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Optimization of Osmotic Desalination Plants for Water Supply Networks

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Abstract Water scarcity and the poor quality of water resources are leading to a wider diffusion of desalination plants using the Reverse Osmosis (RO) process. Unfortunately, the cost of a cubic meter of fresh water produced by an RO plants is still high and many efforts are in progress to increase the efficiency of the membranes used in osmotic plants and to limit the energy required by the process. A further reduction of the energy cost could be obtained by an optimal operation

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of the desalination plant so reducing the hourly energy cost, or by coupling the RO plant with an energy production plant based on direct osmosis (Pressure Retarded Osmosis PRO).

The economic viability of the desalination process has been analyzed until now without accounting for the integration of the RO plant with the existing water network. This analysis is developed in the present paper with reference to a hypothetical change of water supply in a real network, where a desalination plant is used to satisfy the fresh water demand. Several scenarios will be analyzed to assess the minimum cost of fresh water production and water supply to the network, including the use of energy recovery systems, such as an integrated use of RO and PRO processes, or the regulation of pressure at the network intake by a micro hydro power plant.

Keywords Osmosis · Desalination · Water supply network · PAT

Abbreviations

RO	Reverse Osmosis
PRO	Pressure Retarded Osmosis
WSN	Water Supply Network
PRV	Pressure Reduction Valve
PAT	Pump as Turbine
ERD	Energy Recovery Device
HPP	Hydro Power Plant
VOS	Variable Operating Strategy
PES	Pressure Exchange System
S & P	Store and Pump
P & S	Pump and Store
DS	Direct Supply
SPS	Seawater Pumping System

1 Introduction

A modern trend in the sustainable management of environmental resources regards satisfying the requirement of small communities in terms of water and energy by exploiting the natural sources locally available. A wider diffusion of sustainable management techniques is expected due to climate change and water scarcity (Vivas and Maia 2013). In the last twenty years, seawater or brackish water desalination has become a fully developed process. Reverse osmosis has been reported as a diffuse drinking water solution in coastal areas of Turkey (Akgul et al. 2008). Large seawater reverse osmosis plants are also present in Israel and Cyprus (Wilf 2005). The extensive use of desalination is under study for large irrigation areas, as in the case of the San Joaquin Valley in California (Thompson et al. 2013; McCool et al. 2010).

A significant reduction of costs connected with RO fresh water production has been observed compared with the first applications, from 2.0 to 0.5 $/m^3 (Wilf 2005). This cost has been reduced further in the last ten years to 0.4 $/m^3 due to the plant having a larger capacity than 5000 m^3/d (Akgul et al. 2008; Ziolkowska 2015; Ziolkowska and Ziolkowski 2016). The main variables affecting the water cost are the concentration of the feeding water, the membrane recovery ratio, the required quality of the permeate effluent, and the efficiency of the high pressure feed pumps and booster pumps. Other opportunities for cost containment have been found in an optimal design of reverse osmosis systems (Lu et al. 2007) and in a time-dependent operation of the desalination plant (Ghobeity and Mitsos 2010). The implementation of new technologies and the integration of RO with renewable sources of energy represent the future trend in water treatment by osmosis (Charcosset 2009). In particular, the use of the brackish water of the desalination plant as the feeding effluent of a power plant based on Pressure Retarded Osmosis (PRO) seems very promising, with a potential reduction of 40 % in the energy use connected with the water treatment (Prante et al. 2014; Altaee and Sharif 2015; Zhu et al. 2009).

A Water Supply Network (WSN) has been subjected to complex modification in recent years, with a major concern on the optimization of water pumping and the reduction of water leakage. In particular the use of Pressure Reduction Valves (PRV) within the network is recommended to grant optimal pressure values in most of the network's nodes and minimal water volumes dispersed in leakages (Araujo et al. 2006; Walsky et al. 2006; Prescott and Ulanicki 2008; Xu et al. 2014; Dai and Li 2016). Hydro Power Plants (HPP) represents a good alternative to PRV, reducing pressure and enhancing the energy efficiency of the water systems (Punys et al. 2011; McNabola et al. 2011; Gaius-obaseki 2010; Ramos et al. 2010; Carravetta et al. 2012). A new strategy is now available (Fecarotta et al. 2014; Carravetta et al. 2014a, 2014b; Fecarotta et al. 2016) for the design HPP using pump as turbines (PAT), in the presence of variable operating conditions, i.e. daily variations of user demand, flow rate and available head.

