



# Rigid Versus Variable Energy Sources in Water-Pressurized Systems: An Economic and Environmental Analysis

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## Abstract

The layouts of most urban water systems are known. A head tank with an appropriate elevation is used to supply water through the network at a pressure equal (or higher) to that set by the relevant standards. Furthermore, equalization, fire and emergency storage are important benefits of tank use, as is the possibility of avoiding peak rate electricity fares. However, at the end of the last century, some tanks were reported to have a negative impact the quality of water, and recommendations were made to limit their volume and revise their geometry. Recently, alternative options have been considered. Equalization can be achieved with pumps with variable-frequency drivers, emergency situations can be avoided with electric oil generators and solar plants can be used to offset other generation types and reduce energy costs. Therefore, this article analyses the performance of tanks as an energy source, and tank and pump supply methods are directly compared; overall, direct supply through pumps is cheaper, more energy efficient and more environmentally convenient. Therefore, in the context of climate change, it seems reasonable to avoid water tanks as energy sources.

**Keywords** Water distribution systems · Energy efficiency · Water tank · Life cycle cost

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## 1 Introduction

Water systems are designed to be reliable and simple. Therefore, the preferred layout is to pump water to a reservoir and supply water to citizens via gravity. If a city's topography allows, water is pumped to a reservoir located in an elevated zone, from which the entire population can be supplied; when this is not possible, an elevated tank is built. This layout has persisted because in the event of power failures (relatively frequent a few decades ago), the water supply is not interrupted. A pumping system only needs to fill the tank, and the supply is regulated by gravity. Additionally, tanks can maintain pressure, accumulate energy, avoid pumping in peak periods (when energy is more expensive) and mitigate hydraulic transient surges. Therefore, tanks have played a key role in the development of pressurized water systems, with just one drawback: their negative visual impact; because of this issue, suitable locations have been rejected for aesthetic reasons (Walski 2000).

Overall, tanks were considered beneficial until the end of the last century, when it was noted that they could contribute to the deterioration of water quality (EPA 2002). This finding ended the widespread belief that the larger the reservoir is, the better the result. To minimize the loss of residual disinfectant (Rossman et al. 1995) and the residence time of water inside tanks, which depends on the tank geometry and volume (Clark et al. 1996), the main criteria for tank design have been modified. In the past, a minimum water volume was set (for fire protection and emergencies), regardless of the combined operational features of the network and the tank. Currently, the need to consider both the reliability of the supply compatible and the impact on water quality requires a joint tank-network analysis (Batchabani and Fuamba 2014).

In this paper, is questioned the role of tanks as energy sources because with technological progress, the increased reliability of the electricity supply and changes in the energy market have been considerable; of all the functions traditionally associated with tanks, only storage (for emergencies such as fires or breakdowns at water treatment plants) seems irreplaceable. Currently, infrequent electrical failures can be bridged with increasingly autonomous generators that can cover interruptions lasting several days. The other functions, such as matching the supply and demand and damping hydraulic transient surges, are now resolved with other measures. However, although providing a direct supply to a network has been proven effective, in urban networks, it is far to be thought the best solution. Additionally, the chlorination system of drinking water networks must ensure a minimum contact time of 15 min between chlorine and water (WHO 2017). This time is guaranteed by any tank, as a rigid energy source (RES), but not by a variable energy source (VES). In the latter case, to meet the standards, the minimum distance between the chlorination point and the first consumption point must be at least 900 m. In any case, with UV disinfection, this drawback can be overcome.

Therefore, the goal of this paper is to demonstrate that from energetic, economic and environmental perspectives, VESs perform better than RESs. Notably, both alternatives are compared on equal terms. Similar comparisons have been previously made for water networks (Gómez et al. 2015) and tall buildings (Jens and Anders 2014), but only energy and economic perspectives were considered, whereas a full environmental analysis is given in this study.

To assess this conceptual change, it is necessary to refer to a tank as an element that avoids pumping water during peak hours. Thus, tanks promote a cost reduction related to energy use. Nevertheless, with the expansion of renewable energy sources, especially solar energy, and the continuous increase in consumption, hourly rates and emission intensities

are changing. Therefore, within the framework of a changing electricity market in which the structure of energy costs today will be different from those tomorrow, it is reasonable to minimize the energy requirements for both the power demand (kW) and the energy consumed (kWh), which depend on the physics of the system; this is not the case for emissions or final economic expenditures, which vary with the evolution of the energy mix.

In summary, tanks were developed in conjunction with pressurized networks, and with the exception of their negative impact on water quality, until three decades ago, no-one questioned their need. However, technological improvements and the mandate to save energy (Cabrera et al. 2010) have led to reviews of tank systems as energy sources. In coming years, most RESs should be replaced with VESs; this trend is already occurring in Spain, where few new tanks are built and many existing tanks have been removed. These decisions require technical, economic and environmental support. In this context, the objectives of this paper are as follows.

- First, with a real case study, RESs and VESs are compared from three perspectives: hydraulic behaviour, energy and economy.
- An environmental analysis is then performed, and the CO<sub>2</sub> emissions associated with the life cycle of each alternative are calculated.
- Finally, the results obtained are evaluated. It is concluded that from any perspective, a VES is better than an RES. Although these conclusions are drawn for a specific network, the analysis indicates that in other cases, the qualitative results will be similar.

