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Distributed generation and water production: A study for a region in central Italy

Gabriele Comodi[a]*, Luca Cioccolanti[a], Stefano Palpacelli[b], Alberto Tazioli[b], Torquato Nanni[b]

[a]Dipartimento di Energetica, [b]Dipartimento di Fisica e Ingegneria dei Materiali e del Territorio, Università Politecnica delle Marche, via Brecce Bianche, 60131 Ancona, Italy
Tel. +39 (071) 220-4761; Fax +39 (071) 220-4770; email: g.comodi@univpm.it

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ABSTRACT

This study examines the use of distributed power plants coupled to desalination systems to achieve combined production of electrical energy and of water for drinking and similar purposes in Marches, an Adriatic region in central Italy. To reduce Marches' large electricity deficit, the regional government has drawn up an environmental and energy plan promoting distributed generation through power plants built right where the electricity is consumed. At the same time, the region's abundant water resources are increasingly threatened by aquifer pollution, due particularly to fertilizers and to the phenomenon of saltwater intrusion near the coast. Distributed electrical energy generation combined with water production can help meet the goal of reducing the electrical deficit while at the same time improving ground-water quality and reducing the hydrogeological risk. The solution is also efficient, since the more the useful heat recovered by the energy system, the higher its global efficiency. Furthermore, coupling power plants to desalination units is also an excellent application of cogeneration systems, allowing useful recovery of thermal energy in the summer. The study examines different sized plants for the distributed generation of water and power in Marches, from small units to thermal desalination systems that can be coupled to existing power plants. It shows that although endowing existing large power plants with MED (multiple effect distillation) units makes it possible to meet 58% of the freshwater demand in Marches, it further increases the electricity deficit, whereas coupling small or medium-sized distributed power plants to reverse osmosis systems allows meeting 75% of the demand for freshwater and reduces the electrical energy demand by up to 50% in the more energy-intensive districts.

Keywords: Distributed generation; Cogeneration; Groundwater quality; Thermal desalination; Reverse osmosis

1. Introduction

The signatories of the United Nations Framework Convention on Climate Change (UNFCCC) agreed to reduce total emissions by at least 5% of 1990 levels over 2008–2012. In particular, the European Commission and Parliament approved directives on efficient energy use and renewable energies, setting emissions targets for member states. The Italian legislation [1] requires from each region to draw up an energy plan describing current

* Corresponding author.

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circumstances and prospects. The environmental and energy plan of Marches [2], an Adriatic region in central Italy, sets regional targets for energy efficiency, power generation capacity and production from renewables and highlights a large electrical energy deficit, stressing the need and stating the means for reducing it.

In particular, the deficit reduction is to be achieved in the medium term by building multiple medium-sized distributed power plants rather than fewer large ones. The choice of distributed generation rests on a number of benefits, in particular: (i) reduction of electrical transmission losses (4–6%); (ii) readier acceptance by local communities; and (iii) high potential for thermal energy recovery, especially in the region's numerous industrial districts.

However the latter option, known as distributed cogeneration, has several limitations related to "useful" heat recovery. In fact, while thermal energy is easily recovered and used for heating purposes in the winter, it is harder to recover in the warm season. Now, the recent development of absorption chiller units makes it possible to overcome this problem by producing cooling energy in trigeneration systems.

The present work explores the scope for recovering the thermal energy discharged by distributed power plants to desalt water throughout the year, but especially in the summer. In fact, freshwater demand increases in this season, when less water is available and the demand for electrical energy is higher. In addition the water resources of Marches, though abundant, are increasingly threatened by aquifer pollution, due particularly to fertilizers and to the phenomenon of saltwater intrusion near the coast. Therefore, coupling thermal power plants to desalination units can both reduce aquifer stress and improve ground-water quality. The aquifers of Marches have different characteristics depending on location: inland areas have cracked and fractured carbonate aquifers with abundant water; hilly areas have porous aquifers where good quality water is often scarce; finally, coastal aquifers are in river floodplains, where water is often abundant but frequently polluted by farming and industrial activities and by saltwater intrusion.

After providing an overview of the demand and supply of electrical energy and water in Marches, the paper explores the scope for meeting the demand for both through desalination units coupled to medium-sized electrical power plants. In particular, it investigates the possibility of adding thermal desalination units to existing power plants (two combined cycles power plants and a gas turbine plant) and of coupling distributed small or medium-sized power plants to reverse osmosis (RO) units. In the latter case, the thermal energy output can be recovered to reduce feedwater dynamic viscosity in RO plants; according to [3] a 1°C increase in feedwater temperature involves an increase of freshwater production of about 3%.