In a cost optimization analysis of desalination plants the influence of the water supply to WSN has never been considered. This problem will be treated here with reference to a hypothetical change of the water supply of the Oreto-Stazione sub-network in the city of Palermo (Italy), by means of a new desalination plant. Different scenarios will be analyzed to reduce all costs connected with water treatment and supply to the network. Among the different options, a time dependent operation of desalination, a combined or alternate use of RO and PRO operations, and the use of micro hydro power generation at the WSN inlet have been considered in the paper. The RO desalination plant under optimal time-dependent operation was already analyzed by Ghobeity and Mitsos (2010), and these results have been used in the different scenarios considered in the paper. A further scenario has been newly proposed for direct WSN supply from the RO plant. Concerning renewables, Oreto-Stazione HPP was analyzed in Carravetta et al. (2014c), while the use of PRO and RO-PRO power plant in an integrated approach to cost optimization analysis has been newly proposed herein on the basis of RO plant parameters (number and membrane type, salt water density). The importance of an integrated approach will be fully demonstrated by means of economic comparisons among the different options.

2 Literature

2.1 Theory of Osmotic Processes for RO and PRO Operations

In the desalination process, three liquid streams are involved: the supply seawater, the brackish water, and the high concentration brine by-product. In seawater RO, Fig. 1a, the supply seawater is drawn from oceanic or underground sources and it is pressurized at 80–90 bar into a closed vessel against the membrane by a Seawater Pumping System (SPS). Next, as an effect of the desalination process the supply seawater is separated into two output streams: the brackish water and the high concentration brine.

The Kimura–Sourirajan model (Kimura and Sourirajan 1967) is commonly used to describe the transport phenomena of solute and water through each membrane in the vessel. According to the model the pure water flux across the membrane, J_w (kg/m^2/s), and the salt flux, J_s (kg/m^2/s), are given by the following equations:

$$J_w = A[\Delta p - \Delta\pi] \tag{1}$$

$$J_s = B\left(C_w - C_p\right) \tag{2}$$

$$V_w = \frac{J_w - J_s}{\rho_p} \tag{3}$$

$$C_p = \frac{J_s}{V_w} \cdot 10^3 \tag{4}$$

where $\Delta p = (p_{sw} - p_p - \Delta p_f/2)$ and $\Delta\pi = -(\pi_w - \pi_p)$; p_{sw}, $p_{p.}$ (MPa) denote the feed pressure and the permeate pressure, respectively; Δp_f is the pressure drop in the membrane channel; π_w (MPa) is the osmotic pressure of the brine at the membrane wall concentration C_w (ppm); π_P and C_P are the corresponding variables for the permeate; ρ_P denotes the density of the permeate; V_w (m/s) is the permeate velocity, A and B parameters given by membrane industry. Reverse osmosis is possible for $\Delta p > \Delta\pi$. It is useful to observe that in order to maximize the pure water flux the permeate pressure is generally set to zero.

The brine flow rate remainders can pass through an Energy Recovery Device (ERD), and then they are discarded, obtaining a significantly lower specific energy cost, when compared to desalting in the absence of energy recovery (Zhu et al. 2009): e.g. a 40 % lower specific energy consumption, for a recovery ratio $Y = 0.5$ and ERD efficiencies of 80 %.