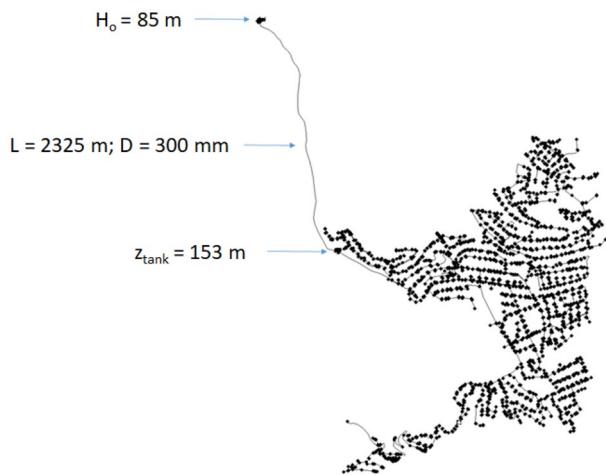
## 2 Case Study

Hydraulic network patterns and the temporal modulation of the corresponding demand have a wide range of variability. Consequently, to assume that a VES is preferable to a RES is risky from an energetic perspective. The highest adaptation capability to variable requirements for flow and pressure give VESs an unquestionable advantage over RESs, but each system is physically and temporally different. For example, an invariable demand over time (typical of a designed irrigation scheme) mitigates the advantage of flexibility. In addition, changes and uncertainty in energy and environmental factors must be considered.

It is therefore appropriate to analyse each case and, based on the results, make a final assessment. The weak points of VESs compared to those of RESs must be considered; the most notable weakness is the response time when a power failure occurs. In this situation, although the operation of a RES is not interrupted, in a VES, an interruption depends on when generator operation begins. However, the installation of an air pressure tank in a VES can address this drawback. Consequently, is not much difference in the response time to a fire, as the response time depends more on the whole system operation than on the tank itself. Even if the pipe feeding a VES has an adequate diameter, the response can be better than that of a tank. In fact, if the increase in consumption as a consequence of a fire decreases the regulation pressure of a VES, the corresponding reaction (increasing the rotation speed of pumps) can be better than that of an RES. Therefore, before diagnosis, each system must be studied in detail.

In this case, the Tossalet sector of the water network in Jávea, Spain, is analysed. This sector has a conventional layout (Fig. 1). The pumping station includes two working pumps (plus a reserve pump) that suction water from one of the general pipes in the system with a diameter of 400 mm. A rising pipe 2325 m in length and 300 mm in diameter conducts the

**Fig. 1** Water sector in Tossalet (Jávea) for which the current RES is compared with a VES



water from the pumping station to a tank located at the highest point in the sector (153 m). The water level of the tank is used to control the start (2 m) and stop (5.5 m) times of the pumps. To avoid pumping at peak times and to economically penalise peak pumping, the volume of the tank considered is 3888 m<sup>3</sup>, a higher value than the real volume. This volume complies with international standards (Batchabani and Fuamba 2014). The regulation volume is 2474 m<sup>3</sup> (practically, the peak daily demand is 2534.7 m<sup>3</sup>), with the rest being held in reserve. This also includes 801 connections, 1,739 customers, 61.9 km of mains, extreme levels of consumption for nodes at 140 m and 2.6 m, and six PRVs (pressure-reducing valves) to reduce the pressure in the lower part of the sector. The operating pressure is 15 m.

Jávea is a highly seasonal tourist city. The maximum monthly demand of the sector is 58247.57 m<sup>3</sup> (August), with the minimum being 18,690.47 m<sup>3</sup> (February). The total volumes (demand plus loss) are 78,575.68 m<sup>3</sup> (August) and 25,222.21 m<sup>3</sup> (February). With buildings that are mainly single-family homes, the sector's demand pattern is residential use. The cost of water production is 0.37 euros/m<sup>3</sup>, calculated as the weighted average between that produced by a desalination plant (1 euro/m<sup>3</sup>) and that from wells in the area (0.1 euros/m<sup>3</sup>). The annual contributions from these sources are 30% for the desalination plant and 70% for wells.

The network is simulated with a mathematical model that is supported by EPANET (Rossman 2000). The model includes 801 connections that can be automatically loaded from a billing database. Leakage accounts for 89% of non-revenue water and is modelled as pressure dependent based on nodal emitters. The remaining 11% is associated with commercial losses, which are included as an additional volumetric demand from consumers.

