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Strategies to improve the energy efficiency of pressurized water systems

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Abstract

As time goes by, the need to move water is greater and this water will be pressurized. Layout flexibility, security, quality care, control, lower environmental impact and higher efficiency justify pressurized transport rather than natural gravitational water transport. On the negative side, we find the enormous amount of energy pressurized systems require with the associated negative economic and environmental impacts. Therefore, it is crucial to minimize these impacts and that only can be achieved by improving the energy efficiency of these systems. To achieve that final goal, the first step is to perform an assessment to estimate the margin of improvement from the actual performance of the system to the maximum achievable level of efficiency [1]. The second step is to perform an energy audit in order to identify exactly how the energy is used and where it is lost [2], with the third step being identification of the different actions that can be implemented in practice in a system. The final step is to perform the cost benefit analysis of the selected actions to prioritize execution.

The focus of attention of this paper is on the third step, actions that can be classified in operational actions (do not require investments) and structural actions (require investments).

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Keywords: Energy audit; water and energy; improve actions; optimal water networks

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1. Introduction

The need to move water is greater and, except in a few cases, this transport is under pressure. Layout flexibility, security, quality care, better control, lower environmental impact and higher efficiency are just some of the benefits of pressurized transport. On the other hand, the negative aspect of pressurized systems is the enormous amount of energy they require (a cubic meter of water weighs a ton). The transformation process of traditional irrigation to pressurized water transport systems is a clear example of the negative and positive angles. Drip irrigation is much more efficient and is increasingly replacing traditional surface flooding irrigation. As a consequence, the energy expense is growing nonstop. California, the electrical energy linked to water pumps is over 6% of the total [3]. In Europe, this value is around 4%. According to the impact assessment study accompanying the 2009/125/EC Directive [4], the energy demand of water pumps in 2005 was 109 Twh (EU-25), although recent estimations [5] raise those figures considerably (10% of global electrical energy is consumed by pumps, representing 259 TWh per year within the EU). Therefore, assuming that most of this demand is linked to water transport and distribution (urban and agricultural) and that electrical energy demand that same year [6] was of 237,537 ktoe (EU-27) or 210,205 ktoe (EU-15), equivalent to 2766 and 2447 Twh respectively, the percentage of energy linked to water pumping ranges from 3.94% to 4.45%. Considering that agriculture represents 2% of total energy consumption in Europe [7], the energy required for urban use (not treatment) can be assumed to be similar. These are average values as the energy required can vary between countries (e.g., in Spain, -Corominas, 2010 [8]-, agriculture uses 3% of the total energy consumed by the country).

Furthermore, wider environmental studies (e.g., lifecycle analysis of the urban water cycle) indicate that the operational phase, closely linked to water transport (two steps of the urban water cycle, supply and distribution), is the main contribution to Global Warning Effects of the lifecycle [9]. Therefore, from both points of view (economical and environmental), it is crucial to be as efficient as possible. Up to now, energy savings of the pressurized water transport process has been analyzed for specific steps, mainly pumping. For instance, the EU [4], estimates savings at the pumping stage around 20-30%, although commercial estimations [5] go much further: 2/3 of all pumps could save up to 60% energy. And both reports assess these savings only considering the pumping stage. This paper identifies and describes up to eight different strategies to save energy (including the pumping stage) and estimates, supported by practical examples and references, the corresponding energy saving margins. When the selected corrective actions have been implemented, the total energy saving can be 60% or more. Although the main objective of this paper is to describe the different actions that can be taken to improve the energy efficiency of pressurized systems, first a general overview of the whole procedure is presented.

2. Road map description

Maximum energy savings can only be achieved from a global system analysis (assessment) followed by a road map, consisting of different stages. The process must include the concept of topographic energy (linked to the network topography) and simultaneous consideration of shaft and natural energy [1]. As Figure 1 depicts, the method is divided into 6 stages: pre-assessment, diagnosis, audit, cost-benefit analysis, decision-making and final rating of the system's energy efficiency, a procedure that fits very well with the statement "think globally, act locally". In order to save as much energy as possible, all phases go through two columns: the consumed and the topographic energies.