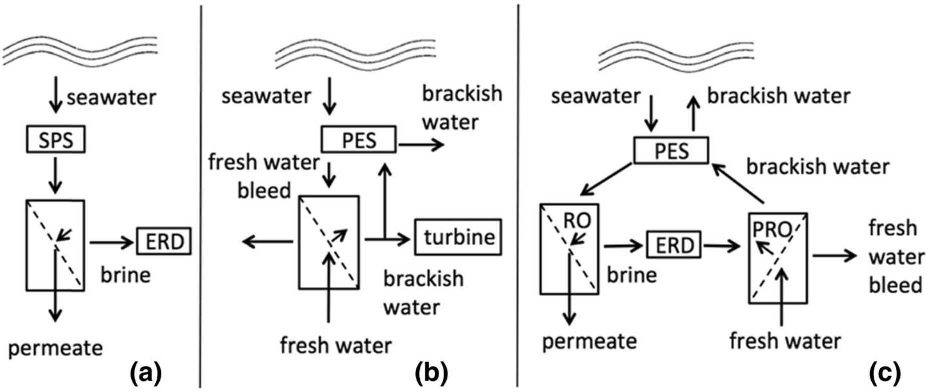


Fig. 1 Osmotic processes in: **a** RO, **b** PRO, **c** RO-PRO

A two or three stage osmotic plant could be more effective than a single stage plant. Equations and mathematical algorithms for the design of a two stage RO have been given, among others, by Marcovecchio et al. (2005). The problem of the design of a multistage reverse desalination plant, for different feed concentrations and product specifications, has been studied by Lu et al. (2007). For feed concentrations between 38,000 and 48,000 ppm a single stage plant is the optimal choice with a product concentration ranging between 300 and 380 ppm, and a unit product cost varying between 0.52 and 0.57 $/m^3.

The process of pumping feeding water to the pressure required at the inlet of the vessel, ranging between 65 and 80 bar, is very energy-consuming, representing 70 % of the operating cost, and 33 % of the total production cost (Akgul et al. 2008). In the presence of a daily variability of electricity prices in Southern Italy, Ghobeity and Mitsos (2010) have demonstrated that the saving potentials of both electricity and plant costs are significant (10.6 and 5.0 %, respectively) by allowing the system to remain idle during high electricity cost hours. By oversizing the desalination plants and increasing the shut off period, the operation cost saving increases by up to 32 %, but the cost-saving potential reduces to 4.4 % due to the increment of the plant cost.

2.2 Pressure Retarded Osmosis (PRO)

In PRO fresh water is pumped into the vessel and a permeate flux is obtained across the membrane to increase the pressure of the seawater. A scheme of the plant in PRO mode is shown in Fig. 1b (Thorsen and Holt 2009).

In PRO $\Delta p < \Delta\pi$, according to Eq. (1), the water from a low salinity feed solution permeates through a membrane into a pressurized, high salinity draw solution, giving rise to a positive pressure drop. The specific power for a PRO plant is given by:

$$P = J_w \Delta p = A(\Delta\pi - \Delta p)\Delta p \tag{5}$$

for the parabolic dependence of P on Δp the maximum of the specific power, P_0, is obtained for $\Delta p = \Delta\pi/2$. Therefore, the PRO process requires a much lower pressure than RO, close to one half of the osmotic pressure of the high salinity permeate. Energy is obtained by depressurizing the permeate water through a hydro-turbine and brackish water is discharged. A fraction of the brackish water is conveyed to a Pressure Exchange System (PES) to transfer its residual energy to the seawater feed.

The efficiency of a PRO plant is expressed by:

$$\eta_E = \frac{P_E - P_{Ep}}{P_0} = \frac{P_0 \eta_V \eta_T \eta_G - P_{Ep}}{P_0} \tag{6}$$

P_0 being the available power at the turbine, η_T and η_G the efficiency of the turbine and of the generator, respectively, and η_V the efficiency of the osmotic process for pressures differing from the optimal value:

$$\eta_V = \frac{p_{SW}}{\pi_{SW}} \tag{7}$$

where P_{Ep} are all parasite powers of the process, such as in the pumps used to achieve the pressure drops on the sea water side and on the fresh water side of the membrane, or in the Pressure Exchange System (PES).

2.3 A Combined RO-PRO System

Recently a combined use of RO and PRO subunits has been proposed to reduce the energy use connected to desalination. A scheme of a RO-PRO system is shown in Fig. 1c (Prante et al. 2014). The concentrated brine stream at the exit of the RO subunit is first depressurized to approximately half of its pressure (e.g. from 700 to 350 psi), to reach a suitable pressure for the PRO process. This energy can be recovered in an Energy Recovery Device (ERD). Following depressurization, the brine stream enters the PRO subunit as a high salinity solution.