The current system is economically and environmentally compared with a possible direct injection into the network (in this case, the length of the rising main guarantees the minimum contact time for chlorine disinfection). Figure 1 shows the framework of the model, in which decoupling the tank is simple because a bypass is sufficient. To analyse this sector independent of the entire Jávea network, the sector operations are simplified by replacing the supply pipe with a reservoir with a height equivalent to the piezometric supply height (85 m). With the tank empty, the minimum height difference to be overcome is 68 m. A comparison is made based on the consumption data for 2018. The pumps

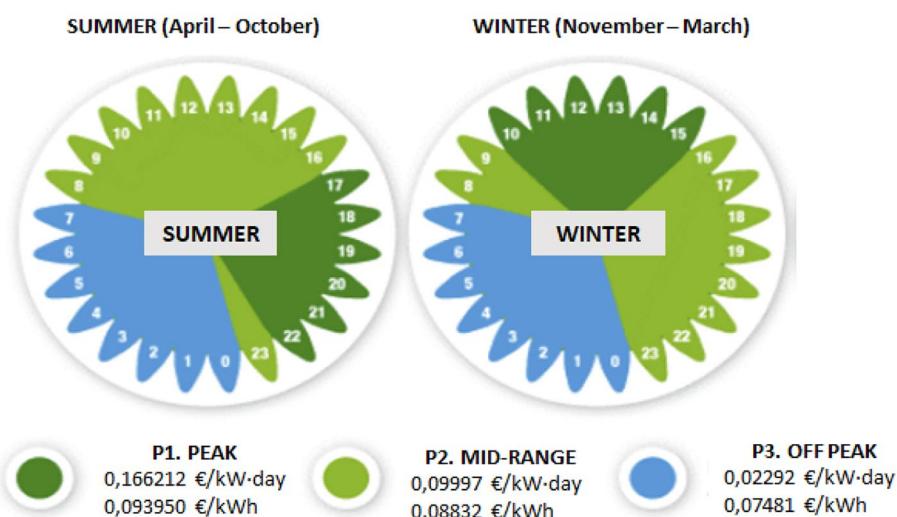
corresponding to each type of supply are adapted to the needs of the case study, and the VES (direct injection) includes frequency drivers.

In economic comparisons, electricity tariffs (Fig. 2) are of great importance, and due to their variability, assessments must be performed annually. In fact, if a comparison is extended over time, the current energy costs, calculated for the same physical system and an identical model load, would be different from those in the following year. Therefore, it does not seem logical to include the changes in the cost of money (interest rate) in the economic analysis. In addition, technological developments have made electronic components, such as variable-speed drives, cheaper. Thus, costs from 2018 are always used in the economic comparison. The values corresponding to this year are detailed in Fig. 2.

## 2.1 Analysis of the Tank-fed System (RES)

The two pumps in the simulation ( $H = 133.77 - 0.023 Q^2$ ;  $\eta = 3.967 Q - 0.054 Q^2$ ) are from a commercial catalogue (the current pumps are not optimized for the state of the system studied, and the objective is to analyse energy cost minimization in both cases, i.e., under equivalent conditions). The working point is associated with a pumping rate of 40.38 l/s and pressure head of 94.28 m. This point is practically constant because the level variations when the tank is filled in relation to the pumping height are small (less than 3%). The unit power of each pump is 56.4 kW (112.8 kW for both), so the power term is 115 kW at P3 and P2 (in peak months, it is inevitable to operate during off-peak hours, P2; see Table 1). At P1, 10 kW is sufficient, as the pumps will be stopped. If the contracted power is exceeded in any month, the excess amount is paid. Table 1 shows the results for the extreme months (February and August) and for the simulation of the twelve months of the year.

In short, the total energy cost is 26379 euros per year, and the annual average operation is 6.83 h/day. Note that 3.86 h in February increases to 9.04 h in August. When



**Fig. 2** Time of use energy prices (year 2018). Power and Energy term

**Table 1** Energy summary system with tank (RES), Months February—August and annual summary

	Rate	Maximum power (kW)	Energy (kWh)	Power term (€)	Energy term (€)	Pump volume (m <sup>3</sup> )	Working hours (h)
February	P1	0	0	38.58	0		
	P2	0	0	273.63	0		
	P3	112.7	11,202	73.82	838.05		
	Total		11,202	386.03	838.05	31,448	108.2
August	P1	0	0	42.72	0		
	P2	112.7	3700	356.41	326.79		
	P3	112.7	27,948	81.73	2090.85		
	Total		31,648	480.86	2417.64	81,677	280.3
Year 2018	P1	0	0	507.11	0		
	P2	112.7	13,656	4022.25	1202.52		
	P3	112.7	266,210	970.20	19,676.42		
	Total		279,867	5499.56	20,878.94	724,639	2492

the 8 h corresponding to the P3 tariff are exceeded and energy is consumed in P2, the energy cost increases significantly; the variation in the power term, a fixed cost, is due to the higher number of days invoiced (August/February). It is clear that with increasing tank capacity, pumping in P2 can be avoided. In any case, it should be determined whether this approach compensates for the high investment in the tank. As mentioned above, the impact of large volumes on water quality has rebuked the concept that the larger the volume is, the better the result (Walski 2000). The volume in this case is already notable, and the operating time at P2 is not very significant (5% of the total).

## 2.2 Analysis of the System with a Pump Directly Feeding the Network (VES)

In this case, the system has the advantage that the pumped volume can be distributed throughout the day (in the previous case, it had to be done in only 8 h). Consequently, the pumped flow is reduced, and therefore, friction losses are reduced. This reduction can be even greater if, as is usually the case with tanks, the head pressure is not adjusted based on the minimum pressure at the most unfavourable node. However, in this case, the height of the most unfavourable node is 140 m, and 15 m of operating pressure requires a pressure head of 155 m. In the previous scenario, when the maximum volume was pumped to the tank (the tank floor is at 153 m), only when the water level was at a minimum (2 m) was the pressure condition met at unfavourable node 15 m. Nevertheless, in most cases, the pressure at this node exceeds 15 m, reaching a maximum value of 18.5 m (full tank). The ability to temporally adjust the pressure based on need is an advantage of the VES. This benefit always exists, but in this case, it is not very relevant because the height of the tank is adjusted to the minimum height required. One of the advantages of this system is the low friction in the rising main (proportional to the square of the flow), which in this case is remarkable. Consequently, the pumping head is relatively low. Although the head provided by the pumps in both scenarios is similar, the power is very different because the flows vary.