The variables included in the flow chart (listed from top to bottom and from left to right) are: E_{uo}, minimum required energy by users (constant, regardless of whether the system be real or ideal); η_{ai} and η_{ar}, ideal and real performance of the system without recovery (with pumps as turbines, PATs); $\eta_{ar,o}$, target energy efficiency performance of the system without recovery; θ_{ti}, percentage of total topographic energy (ideal case); E_{yr},, recovered energy (from the topographic energy); λ_{wf}, percentage of reducible friction energy related to the supplied energy; λ_{wl}, percentage of reducible energy embedded leaks related to the injected energy; λ_{wo}, percentage of other energy losses related to the supplied energy; λ_{wp}, percentage of reducible energy in pumping related to the supplied energy.

A brief description of the six stages follow:

1. *Assessing initial requirements.* The flow chart (Figure 1) assumes that the useful energy, E_{uo}, is a starting point (E_{uo}, is the result of multiplying the volume demanded by the pressure of service). However, before starting, the

water consumption must be assessed (see preliminary box). If there is room to reduce that demand, it makes sense to optimize the energy consumed beforehand in order to explore how to reduce it. Even rainwater can be used to minimize E_{uo} if energy implications are studied [10].

2. *Diagnosis (left column, required energy).* Because the first condition to solve a problem is to be aware of the fact that it exists, in order to accurately determine the starting point is an obvious pre requisite. This is done through the ideal efficiency, η_{ai}, and real efficiency η_{ar}. This stage also includes the estimation of the $\eta_{ar,o}$, the performance that, with few, although achievable, losses (in pumps, leaks, friction and others), can be established as the final goal (η_{ai} does not include losses). A previous paper [1] describes this assessment in more detail.

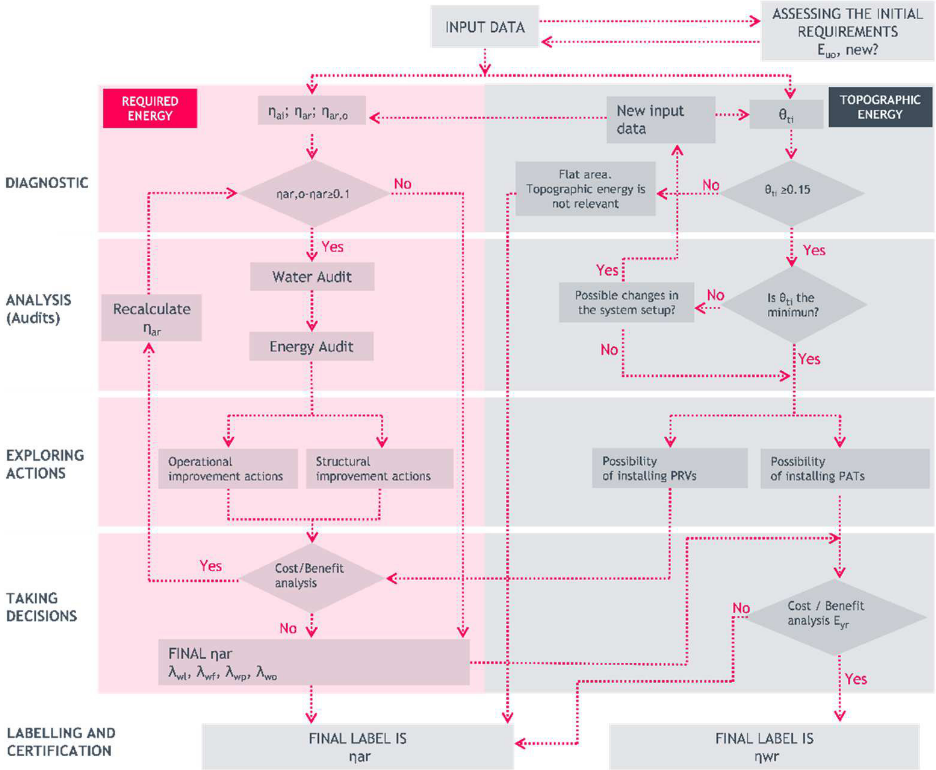

Fig. 1. Roadmap to achieve maximum energy savings in pressurized water network

3. *Diagnosis (right column: topographic energy).* The percentage of a system's topographic energy, θ_{ti}, is calculated. This parameter synthesizes two system characteristics, network topography and system layout. On the basis of this value, the possibility of reducing it (even at the analysis stage) must be explored. If it is not possible, the third stage includes energy recovery using PATs and/or minimizing the impact of higher pressures with PRVs.