2.4 Pressure Control and Energy Recovery in WSN

The pressure control in a WSN is based on the dissipation of the excess energy of water by PRV or on energy recovery by an hydro power plant equipped with a PAT. In the presence of variable working conditions, the HPP requires an appropriate control system (Fig. 2a). The WSN operating conditions have to be compared with the characteristic PAT curve (Fig. 2b). For an available head, ΔH^d, higher than the head-drop deliverable by the PAT, ΔH^t, the series valve dissipates the excess pressure. Instead, when the discharge is larger, the PAT produces a head-drop higher than the available head: in this case the bypass is opened to reduce the discharge flowing into the PAT. Power plant design can be performed by an ad hoc procedure, named the variable operating strategy, with a number of straightforward item rules determining the size and rotational speed selection of the PAT for given flow-head distribution patterns and network backpressures, ensuring quite high efficiency values (Carravetta et al. 2014a, 2014c).

3 Methodology

3.1 WSN Case

The water supply network of a district area named Oreto-Stazione, part of the larger water distribution network of Palermo, Italy, has been selected as a case study (Fig. 3a).

This network has been designed to supply approximately 0.4 m^3/capita/day, with pipe diameters in the range of 110–225 mm, with a consumption of 0.26 m^3/capita/day (De Marchis et al. 2011). The water supply is granted by a reservoir, located at an altitude of 88.5 m, through one cast-iron pipeline with a diameter of 500 mm and a length of 2300 m. To avoid dangerous pressures and limit the water leakage, a PRV that reduces the upstream head at a

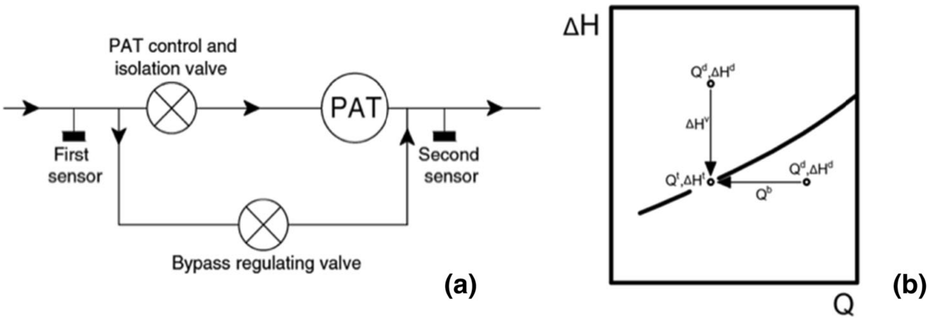


Fig. 2 Hydraulic scheme of a WSN hydropower plant and its working conditions

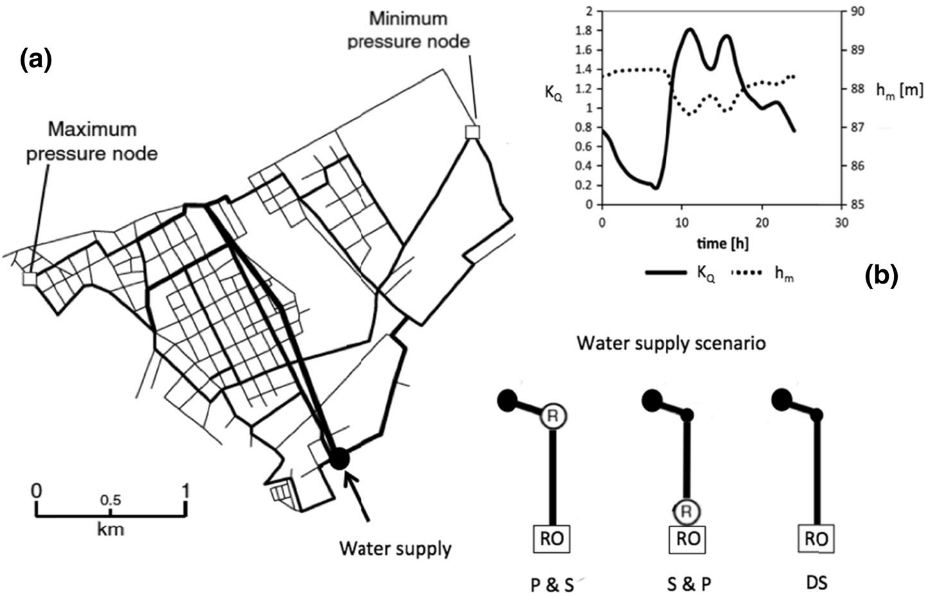


Fig. 3 Oreto-Stazione WSN and water supply scenarios

pressure value $h_v = 55$ m is installed at the water supply node, located at the end of the cast iron pipeline pipe.