In this case, both pumps are equipped with a speed driver. Since the peak flow and the pump head to be supplied in this system are lower than those in the RES system, the pumps are smaller. To ensure similar pumping conditions and prices, the pumps used are the same as those in the previous case; the corresponding curves are  $H = 126.9 - 0.041 Q^2$  and  $\eta = 5.671 Q - 0.099 Q^2$ . For the main pump, the relative speed varies in the interval of  $\alpha = 0.75 \div 1$ , with minimum and maximum working conditions of  $Q = 7.18 \text{ l/s}$  and  $H = 70.18 \text{ m}$  and  $Q = 34.81 \text{ l/s}$  and  $H = 74.95 \text{ m}$ , respectively. For the support pump, the relative speed is  $\alpha = 0.83 \div 0.91$ , with minimum and maximum working conditions of  $Q = 19.89 \text{ l/s}$  and  $H = 75.28 \text{ m}$  and  $Q = 25.24 \text{ l/s}$  and  $H = 80.33 \text{ m}$ , respectively. Table 2 summarizes the working regime.

The working point of a VES depends on the demand, and the speed of the pumps is adjusted to the height that guarantees the minimum pressure at the critical node. There are months (October to April) when a single pump with a variable speed can serve the system. However, during peak hours in the months with the highest consumption levels (May to September), both pumps are necessary; because the pumps are identical, tasks (main or accompanying) can be alternatively performed.

**Table 2** Working regime of the PS (direct injection) in extreme months (February and August)

		Rate	Maximum power (kW)	Energy (kWh)	Pump volume (m <sup>3</sup> )	Working hours (h)
February	Pump 1	P1	15.70	2552		
		P2	16.67	4401		
		P3	18.43	3147		
	Total P1			10,100	30,794.40	672
	Pump 2	This pump is stopped				
August	Pump 1	P1	36.68	4807		
		P2	36.67	9103		
		P3	26.49	4684		
	Total P1			18,594	63,808.95	744
	Pump 2	P1	21.64	2593		
		P2	21.07	1251		
		P3	26.48	1626		
Total P2				5470	18,379.40	248

In short, the differences between the two systems are as follows:

- a) From an energy perspective, the ability to adjust the pressure at the head node over time to the needs of the system enhances energy savings. Additionally, the reduction in friction in the adduction pipe reduces the energy expenditure.
- b) From a hydraulic perspective, in addition to the reduced friction, there is less volume leakage due to improved pressure adjustment. In systems with tanks, the pressure is adjusted with PRVs (which are energy dissipation devices), and with a VES, the regulation is direct; therefore, energy use is reduced.

All the physical parameters are improved with the VES. By consuming less energy and demanding less power, direct pumping is favoured. The only disadvantage, which is a consequence of having to pump at any time of the day, is economic, especially during periods of high demand when energy is more expensive. However, as previously mentioned, the forecast for the development of energy market suggests that this advantage will be reduced in the near future and could even be reversed over time.

In economic terms, tariffs are important to consider. This second direct injection scenario with a VES, due to its continuous work, is simulated with a contracted power of 40 kW at P1, P2 and P3 (Table 3). However, during peak hours in the months of greatest consumption, when both pumps are operating, the power demand slightly exceeds 55 kW. In particular, as shown in Table 3, in August, during the P1 working period, the power demand is 58.32 kW. Nevertheless, because the contracted power must be maintained for a minimum period of 12 months, it is more economical to pay for exceeding the contracted power than to contract a higher annual power. This is a common problem for areas with many seasonal activities, such as tourism or irrigation. As the demand for energy is highly variable, these activities make it desirable to be able to adapt to the needs of the moment, at least every six months. In any case, these are issues linked to energy policy that therefore depend on the evolution of the market and its regulations.

**Table 3** Summary of systems with direct injection (VES): Months February to August and the annual summary (2018)

	Rate	Maximum power (kW)	Energy (kWh)	Power term (€)	Energy term (€)	Pump volume (m <sup>3</sup> )	Working hours (h)
February	P1	15.70	2552	154.34	239.77		
	P2	16.67	4401	95.18	388.68		
	P3	18.43	3147	21.82	235.44		
	Total		10,100	271.34	863.89	30,794	672
August	P1	58.32	7399	457.12	695.18		
	P2	57.74	10,354	276.55	914.49		
	P3	52.97	6310	53.25	472.11		
	Total		24,064	786.92	2081.77	82,188	744
Year 2018	P1	58.32	55,788	2872.12	5241.26		
	P2	57.74	83,865	1752.12	7406.99		
	P3	52.97	55,582	376.39	4158.25		
	Total		195,235	5000	16,807	664,038	8760