4. *Analysis (left column: required energy).* If $\eta_{ar,o}$ - η_{ar} is low in terms of energy, the system is efficient, and it is not necessary to move on to the analysis stage. If not, in order to know how and where these two resources are lost, water and energy audits are required [11, 2]. Once the inefficiencies have been located and assessed, action to save energy can be explored (next stage).

5. *Analysis (right column: topographic energy).* Decreasing the value of θ_{ti} requires restructuring the network. However, because satisfying demand on high ground requires raising pressure above what is necessary in the rest of the network, it is appropriate to explore the possibility of using other supply sources for high points. Decoupling high points from the rest of the system will decrease the value of a weighted θ_{ti}, therefore improving efficiency.

6. *Exploring actions (left column: required energy).* The audits will identify the most inefficient parts of the system (pumping stations, network, etc.) and therefore the most effective actions (those presenting a better cost/benefit relation) will also be identified. They can either be operational (do not require investments) or structural involving investments in the system, such as pumping station refurbishments and pipe replacements.
7. *Exploring actions (right column: topographic energy).* Recovering topographic energy is possible with PATs. For such purpose, a three-stage analysis is required. First, selecting the right pipes that must harbor them (defining, for example, minimum PAT power); second, calculating the amount of energy that can potentially be recovered, and third specifying how the system can be operated while at the same time satisfying the required level of service. If PATs are not viable, PRVs are used instead to dissipate this excess energy. As will be demonstrated in the first example, to install PRVs is profitable because the amount of injected useful energy is the same (only dissipate topographic energy) while the required energy decreases in terms of leaks (PRVs reduces leaks). The main goal of this paper is to describe and present practical examples of these potential actions.
8. *Making decisions (required and topographic energy).* A cost benefit analysis of each action is necessary before deciding if the action must be implemented or not.
9. *Labelling and certification.* At the end of this process, it seems appropriate to evaluate and certify how efficient, in terms of energy, the system actually is [12].

In conclusion, the road map includes five stages (assessment, analysis, exploring actions, decision-making and labelling) in each column (energy required and topographic energy). In the following lines attention will be paid to the third stage - exploring actions.

3. Strategies to improve energy efficiency

Depending on whether investments are required or not, actions can be classified as structural or operational. Four different actions are in each group. The operational ones (with the corresponding potential savings) are as follows:

1. *OP1: Operate the pumping system at its BEP (Best Efficient Point):* Flow must always be as close as possible to the pump's BEP. When possible, as in the case of irrigation, a pattern demand schedule must be ordered adequately. (Expected savings: up to 10%, [1])
2. *OP2: Avoid surplus energy by improving regulation of the system.* This action can be structural if major investments are required for this purpose. Minor investments, such as variable frequency drivers, are not enough to requalify the action as structural. (Expected savings: 10-15%, [5]).
3. *OP3: Minimize leaks:* This is an operational action when water losses are minimized through active leakage control or, alternatively, with pressure control. It should be structural if pipes are renewed. (Expected savings: according to a study sponsored by the European Commission [13] leaks in water supply can lead to savings of up to 33%).
4. *OP4 or ST0: Minimize friction losses:* Again, it is operational (OP4) if reduction is achieved through operational actions (e.g. forcing a more uniform flow distribution). But it should be structural (ST0), when pipes are substituted for new ones, with larger diameters or if a new and more rational layout is set up to avoid high local losses. (Expected savings: up to 10%, [1]).

While the four structural actions are as follows:

1. *ST1: Use more efficient pumps* (old pumps can be refurbished or replaced by new, more efficient ones): (Expected savings: between 20-30%, [4]).
2. *ST2: Recover or reduce the topographic energy installing Pumps as Turbines*, -to recover energy- or dividing the system in separate sectors with different geometric levels (energy platforms). This action will reduce the topographic energy. The decoupled energy sectors will be fed by different pumps (with head –flow curves tailored in accordance with the energy requirements for each platform). Alternatively, booster pumps can supply the additional energy required to highest sectors. (Expected savings: up to 15%, [1]).

3. *ST3: Improve old designs and layouts:* Networks have been traditionally designed on the back of energy efficiency criteria, e.g., tanks have been built at the highest level of the city to provide adequate pressure to any demand point. But this increases the topographic energy in detriment of efficiency. Minor changes (such as direct supply instead of indirect) can save a lot of energy. (Expected savings: up to 30%, [14]).
4. *ST4: Avoid losses not included in previous sections:* (e.g. break pressure recovery). (Expected savings: Over 50 %, [15])

In the preceding list, electrical inefficiencies (and the corresponding actions to avoid them) are not explicitly included because they are seen as a part of pumping station inefficiencies. In any case, it is important to underline that the order of magnitude of hydraulic losses is currently far higher than the electrical ones. In any case, there are excellent reports [16], which exclusively focus on water pumping stations (including the electric components), although in these reports the system is not analyzed as a whole (pumping station and network).