2. Energy

In Marches electricity is delivered to final users through a grid with only three primary and 62 secondary distribution stations. This infrastructure is characterized by geographical and seasonal criticalities, due especially to electrical peak loads occurring in coastal areas in the summer. In addition, old and undersized networks in some areas are prone to seasonal congestion and power breakdowns. For these reasons, the national grid company is planning to improve grid infrastructure by building new primary stations [4]. According to the energy plan of Marches, local energy production could lighten the electrical load burden on the grid. Fig. 1 shows current high voltage (HV) and extra high voltage (EHV) network lines in Marche.

Marches has a large energy deficit and imports significant amounts from the neighboring regions. In 2008, its electrical energy demand was about 7956 GWh and total internal production was about 4049 GWh, with a gap of 3907 GWh [5].

Table 1 shows the electrical energy balance of Marches in 2000–2008.

The diagram in Fig. 2 reports the demand and supply figures from 1973 to 2008.

Energy production in Marches increased significantly in 2001–2004 thanks to a 104 MW gas turbine (GT) power plant based on a simple Brayton cycle and two new power plants, a 280 MW integrated gasification combined cycle (IGCC) plant built in an oil refinery and a 150 MW cogeneration combined cycle (CCC) plant near a sugar refinery. Nevertheless, supply still meets only about half of the demand. The gap could be bridged by internal produc-

Table 1
Electrical energy balance of Marches (2000–2008)

	2000	2001	2002	2003	2004	2005	2006	2007	2008
Demand (GWh)	7,000	6,625	6,818	7,740	8,083	8,133	8,339	8,341	7,956
Supply (GWh)	1,226	2,464	3,136	3,222	4,142	4,105	3,936	3,791	4,049
Deficit (GWh)	5,774	4,161	3,682	4,518	3,941	4,028	4,403	4,550	3,907
Deficit (%)	82	63	54	58	49	50	53	55	49

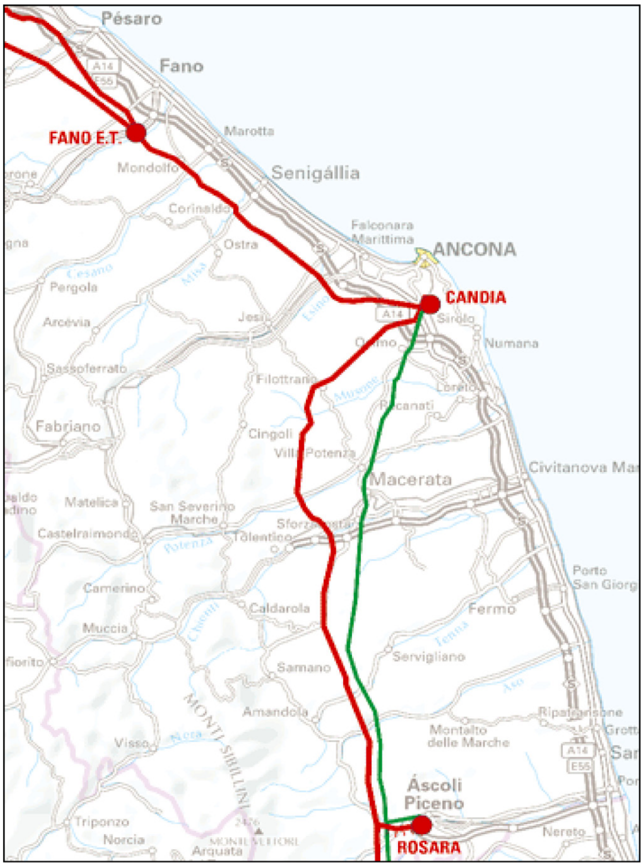

Fig. 1. HV and EHV network lines.

tion of an additional 550 MWe by one or two large plants operating about 8000 h/y.

The environmental and energy plan subdivides Marches into 26 areas, of which 11, hosting the main industrial districts, have very high energy consumption; in particular, 36% of the municipalities (shown in Fig. 3) consume 63% of the energy. The three existing power plants are located in districts 2 and 6.

As mentioned above, in summer the demand for electricity and water rises steeply in coastal areas, due to tourist flows. This work therefore focuses on the coastal districts; districts 4 and 6 are included in the analysis because they are under the same water authority as the three large thermal power plants. In fact, one of the aims of this study is to evaluate the scope for coupling these power plants to thermal desalination units, to meet the water demand of the water authority managing districts 2, 4 and 6. Table 2 reports the electrical energy demand by the main consumption sectors and the main town of each district.