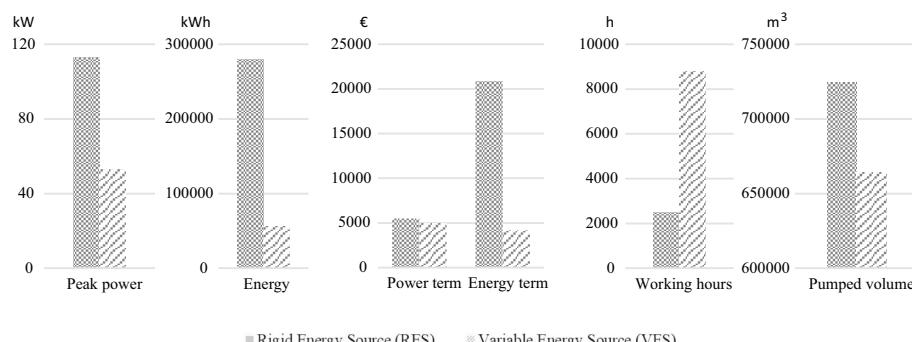
Therefore, in a changing scenario such as the present one, it is reasonable to adapt the contract based on the evolution of tariffs. However, it should be noted that the same physical systems with the same demands may generate an economic outcome in 2019 different than that in 2018.

In summary, the main hydraulic differences between the RES and VES (see Tables 1 and 3) are:

- Peak power demand: 112.7 kW (RES) versus 58.32 kW (VES);
- Annual energy consumed: 279,867 kWh (RES) versus 195,235 kWh (VES); and
- Pumped volume: 724,639 m<sup>3</sup> (RES) versus 664,038 m<sup>3</sup> (VES).

The economic differences (depending on the system and electricity tariff) are:

- Total energy cost: 26,379 € (RES) versus 21,807 € (VES); the difference is due to both energy savings and the lower cost of the power demand.

**Fig. 3** Energy and economic results for both sources

- b) Power term cost: 5500 € (RES) versus 5000 € (VES), a small difference considering that the VES peak power is almost half the RES peak power.

Figure 3 illustrates these results. Except for the working time, the VES performs better than the RES.

The hydraulic-energy binomial, calculated with physical laws, only depends on the system and the workload. However, this is not the case for the economic term, which is very sensitive to the changing tariff system. For example, in Spain, 2018 prices no longer apply (BOE 2020). With the new tariffs, energy costs would be similar but not the same.

### 3 Comparative Economic Analysis

An economic balance was constructed based on 2018 prices, and due to the temporal variability of the economic and environmental analyses, it is not reasonable to extrapolate these results over time. Therefore, possible variations in the price of money are not considered. With current prices, only the necessary physical elements and the resources consumed to achieve each solution are considered. These factors are as follows:

- For the RES: A tank, selected pumps, energy costs and the cost of excess leakage compared to the other alternative.
- For the VES: A power generator (capacity of 44 kW to prevent electrical failures), specific variable-speed pumps and energy costs.

The costs of the pumps and of the power generator were obtained from the manufacturers' price tables, and the cost of the tank was calculated by comparison with similar elements built in the area, with prices adapted to the year of study.

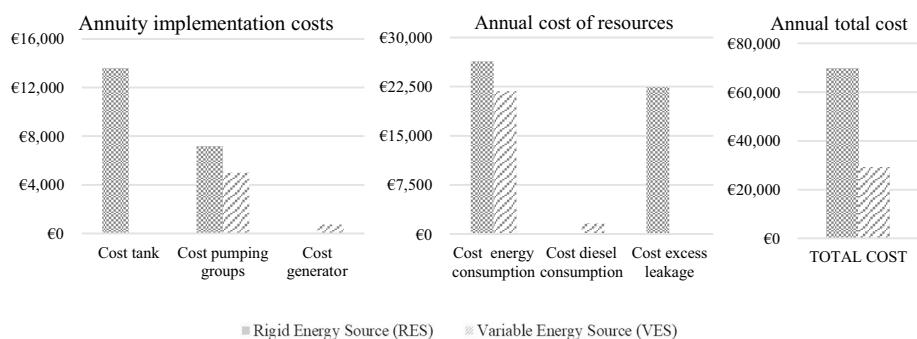
In addition to the above factors, the following assumptions are made:

- The depreciation time for the reinforced concrete tank is 70 years. Conservative proposals set their useful life at 50 years (Everhart 2010), while risky proposals set it at 100 years (WC 2017). Thus, an intermediate value of 70 years is adopted.
- The amortization time for electromechanical equipment is estimated to be between 15 and 20 years (SV 2009). In this study, fifteen years is adopted.
- The annual maintenance cost of the 44 kW power generator is 1650 euros; this value is calculated based on 100 h/year of operation (revision tasks and covering possible electrical faults). Overall, 4400 kWh/year corresponds to a rate of 0.25 l/kWh, and 1.5 euros/l is used for the price of diesel.

Table 4 summarizes the above costs. First, the differential investments are listed: the tank, pumps (the VES includes variable-speed drives) and the power generator. The remaining elements of the pumping station (transformer station, regulation system, etc.) are common to both sources, and the economic differences that could exist are negligible from the perspective of this analysis.