Water demand is highly variable during the day with a peak coefficient (ratio between maximum and average discharge), K_Q, as high as 1.8, according to Fig. 3b. As an effect of flow resistances in the cast iron transmission pipeline, the PRV inlet head, h_m, is largest during the night and reduces in the hours of high water demand.

Within the framework of a change in the WSN water resource supply, different scenarios can be analyzed, as reported in Fig. 3b. Water from the desalination plant, close to the coastline, could be pumped into the existing reservoir (P & S, Pump and Store), or the water could be stored at the exit of the RO plant and pumped directly into the network (S & P, Store and Pump), or, finally, water could be injected directly into the WSN (DS, Direct Supply). In the pump and store scenario through the realization of an HPP a large proportion of the water excess energy can be recovered.

3.2 Desalination Plant

Ghobeity and Mitsos (2010) optimal RO design was adopted for the Oreto-Stazione fresh water production by scaling plant size to the WSN water demand. The following RO operation case studies were identified:

- variable operation with idling period not allowed (CS1),
- variable operation with idling period allowed once per day (CS2),
- variable operation in an oversized plant with idling period allowed once per day (CS3),
- variable operation in an oversized plant with direct WSN supply (CS4).

Fresh water productions corresponding to CS2 and CS3, WSN water demand and electricity price distributions are plotted in Fig. 4a, b).

In case CS4 the RO plant was connected directly to the WSN at the PAT node and the RO fresh water production is equal to the WSN water demand. In this case, corresponding to the DS scenario of Fig. 3a, the RO plant has to be oversized to meet the peak in the water demand. During the day, for flow rates smaller than the peak value, different groups of vessels are shut off, and the fresh water demand is satisfied by an SPS pump speed variation in the range 45–55 Hz. The flow rate distribution and the number of operating vessel distribution are plotted in Fig. 5a, b.

3.3 Alternate RO-PRO Operation

Considering that, in cases CS2 and CS3, all the vessels of the RO plant are idling during the hours of higher energy cost, a viable solution could be to use the desalination plant in PRO mode during the RO shut off period (Thorsen and Holt 2009). A drawback of the alternate use of the plant in RO and PRO mode is the limited power that can be extracted in the PRO with industrial RO membranes. Many studies in literature indicate that the PRO potentiality will be enhanced by the design of specific industrial membranes reducing the effects of internal concentration polarization (Kim et al. 2015). To account for the low efficiency of the industrial RO membranes a low permeate flux value J_w = 0.33 m^3/(m^2 day) was assumed. Based on the membrane parameters (Ghobeity and Mitsos 2010), a 43.5 kW plant size was obtained, corresponding to a specific power of 0.57 W/m^2. The following efficiency values were considered in the design: η_P = 0.9; η_T = 0.92; and η_G = 0.98. A value of 0.375 was found for the efficiency of the osmotic process, assuming a pressure at the exit of the PES of 9 bar. Finally, all parasite powers were estimated at 10 % of the available power of the turbine $\eta_V = 0.10 P_0 \eta_V$. By adopting Loeb (1998) PRO plant configuration, no appreciable additional component cost is necessary. The calculations were limited only to the only CS3 case on account of the larger extension of the RO idling period. Economical advantage is expected only in the presence of a