These data show that there are several areas where distributed power plants could be installed to meet the local energy demand and at the same time reduce the electrical deficit of Marches. Of the main benefits of distributed generation mentioned above, i.e. reduction of electrical transportation losses; readier acceptance by local communities (compared with a large plant) and reduction of nimbyism; and greater overall system efficiency, the last is currently the most critical in Marches. In fact, distributed cogeneration is feasible only if the thermal energy

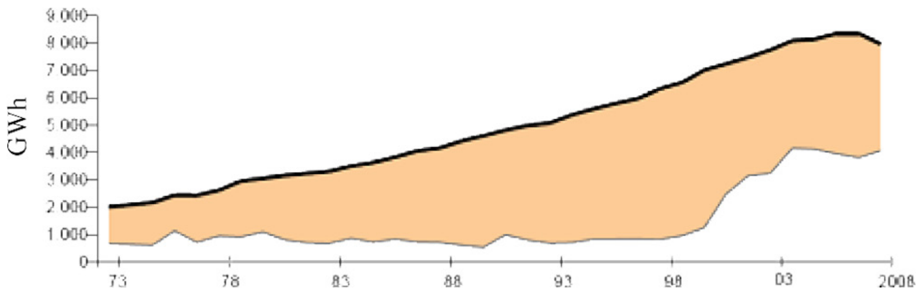

Fig. 2. Energy demand and supply in Marches from 1973 to 2008 [5].

Table 2
Electricity consumption in the main towns of the districts of interest (2007)

District (main town)	2 (Ancona)	3 (Fano)	3 (Pesaro)	4 (Fabriano)	5 (San Benedetto del Tronto)	6 (Jesi)	7 (Senigallia)	9 (Civitanova Marche)
Population	100,507	57,529	91,086	30,019	45,054	39,224	41,550	38,299
Agriculture (MWh)	1,808	3,007	1,177	527	928	2,077	1,095	1,178
Households (MWh)	105,649	68,419	104,128	30,509	51,243	42,254	48,478	44,784
Industry (MWh)	81,505	104,848	127,663	106,551	29,438	92,804	32,279	67,896
Tertiary (MWh)	240,786	90,252	148,189	52,426	106,469	68,196	72,569	75,878
Total (MWh)	429,748	266,526	381,157	190,013	188,078	205,331	154,421	189,736

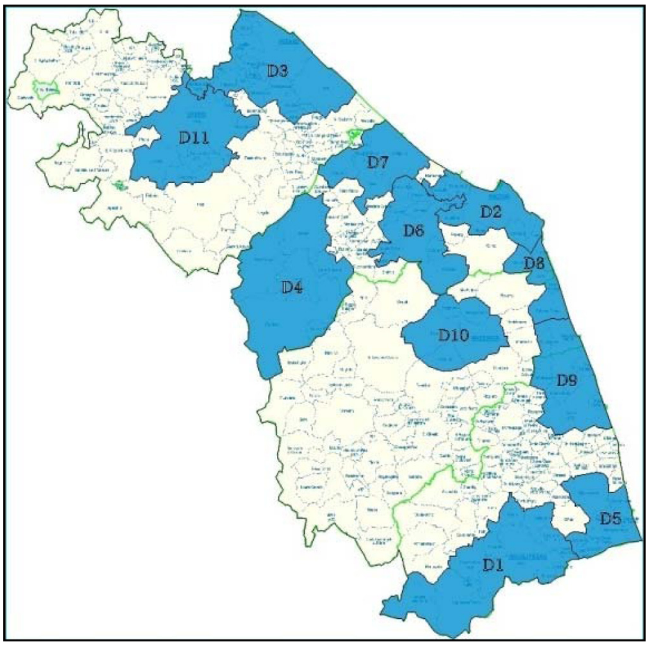

Fig. 3. Position of the more energy-intensive districts (in blue).

discharged by power plants is usefully recovered. The main application of distributed cogeneration is district heating, but this is not very profitable in Marches, due to the short duration of the cold season [6]. Other potential applications are industrial districts or large service sector users, e.g. shopping malls, cinemas, office blocks. In these cases the thermal energy is commonly recovered for industrial processes or in trigeneration applications (heating in winter and cooling in summer, thanks to absorption chillers). However, Marches is characterized by a large number of small and medium-sized enterprises (SME), entailing limited thermal energy use for industrial processes. Although cogeneration and trigeneration applications have recently increased, their size, usually <1 MWe, means that they contribute little to reducing the electrical energy deficit.

In this work we suggest that the goal of distributed (co)generation could be met by using the thermal output of power plants to desalt water; this solution would both make cogeneration profitable and also increase the freshwater supply. In particular, thermal energy could be applied to reduce water dynamic viscosity in RO plants, or to help water evaporation in thermal desalination plants, depending on inlet water salinity and plant scale.