**Table 4** Economic balance of the RES versus the VES

COSTS	Implementation costs	RES		VES	
		RES	VES	RES	VES
ANNUAL COSTS					
	Annual implementation costs				
		Cost of the tank	1,021,270 €	0 €	0 €
		Cost of pumping groups	108,003 €	75,085 €	75,085 €
		Generator cost	0 €	11,126 €	11,126 €
		Annual deposit (70 years)	13,617 €	0 €	0 €
		Annual cost pumping groups (15 years)	7200 €	5006 €	5006 €
		Annual generator cost (15 years)	0 €	742 €	742 €
		Cost of annual energy consumption	26,379 €	21,807 €	21,807 €
		Cost of annual diesel consumption	0 €	1650 €	1650 €
		Cost of excess leakage (60,601 m <sup>3</sup> )	22,422 €	0 €	0 €
		TOTAL ANNUAL COST	69,618 €	29,205 €	29,205 €



**Fig. 4** Annual economic balance (RES versus VES)

The final balance is very favourable to the VES since it requires a smaller investment and, moreover, is hydraulically and energetically more efficient. In short, regardless of the peculiarities of each case, the economic results are clear.

Figure 4 illustrates these results.

#### 4 Life Cycle Analysis

After the hydraulic-energy-economic study, an environmental study was performed from the perspective of life cycle analysis (LCA). This is the most appropriate perspective because it allows us to evaluate the potential environmental impact over the life of a product or process, and within each particular analysis, the most relevant stages of the cycle can be identified. In this case, the comparison is limited to the different elements and considers identical hypotheses and working conditions (energy consumption, useful life, generator operation, etc.)

LCAs of hydraulic projects with real data are becoming, although complex, rather common (Petit-Boix et al. 2016). The analysis requires a complete detailed inventory of the resources used during project execution, which, in many cases, is not feasible to obtain. Therefore, a simplified analysis is typically performed with data obtained from input/output tables for the consumption of materials per unit of product. This procedure has already been used in California (Stokes and Horvath 2006), a pioneering state in the economic-environmental optimization of water planning. With the available documentation, comparative environmental analyses of water supply alternatives in Spain can also be performed for relatively dry areas, both new projects (Raluy et al. 2005) and existing facilities (Uche et al. 2014) and even for cycles at the city scale (Pillot et al. 2016) with different supply alternatives (Tangsubkul et al. 2005). Urban uses can be considered to assess the relations between water cycle and domestic and industrial uses (Uche et al. 2013).

As a functional unit, 1 m<sup>3</sup> of pumped water is considered. The impact assessment method selected, within the framework of SimaPro, is ReCiPe2016; this is one of the most widely accepted methods at present, with a medium-term scope (midpoint) and hierarchical approach at 100 years. A set of impact categories (18) that cover the majority of known environmental conditions is considered. For comparative analysis, the global warming potential impact category (kg CO<sub>2</sub>-eq) is used, given its wide acceptance in the scientific-technical field and interest to a broad spectrum of the population. However, for

comparison with the values obtained with this method, another method is used; a single environmental impact category (IPCC GWP at 100 years) measured in the same terms is considered, and the error range of the results is less than 0.01%. For the environmental impact assessment, SimaPro software (Version Ph.D. 8.5) was used.

Furthermore, given the foreseeable and notable influence of energy consumption on the final environmental impact in the case study, the origin of the electrical energy consumed must be carefully analysed. In the initial comparison (base), the Spanish electricity mix for low voltage supply (< 1 kV) in 2014 is selected. The more recent emission value available in the SimaPro database (Ecoinvent 3.3; Wernet et al. 2016) is 0.682 kgCO<sub>2</sub>eq/kWh<sub>e</sub>. Then, as an example of a European country with a very high use rate for renewable energy (96% hydroelectric and 1.9% wind), Norway is considered; the corresponding net emission value is only 0.0312 kgCO<sub>2</sub>eq/kWh<sub>e</sub> in the same year.

#### 4.1 Life Cycle Inventory

Table 5 shows the flows of materials and energy for the two pumping systems analysed. The amounts of material used in the construction of the tank and the manufacturing of the pumps and the generator were estimated from the literature and the manufacturers' references (Dias et al. 2013; Nee 2015; Grundfos 2019); the processes used to produce the materials were specified in the Ecoinvent database (Wernet et al. 2016). Given its low representativeness, Earth movement in the construction phase is neglected.

**Table 5** Material and energy flows corresponding to each pumping system analysed

	Inputs	Unit	RES	VES
Materials	Corrugated steel	t	17.22	
	Concrete at 30–32 MPa	m <sup>3</sup>	256.21	
	Concrete bricks	t	12.32	
	Polystyrene	kg	6.28	
	Cast Iron	kg	2934	2150.83
	Stainless steel	kg	5868	3144
	Steel	kg		188.19
	Ferrite	kg	198	180
	Copper	kg	82.5	74
	Aluminium	kg		39.9
Energy	Coal (bituminous)	kg		2200
	Oil	kg		59.5
	Natural gas	m <sup>3</sup>		17
	Electric < 1 kV (Mix SP)	GWh	14.64	20.99
Outputs	Electric GE diesel	MWh		167.15
	Water	Pumping tank	m <sup>3</sup>	54,347,943
		Direct pumping	m <sup>3</sup>	49,802,819