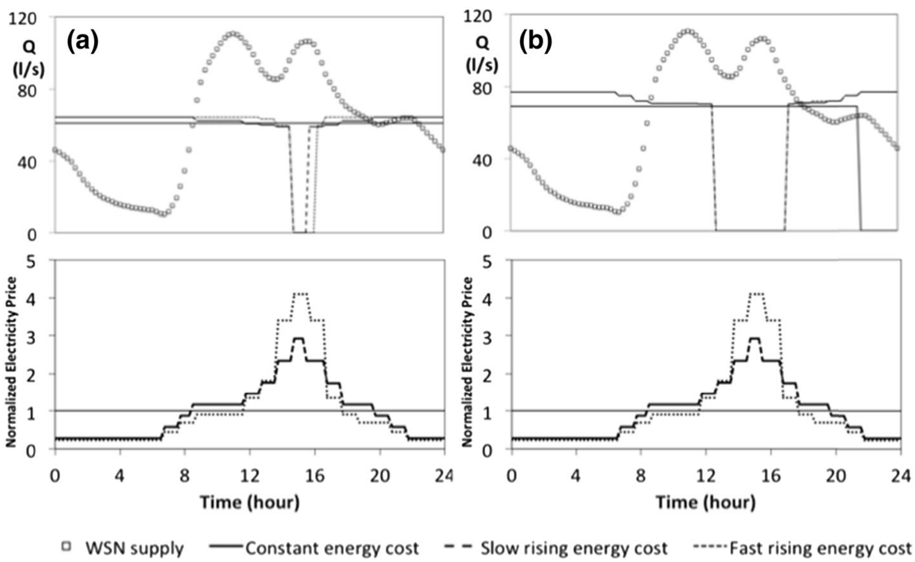


Fig. 4 Fresh water production in RO operation cases CS2 **a** and CS3 **b**

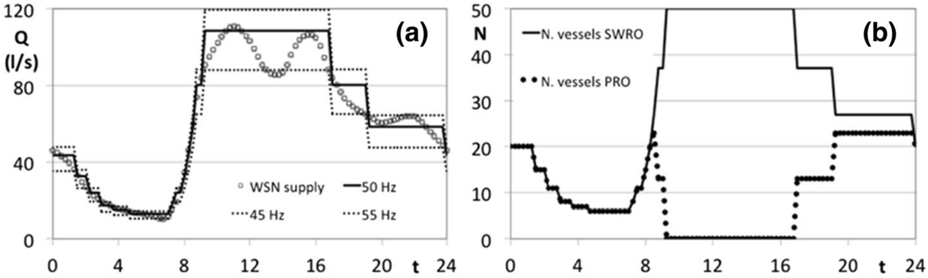


Fig. 5 Fresh water production and operating vessels in case CS4

PRO fresh feeding water of lower quality to be used for the energy production. In the case of the Oreto-Stazione network the PRO fresh feeding could come from the Risalaimi depuration plant, or from low quality underground waters.

3.4 Combined RO-PRO Operation

In the case of the WSN supply by direct supply (DS), a variable number of vessels are idling. The energy recovery is therefore possible by the combined use of RO and PRO subunits, with vessels not necessary for fresh water production being used for energy production, as plotted in Fig. 5b. The energy recovery rate is variable during the day, depending on the number of vessels in operation in the PRO mode. According to Prante et al. (2014), by using the same number of membranes in parallel for the RO and PRO, and with an RO recovery ratio of 0.4, the PRO energy recovery attains a value of 0.5 kWh/m^3. An additional cost of 50 k$ was considered for the installation of additional control valves. RO-PRO was analyzed for the only the CS4 case representing the most advanced possible configuration (Reimund et al. 2015).

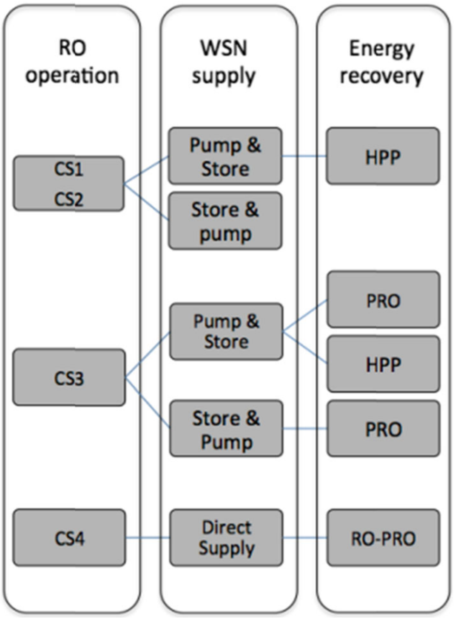
3.5 Hydropower Generation and Pressure Control

A variable operating strategy was applied for the design of a hydropower plant. To obtain the best pressure distribution in the network, the HPP control system (Fig. 2a) was set to satisfy the pressure constraints in all the branches of the network. By simulating the network with EPANET (Rossman 2000) the nodes of the minimum and the maximum pressures were identified. The HPP design was performed to obtain the best PAT effectiveness satisfying the required minimum and maximum pressure constraints (further details on the Oreto Stazione HPP design can be found in Carravetta et al. 2014c). The design solution was a Caprari centrifugal PAT producing energy of 282.92 kWh/day out of a potential of 592.49 kWh/day. The h_v values at the PAT node were found to be variable between 46.2 m and 46.5 m.