4. Examples

In this section, two examples are presented. The first one, a synthetic irrigation network, has poor energetic performance. It is a current situation, because these networks have been mainly designed from the economic point of view, ignoring energetic issues. In this case study, the four operational actions are being successively implemented and the corresponding energetic improvements assessed. The order of these actions has been decided from least to most aggressive. When operational actions cannot provide any further significant improvements, and on the basis of the final energy audit, structural actions can be considered. In this case two structural actions (ST0 and ST1) make sense. The second real example is addressed to show the high benefits of some structural improvements. In this particular case two structural measures (ST3 y ST4), with an excellent cost/benefit ratio, are implemented. In the end, only one improvement action, the topographic energy recovery (ST2), is not showed in this paper. In any case, it is well documented in the literature [17].

4.1. Example 1.-

Figure 2 depicts the considered irrigation network.

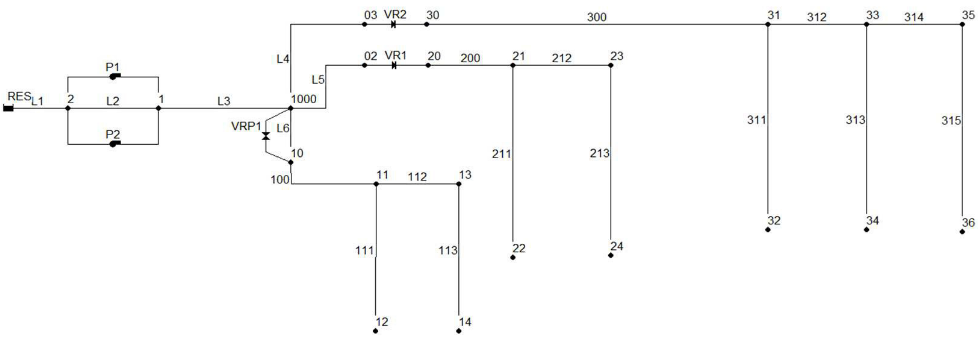

Fig. 2. Irrigation network layout.

Table 1 depicts the main network characteristics while Table 2 shows pump's performance (two pumps working in parallel). The energy required by the system is mainly shaft energy (supplied by both pumps) with a minor percentage of natural energy coming from the tank located at the head of the system.

Table 1. Main network characteristics of the irrigation network (Figure 2, example 1).

Pipe	100	111	112	113	200	211	212	213	300	311	312	313	314	315
Length (km)	500	500	500	500	1000	500	500	500	3000	600	500	600	500	600
Diameter (mm)	350	200	300	200	350	175	300	175	450	200	350	200	300	200

Node	11	12	13	14	21	22	23	24	31	32	33	34	35	36	RES
Length (km)	10	0	15	10	45	50	50	55	75	80	80	85	85	90	40
Diameter (mm)	20	20	20	20	20	20	20	20	15	15	15	15	15	15	-
Emitter coefficient ($m^{3-\gamma}$/s)	0.12 122	0.02 660	0.12 122	0.02 660	0.10 826	0.08 356	0.05 817	0.05 649	0.39 056	0.05 649	0.09 895	0.05 364	0.09 842	0.09 182	
Demand pattern	DP2	DP1	DP1	DP2	DP1	DP2	DP2	DP1	DP1	DP2	DP2	DP1	DP1	DP2	

Table 2. Pump curves characteristics

Pump	Head – flow curve	Efficiency – flow curve
P1 = P2	$H = 74{,}251 + 0{,}2969\,Q - 0{,}0011\,Q^2$	$\eta = 15{,}703 + 0{,}7098\,Q - 0{,}00195\,Q^2$

Originally, the irrigation is on-demand, and it is simulated with two hourly patterns (24 factors). Each node has an assigned pattern (see Table 1). Initially, leaks represent 33% of the total injected flow (28,638.2 m^3/day), therefore the registered volume by hydrant's meters is 21,532.5 m^3/day. The minimum pressure required by any hydrant is 10 wcm. In order to fulfil this requirement in the most unfavorable hydrant implies satisfying the consigned curve showed by Figure 3. As the pumping station is still not regulated, the pump system works providing higher pressure than actually required (see Figure 3).