**Table 6** Intermediate impact of GW (Spanish mix)

Total emissions	RES	VES		
ReCiPe2016	1.45E + 07 0.2668	kg CO <sub>2</sub> -eq kgCO <sub>2</sub> -eq/m <sup>3</sup>	1.03E + 07 0.2068	kg CO <sub>2</sub> -eq kgCO <sub>2</sub> -eq/m <sup>3</sup>
IPCC GWP (100a)	1.44E + 07	kg CO <sub>2</sub> -eq	1.02E + 07	kg CO <sub>2</sub> -eq
Component	Emissions kg CO <sub>2</sub> -eq	Percentage %	Emissions kg CO <sub>2</sub> -eq	Percentage %
Deposit	1.46E + 05	1.01	n/a	
Pumping group manufacturing	8.63E + 03	0.06	4.74E + 03	0.05
Operation of pumping groups	1.43E + 07	98.93	9.99E + 06	97.28
Manufacturing of generator equipment	n/a	n/a	2.78E + 03	0.03
Generator operation	n/a	n/a	2.72E + 05	2.65
	1.45E + 07	100.00	1.03E + 07	100.00

## 4.2 Life Cycle Impact Assessment

Table 6 shows the intermediate impact of the global warming (GW) category on energy consumption based on the Spanish mix.

Table 7 details the impact analysis results for Norway.

In summary, the results for the Spanish energy mix show that the environmental impact generated by the higher energy consumption of the RES (24.1%), with respect to that in the VES case, has a higher measured impact (22.5%) in terms of the CO<sub>2</sub> equivalent per cubic metre of pumped water (0.2668 versus 0.2068 kgCO<sub>2</sub>eq/m<sup>3</sup>). Consequently, the environmental impact due to infrastructure (amortised over 70 years) is only 1%, and the weight of the pumps is irrelevant, although they are replaced every 15 years. However, the impact of the generator on the VES result reaches almost 3%, with only 100 h/year of operation. This impact of diesel consumption, in the case of a country with a purely renewable energy mix such as Norway, increases to 37% of the total impact, but the total value is otherwise minimal (0.015 kgCO<sub>2</sub>eq/m<sup>3</sup> in both cases).

**Table 7** Intermediate impact of GW (Norwegian mix)

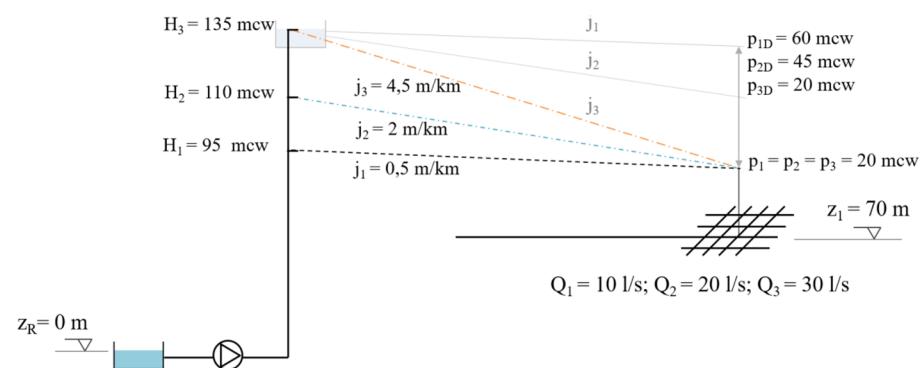
Total emissions	RES	VES		
ReCiPe2016	8.08E + 05 0.0149	kg CO <sub>2</sub> -eq kgCO <sub>2</sub> -eq/m <sup>3</sup>	7.36E + 05 0.0148	kg CO <sub>2</sub> -eq kgCO <sub>2</sub> -eq/m <sup>3</sup>
IPCC GWP (100a)	8.05E + 05	kg CO <sub>2</sub> -eq	7.34E + 05	kg CO <sub>2</sub> -eq
Component	Emissions kg CO <sub>2</sub> -eq	Percentage %	Emissions kg CO <sub>2</sub> -eq	Percentage %
Deposit	1.46E + 05	18.06	n/a	
Pumping group manufacturing	8.63E + 03	1.07	4.74E + 03	0.64
Operation of pumping groups	6.54E + 05	79.83	4.56E + 05	62.00
Manufacturing of generator equipment	n/a	n/a	2.78E + 03	0.38
Generator operation	n/a	n/a	2.72E + 05	36.98
	8.08E + 05	100.00	7.36E + 05	100.00

In summary, the analysis of the environmental impact reinforces the results obtained in the energy analysis when the infrastructure is amortized in the long term and is used continuously throughout the year in a reasonable manner. However, it should be stressed that in civil work inventories, because common elements are not considered, the value that is obtained for the relative impact of the civil works compared to that of energy consumption is somewhat lower than the real value in this case study. This type of global analysis that is not relevant from the study perspective (an environmental comparison of the two alternatives).

## 5 Global Evaluation of Scenarios

With direct injection (VES), the pressure at the head node can be adjusted based on the strict requirements of the system. This reduction in pressure is transferred to the leaks and therefore to the pumped water (8.4% less). The rigidity of the tank (RES) prevents the pressure from being adjusted naturally (this can be achieved by dissipating the excess energy with a PRV). The above difference would be even greater if the height of the tank was higher than strictly required. In this case, when the water level of the tank is at a minimum, the minimum pressure required at the most unfavourable consumption node is obtained. Therefore, the excess height coincides with the water level, referred to as the minimum level. Nevertheless, this situation is not common. Hence, the advantage of the VES over the RES becomes more relevant in highly pressurized water networks where tank heights are raised above the levels required by the corresponding systems.