4 Case Studies

A number of different cases can be built up considering different combinations of the RO operation schedule, WSN supply conditions, and energy recovery by renewables (HPP, PRO, or RO-PRO), reported in Fig. 6.

Fig. 6 Analyzed case studies



4.1 Pump and Store (P & S)

In this case the fresh water at the exit of the RO plant is pumped to the reservoir, located at an altitude of 88.5 m. Storage capacity is used to compensate the difference between the RO production and the water demand, Fig. 1a-c. The calculated values of storage capacities were found to be variable between 1154 m^3 (for case CS1 and constant electricity price distribution) and 1988 m^3 (for case CS3 and fast rising electricity price distribution). A unit cost for the tank construction of 500 $\$/m^3$ was considered. The efficiency of the pumping station was set at $\eta_{ps} = 0.85$. This value is quite high but consistent with the efficiency of the high pressure pump of the desalination plant assumed by Ghobeity and Mitsos (2010). The pump size for different electricity price distributions was determined on the basis of the peak flow rate. The calculated values of pump power, PPS, were found to be variable between 62 kW (for case CS1 and constant electricity price distribution) and 98 kW (for case CS3 and fast rising electricity price distribution). Pumping station costs were evaluated on the basis of the standard cost for waterworks in Italy by:

$$C = 1319.8P_{ps} + 39594 \tag{8}$$

4.2 Store and Pump (S & P)

A second supply methodology is based on the presence of a storage tank at the exit of the RO and the use of a pumping system connected to the WSN. The required pressure head is set at $h_v(t)$. A variable frequency driver is used to control the pumping operation granting the pressure head point set. No difference in storage tank dimensions and cost is present between the S & P and P & S. The efficiency of the pumping station was reduced to $\eta_{sp} = 0.80$ accounting for the efficiency reduction at the lower pump speed. The pump size was determined on the basis of the maximum RO permeate flow rate, namely 55 kW, 72 kW and 77 kW, for cases CS1, CS2 and CS3, respectively. The pumping station costs were evaluated by Eq. (8).

4.3 Direct Supply (DS)

The final way to supply the fresh water to the network is represented by a direct supply of RO fresh water to the network. In this case the permeate pressure head at the outlet of the vessels is set at $h_v(t)$, granting optimal pressure values in the network. According to Eq. (1) the fresh water flux per unit surface of the membrane is reduced of 10.6 % for the highest pressure of the permeate, with an h_v set point of 46.5 m. The number of membranes was increased to 400 to obtain the peak flow rate for the corresponding fresh water flux. The RO plant for direct supply corresponds to a capacity of 9572 m^3/d. The RO operation is performed by switching off the vessels that are not required and by varying slightly the SPS regulation to obtain the WSN pressure head at the exit of the RO plant.

5 Results and Discussion

Production and energy costs for all scenarios have been calculated. The RO investment, maintenance, and energy costs have been evaluated using a general production cost breakdown from the literature (Akgul et al. 2008): 0.24 \$/ m^3 for the investment cost, 0.27 \$/ m^3 for the maintenance cost, 0.19 \$/m^3 for the energy cost. Maintenance takes into account all the aspects of RO operations like the substitution of exhausted membranes and the fast decay of components operating with salt water.

The feasible life of the systems was assumed to be 15 years and capital costs were calculated for the first 5 years. The capital costs of the designed systems were calculated using a combined interest rate of 8 % and a 5-year bank credit. The calculated costs for case study CS1, pump and store, and HPP with constant electricity price (the reference case) are given in Table 1. Based on a recent analysis of energy tariff for many countries (Fecarotta et al. 2014) an average energetic cost of 0.08 \$/kWh has been fixed both for energy selling or purchasing. The RO cost is approximately 85 % of the total, and that the reservoir cost is as large as 10 % of the total.

The energy and production costs reported in Table 1 were used as comparative values to calculate the percentage differences of all the others scenarios of Fig. 6, where positive

Table 1 Calculated costs for the reference case

Cost	[k\$]	[\$/m^3]	%
RO investment	461	0.24	40.2
RO maintenance	161	0.08	14.0
RO energy	358	0.16	31.2
WSN reservoir	106	0.06	9.3
WSN pumps	22	0.01	2.0
HPP	28	0.00	0.2
WSN energy	35	0.08	3.1
Total	1147	0.60	

(negative) differences show savings (overcharges) compared to the reference case. In Table 2 the energy cost savings are given for all the other cases.