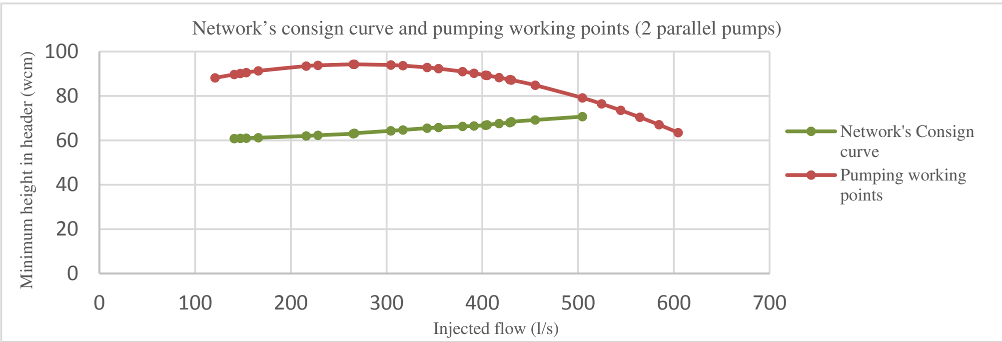

Fig. 3. Network's consign curve and the corresponding pumping working points.

Table 5 (second column) shows the initial energy audit where it can be seen that there is much room for improvement. The main inefficiencies are due to the energy lost embedded in the leaks (24.33%), losses at the pumping station (17.95%) and friction losses in pumps and valves (15.4 %). Total energy losses (57.68 %) are the complementary value of the total energy supplied to the hydrants (42.33 %) a value that collects the minimum energy required (E_{uo}), the topographic energy, and the excess of delivered pressure. As can be seen, E_{uo} represents less than 25% (24.67%) of the total energy supplied.

In order to improve the efficiency three operational actions (although in this case the first one, see Table 3, has a double positive impact) are considered. A brief description follows:

a) Installation of three (one per line) PRVs (Pressure Reducing Valve). For each PRV valve, pressure is set as low as possible (the minimum pressure at the least favorable hydrant must be satisfied).

b) On-demand irrigation system is changed for a scheduled demand system in three turns (one per line) of eight hours each. This action dramatically reduces the pump working points (from 24 different points to three). The efficiency of the pumping station is significantly increased.

c) To reduce the surplus of energy, the pumping station is regulated with variable frequency drivers.

The order in which the actions are implemented does not matter. In this case, the first action is the less intrusive one and, probably, the most intuitive one. Table 3 summarizes the actions:

Table 3. Actions summary

Action	Positive impact	Negative impact	Comments
VRPs installation	Leaks are reduced (OP3) Friction is reduced (OP4)	Topographic energy is consumed.	Is the most intuitive action
Irrigation scheduled in three turns	Pumping station efficiency is improved (OP1)	Head losses in pipes are higher	Only the VRP installed in the lower line is active.
Pumping station regulation	Minimize the excess of pressure (OP2)	----	No VRP works

With these three actions having been implemented, significant energy improvements are achieved. Table 4 shows how the pumping station works once they are applied, while Table 5 show the evolution of the energy audits (from the initial scenario to the final one) with the three actions.

Table 4. Pumping station work after its regulation.

	Turn 1 (0-8h)	Turn 2 (8-16h)	Turn 3 (16-24h)
Pump 1	Stopped	(260,68 l/s; 63,97 wcm), α=91,5% (pump speed 91.5 % of the nominal)	(152,14 l/s; 93,28 wcm)
Pump 2	Stopped	Stopped	(152,14 l/s; 93,28 wcm)

Table 5. Energy audits evolution after action's implementation (kWh/day)

