusion is very sharp and clear: while the price of energy is not a strong incentive in terms of the choice of design, a cost minimization approach generally leads to medium-to-low energy consumption. This conclusion is reinforced by the fact that the two locations considered have very different water requirements (with Elche having approximately 2.5 times that of Girona), which implies that the energy consumption of the first location is much higher, but despite this, energy price does not represent a key incentive in terms of design.

Discussion

The methodology used allows the energy consumption to be compared for possible combinations of sprinklers and working pressures in gardens of different surface areas. In the analysis it is assumed that the developer selects the combination of material and pressure that minimizes the irrigation installation costs.

One of the assumptions was that the gardens were covered with turfgrass, since this is the most common vegetation in gardens. Domene & Saurí (2003) indicate that in the Mediterranean area a culture of humid weather gardening is becoming popular. Designed according to the Anglo-Saxon model, it uses turfgrass as the main ornamental plant instead of native species, which need less water. In any case, the selection of the species would not change the order of the designs according to consumption, but only the absolute value of consumption.

The study assumed that irrigation management is based on evapotranspiration following the methodology adapted to gardens by Costello *et al.* (2000). However, domestic gardens are usually over irrigated (End-

ter-Wada *et al.*, 2008), although Salvador *et al.* (2011) highlight that a water deficit occurs during the summer period as a result of Spanish holiday habits. Considering different irrigation schedule criteria would not alter the order of the designs according to energy consumption.

Another important consideration is the design of the irrigation system. Although all the hydraulic designs were correct in the methodology followed, this is not always true in practice. Arbat *et al.* (2004) analyzed irrigation uniformity in public parks and gardens and found that the poor design of irrigation systems is the major cause of low distribution uniformities.

Material selection is a key point in the design, as stated by Ferguson (1987). Carrying this out correctly is critical in terms of applying the required volume of water in gardens. On the other hand, the sprinkler working pressure is important in saving energy, thus Gilley & Watts (1977) indicate that improving irrigation efficiency and reducing the sprinklers' working pressure can reduce energy consumption by 30%. In this paper, the average energy saving (taking into account all the surface areas studied) was 77% when the most suitable sprinklers were chosen over those that consumed the most energy and 36% when compared with the design with the minimum installation cost.

The results related to the pumping system show that for a given pressure requirement, the lowest energy consumption usually corresponds to pumps belonging to the higher series. This is because the lower pump series exhibit a high efficiency values only in a reduced range of flow rates for inherent limitations to its design. These results agree with those obtained by Pérez Urrestarazu & Burt (2012), who conducted 15,000 tests on electric pumps used for irrigation in California and concluded that the pumps with the lowest flow rates and pressure values usually have poorer overall efficiency. However, these authors also note that, for the majority of the time, pumps work below the design flow rate and pressure; it is therefore convenient to install variable frequency drives. In most home gardens, due to their small size, pumps with low flow rate and pressure are required and the use of variable frequency drives is very rare. It should be noted that the efficiencies of commercial pumps suitable for the typology of the gardens studied have very low efficiency values (below 50%) which greatly limits the potential for achieving high-quality energy solutions.

If the cost factor is added to the study, the predominance of the installation costs over the energy costs is

remarkable. This means that the savings in energy consumption are not an important incentive in the selection of irrigation equipment. Moreover, if it is taken into account that demand variation is a smaller ratio than the ratio of water cost variation (Renzetti, 2002), the result is that neither the energy price (at current levels) nor the water price decisively affect the design or irrigation management.

The basic conclusions of this paper are that, for a given surface area, there are many potentially correct irrigation system design possibilities (depending on the type of sprinkler, working pressure and design geometry). Proper selection of these variables leads to substantial energy savings: in the cases analyzed, these savings ranged from 53% to 84% depending on the garden surface area, with an average value of 77%. However, the low cost of energy in relation to the installation cost does not make the energy savings an important incentive in sprinkler irrigation design in private urban gardens.

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