The length of the rising main (2.3 km) has a considerable impact on energy consumption. In fact, in the first scenario, the energy consumption is greater than 30%, although the pumps only work 2492 h a year, as opposed to 8760 h in the second scenario. Notably, for this reason, the latter scenario is less demanding. To pump water to the tank, the pumps require almost 60 kW of electricity, as 40 l/s must be delivered to a fixed height of 94 m during all hours of operation. In the VES case, the most critical condition for the pumping station is a maximum power of nearly 40 kW. However, this peak is temporally uncommon and only occurs at specific moments in the months of greatest consumption; at other times, the power is significantly lower.



**Fig. 5** VES versus RES (Cabrera et al. 2019)

The possibility of adjusting the pumps to the needs of the system results in a significant decrease in energy consumption. This case is similar to that detailed in Fig. 5 (distance from the source to the first node is 10 km), which shows the difference between the flexibility of the VES versus the rigidity of the RES for different operating flows.

In summary, the RES consumes more energy than the VES because although both must pump high flows, the pressure head is impossible to adjust over time. However, the energy savings do not transfer equally to economic savings, which are strongly dependent both on the tariff market and on the adaptation of the contract to the characteristics of the system. It is also important to reduce the number of hours in which the power demand exceeds the contracted power. In the case analysed, energy savings of greater than 30% correspond to an economic cost reduction of 17% (energy savings depend on physical and hydraulic patterns, and economic savings depend on energy market policies).

The cost of the pressure groups is also highly variable. In this specific case and for the same reason as discussed above (less power is required), the VES is favoured. However, the price of the pumps must be analysed carefully since in addition to the power, the cost depends on the flow rate or even the flow rate-to-height ratio (Walski 2012). In this analysis, with real catalogue prices, no discussion of these factors is given. In general, the pumps used in a VES will be cheaper than those used in a RES, but for the former, we must add the cost of variable-speed drives.

The construction cost of a tank is highly variable, and it depends on the tank volume, characteristics, location, and difficulty of construction, as well as auxiliary elements and local labour costs. In any case, construction costs will always be relevant and represent the main difference between both scenarios because a direct supply will eliminate this cost; in some ways, this cost can only be offset by the supply guarantee resulting from the energy that the tank stores. However, technological improvements can neutralize this advantage.

In short, in the studied case, the annual economic savings of the VES is significant at 42%. Moreover, the final economic costs will hardly be balanced. Indeed, the analysis in Table 4 shows that the variable costs of direct injection will always be lower than those of a tank. The large price difference between the valley and peak periods disrupts the economic balance for the tank system, although the final balance is not considerably affected because the energy difference is complex when transformed into economic terms. Moreover, all results seem to indicate that the increases in renewable energy sources and consumption may negate the main advantage of tanks from an energy perspective: the possibility of always pumping during off-peak hours.

Nevertheless, as an important part of the economic analysis, the ambitious environmental objectives that must be reached in the immediate future (decarbonizing the economy) are best assessed through LCA. The analysis in this work is limited to comparing the different elements and their corresponding impacts (in terms of water and energy) on the process. Although the results of the LCA are clear, considering both the low energy expenditure and the material flows that each solution entails, the quantitative analysis results further support the LCA results. The environmental impact, measured in terms of CO<sub>2</sub> equivalent, for the RES is 20% higher than that for the VES. Additionally, the impact of civil works is irrelevant compared to that of energy consumption. However, one exception is for purely renewable energy, for which support based on fossil energy consumption highly limits decarbonization. This factor should be considered in analyses, as should supply and demand failures. Thus, all the results highlight the increased sustainability of energy sources, which allows us to adjust contributions and meet energy needs at any moment.

## 6 Conclusions

In this work, the role of the tank as a RES is compared to that of a VES, consisting of a pumping group plus a variable-speed drive. The comparison shows that a VES is a preferred alternative to an RES from both energy and environmental perspectives. From an economic perspective, distorted by energy pricing, the results are not conclusive. However, it is forecasted that over time, pricing changes will likely eliminate the current distortion effect.

In short, all results indicate that reservoirs will gradually become inferior as energy sources, and in practice, the corresponding transition is already happening, either because of the need to reduce investment or because of the lack of suitable locations. This work adds reasons for such changes, which should be promoted because VESs are more economical and environmentally friendly than RESs.

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**Availability of data and material** All data and models used in this study are available from the corresponding author by request.

## Declarations

**Ethics approval** All authors certify that they have no affiliations with or involvement in any organization or entity with any financial interest or non-financial interest in the subject matter or materials discussed in this manuscript.

**Consent to participate** Informed consent was obtained from all individual participants included in the study.

**Consent for publication** The participant has consented to the submission of the case report to the journal. Additional informed consent was obtained from all individual participants for whom identifying information is included in this article.

**Conflicts of interest** The authors have no conflicts of interest to declare that are relevant to the content of this article.

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