	Initial System	OP3-OP4. Pressure reduction	OP1. Limit operating point (Irrigation Scheduled)	OP2. Avoid excess energy (Pumping station regulation)	
Energy supplied	13916.22	11497.09	10705.08	6859.86	
Shaft energy (supplied by pumps)	10382.93	8660.21	8066.79	4311.03	62.84 %
Shaft energy pump P1	5191.46	4330.10	4033.39	3019.99	70.05 %
Shaft energy pump P2	5191.46	4330.10	4033.39	1291.04	29.95 %
Natural energy (by external sources)	3533.30	2836.89	2638.29	2548.82	37.16 %
Energy consumed	13916.22	11497.09	10705.07	6859.85	
Useful energy	5891.16	4101.58	5064.30	4204.34	61.29 %
Minimum required energy by users	3432.59	3432.59	3443.31	3443.31	81.9 %
Topographic energy	1623.76	570.109	1348.55	604.093	14.37 %
Excess energy delivered	834.805	99.093	272.438	158.155	3.76 %
Friction energy losses	517.093	312.037	1565.30	1427.58	20.81 %
Valve energy losses	1625.00	3859.68	1489.89	0	0 %
Leakage energy losses	3385.68	1059.49	707.269	452.897	6.6 %
Wasted energy in pumping stations	2497.28	2164.31	1878.32	775.034	11.3 %
Wasted energy in pump P1	1248.64	1082.15	939.162	597.672	77.12 %
Wasted energy in pump P2	1248.64	1082.15	939.162	177.362	22.88 %
Improvement over the initial		17.34%	23.07 %	50.71 %	

As can be seen, the final energy reduction is 50.71%, with an even higher value, 58.5%, if only shaft energy is considered. In any case, the final energy audit shows that there are still some weak points. The scheduled irrigation implies higher flows and, therefore, higher pipe friction losses (20.81%). On the other hand, losses at the pumping station are still significant (11.3%). To reduce these values it is necessary to apply structural measures. In particular, renewing pipes with higher diameters (ST0) and installing new, more efficient pumps (ST1). The other three structural actions (ST2, ST3 and ST4) are not applicable in this case because there is a poor cost/benefit ratio.

4.2. Example 2.-

This is a real case [15] and reproduces a rather frequent design. The depicted adduction had two main problems: a pressure break on the suction side of the pumping station and coupled pumps to rise at different geometric heads. From an energetic point of view, it was a very poor design. The pumping station was modified according to Figure 4. With this action two structural actions (ST3 and ST4) were simultaneously implemented.

The achieved results were: a) Energy intensity reduction: from 0.624 kWh/m^3 to 0.277 kWh/m^3. The energy savings represented 56%. b) GHG reduction of emissions of 334,9 Tm CO_{2e}/year. c) Economic savings = 100.000 €/year achieved with an investment of € 250,000. Return on investment period 2.5 years.

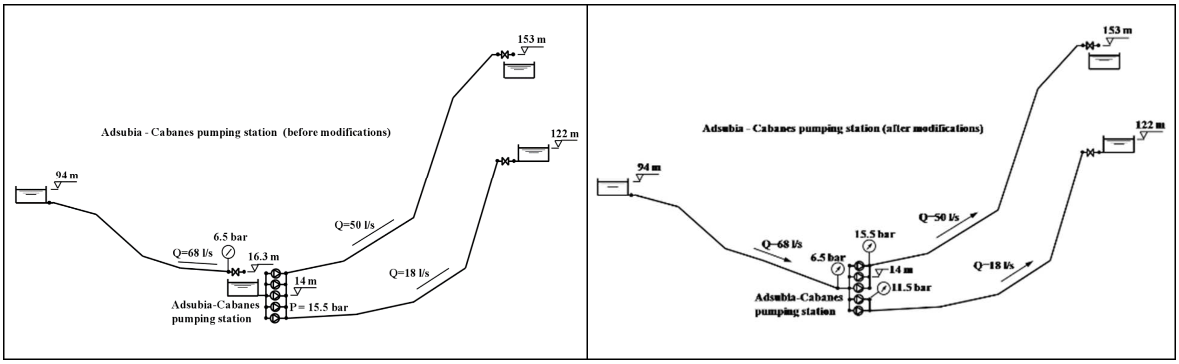

Fig. 4. Adsubia – Cabanes pumping station. Jávea (Spain)

5. Conclusions

Only in the EU 100TWh/year are used to pump water in irrigation and drinking water supply systems. All around the world, this amount can be several times higher. Therefore, the interest in an integrated strategy to improve efficiency (from the beginning, the assessment, to the end, to label and certify the level of efficiency) is outside any doubt. This is mainly because field experience shows that, in general, energy consumption can be reduced by 60% or more. This integrated strategy (Figure 1) has six steps, pre-assessment, diagnosis, analysis, exploration of potential actions, prioritizing actions through a cost – benefit analysis and labelling and certification. This paper has paid special attention to one of these steps - the catalogue of different actions that in practice can be adopted. Two examples have been included in the paper to illustrate these actions.

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