Plant energy cost is an important element in plant choice, representing 31 % of the total cost. Energy cost–savings come out from a combination of factors: the cost of fresh water production (RO or RO-PRO), the cost of pumping, and the income from renewable production (HPP and PRO). For any electricity price distribution a specific combination of RO operation, WSN supply mode and renewable power plant system gives the maximum energy cost savings. In particular, for constant and slow rising electricity prices the best choice is represented by the direct supply of the WSN (case CS4). Case CS3, i.e. fresh production with idling periods, water pumping to an elevated tank and HPP production, is the best choice for fast rising electricity prices. Considering only cases CS1 and CS2, not requiring any power plant oversizing, the best solution is represented by the RO operation with idling periods, and store and pump to the WSN for constant energy prices, while for variable energy prices the best solution is the same RO operation but with pumping to the storage tank and HPP energy production.

When all production costs are considered, the conclusions may change, as reported in Table 2. Obviously the presence of an existing reservoir at the exit of the RO plant or an existing WSN elevated tank could be an important factor in the selection of the best design solution. Case CS4 is never an advantageous solution due to the high cost of the oversized RO plant with a maximum fresh water production equal to the peak WSN demand. The benefit of the combined RO-PRO operation is not sufficient to overcome the higher plant cost. Storage at the exit of the desalination plant and direct pumping is a very favorable solution for constant and slow rising electricity prices. Pump and storage with the CS2 RO operation is the best solution for fast rising energy prices.

Table 2 Energy and production cost saving [%]

	Energy cost saving [%]			Production cost savings [%] (No renewables)		
	P & S	S & P	DS	P & S	S & P	DS
Saving with constant electricity price						
CS1	0.0	2.7		0.0 (−0.5)	1.6	
CS2	0.0	2.7		0.0 (−0.5)	1.6	
CS3	1.7	4.5		−12.5 (−12.9)	−10.7 (−10.7)	
CS4			56.5			−14.3
Saving with slow rising electricity price						
CS1	4.1	4.2		0.8 (0.0)	1.6	
CS2	8.8	8.1		2.1 (1.3)	2.6	
CS3	33.4	30.3		−3.7 (−4.9)	−3.7 (−4.2)	
CS4			41.0			−19.6
Saving with fast rising electricity price						
CS1	4.9	4.3		1.0 (0.2)	1.6	
CS2	16.9	14.2		4.8 (4.0)	4.7	
CS3	52.5	46.9		2.9 (0.6)	2.0	
CS4			36.3			−21.2

Finally production cost savings without renewables are reported in brackets in Table 2. The effect of the renewable power plant (HPP, PRO) on production costs is really small in the presence of a constant electricity price or slow rising electricity price distribution. These energy sources are relevant in the presence of fast rising electricity price distribution where a substantial variation of the total production cost is observed if the use of HPP and PRO is not considered. The contribution of the renewables to the production cost savings can be as high as 79 % (CS3 RO operation, pump and store, combined RO-PRO and HPP production).

6 Conclusions

In a desalination plant for the fresh water supply to an existing distribution network, the cost of the RO plant is approximately 85 % of the total, and the cost of the storage tank and of water pumping to the network covers the remaining 15 %. Therefore, the research into an optimal configuration of all these three components could produce appreciable savings. Two factors seem to be the more influential in the design choice: the daily distribution of electricity prices, and the location of the storage tank. In the presence of an hour variability of electricity prices a variable operation of the RO plant seems the best opportunity. Pumping to an elevated storage plant is the best solution in the case of a fast rising electricity price curve. The economic advantage of this solution is granted by the use of renewable energy production systems: a PRO plant working in the idling periods of the RO; and a hydro power plant using the excess pressure at the inlet of the water supply network. In contrast storage at the exit of the RO plant and direct pumping in the network is the best solution for constant electricity prices.

An advanced solution based on a combined RO-PRO plant with direct pumping in the network without storage has been explored. This solution grants up to 56 % of energy savings, but was found to be between 14 and 21 % more expensive than the traditional solution for the necessity of oversizing the desalination plant to face the larger fresh water production in the hours of peak demand and a higher permeate pressure at the exit of the desalination plant.

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