3. Water

The alluvial aquifers of river floodplains are a major source of water in Marches. This is due to a number of factors including relatively low drawing costs, acceptable quality and large amounts of available water. In addition, the proximity of several settlements makes such aquifers crucial for the Region's economy. Indeed about 142×10^6 m^3 of water a year are extracted for domestic, farming, and industrial use, according to data from public and private companies. However, the actual figure is probably higher, given the lack of reliable data regarding consumption for industrial and irrigation use and rough private consumption figures. Although these resources are vital, few alluvial aquifers have been thoroughly investigated. Table 3 shows a rough estimate of water consumption in the districts included in the study and the main town in each district.

3.1. Groundwater situation

A phreatimetric aquifer survey [7] identified three zones with distinctive characteristics: the upper part of alluvial aquifers; the areas of flood terraces, and the lower terraced deposits, usually the largest and most important zones. In mountain areas the alluvial deposits are neither large nor thick. The phreatic line is conditioned by a single underground drainage direction, sometimes coinciding with the current river line. The water flows in the direction of the river and the paleothalwegs. There is an intense exchange between ground-water and river.

Table 3
Rough estimate of water consumption in the main towns of the districts of interest

District (main town)	2 (Ancona)	3 (Fano)	3 (Pesaro)	4 (Fabriano)	5 (San Benedetto del Tronto)	6 (Jesi)	7 (Senigallia)	9 (Civitanova Marche)	Total (Marches)
Population	100,507	57,529	91,086	30,019	45,054	39,224	41,550	38,299	1,552,968
Average daily per capita water consumption in Marches (l/d)	252	252	252	252	252	252	252	252	252
Average yearly water consumption (m^3/y)	9,244,634	5,291,517	8,378,090	2,761,148	4,144,067	3,607,824	3,821,769	3,522,742	142,841,997

In the high terraces, usually limited at the right, the phreatimetric line pattern is roughly parallel to the edges of the floodplain and to the riverbed, and reflects the surface morphology. The flow is directed by the limits of flooding to the lower terraces. Gradient is generally high and rarely identifies preferential and well-marked flow lines. In areas occupied by low terraces phreatimetric lines have a more complex evolution, with strong differences between river basins. Near the coast the gradient ranges from 0.002 to 0.0057. The greater phreatimetry complexity is due to lithological variations in the alluvial complex, substrate morphology, uptake of groundwater and infiltration of surface water from the riverbeds of the tributaries. Again, the general direction of the flow is from high terraces to riverbed, however, conditioned by well-marked flow directions and persistent throughout the year. Another phreatimetric pattern is found close to the shore, where the phreatimetric lines, though still influenced by the preferential flow directions, tend to arrange themselves parallel to the coast. The differences, based on the phreatimetric trend, remain constant (Fig. 4) during the year. Important seasonal changes occur only at the bottom of the aquifer and along the coastline. This is mainly due to heavy ground-water pumping in the summer. Moderate to severe aquifer pollution due to saltwater intrusion into coastal wells affects not only Marches, but also other alluvial plains in Italy, causing a reflux of brackish water into the coastal zone due to the lowering of phreatic surfaces induced by extreme drainage of wells. In particular in Marches values of electrical conductivity up to 10,000 μS·cm^{-1} are often observed, as shown in Table 4. The final tract of all coastline aquifers (up to 3–4 km from the coast) is characterized by saltwater and brackish water. The alluvial aquifers of the floodplain of rivers Musone, Esino and Aspio contain sodium chloride groundwater with a strong magnesium content; such waters are related to rising brackish waters which are found in Lower Pliocene turbidite sequences. Parts of the aquifers with greater electrical conductivity also contain calcium-bicarbonate waters, sodium and magnesiac chloride waters, calcium and magnesiac chloride waters at a high saline concentration, up to 17 g·l^{-1}. The areas characterized by low electrical conductivity (i.e. 500–900 μS·cm^{-1}) have calcium-bicarbonatic waters. These areas are characterized by drainage of surface waters and are mainly located in the upper part of the alluvial aquifers and in mountain areas. The water of the alluvial plains is characterized by rising conductivity from upstream to the river mouth, and consistency over time, of areas with low and high electrical conductivity. The maximum extension of high-conductivity areas is seen in correspondence with water table minima. The maximum extension of low-conductivity areas is found when the water reaches peak levels, usually at the end of spring. Along the coast, between the coastline and the high-conductivity areas, there is an area characterized by low conductivity throughout the year because the saltwater intrusion is not direct, but related to the cone

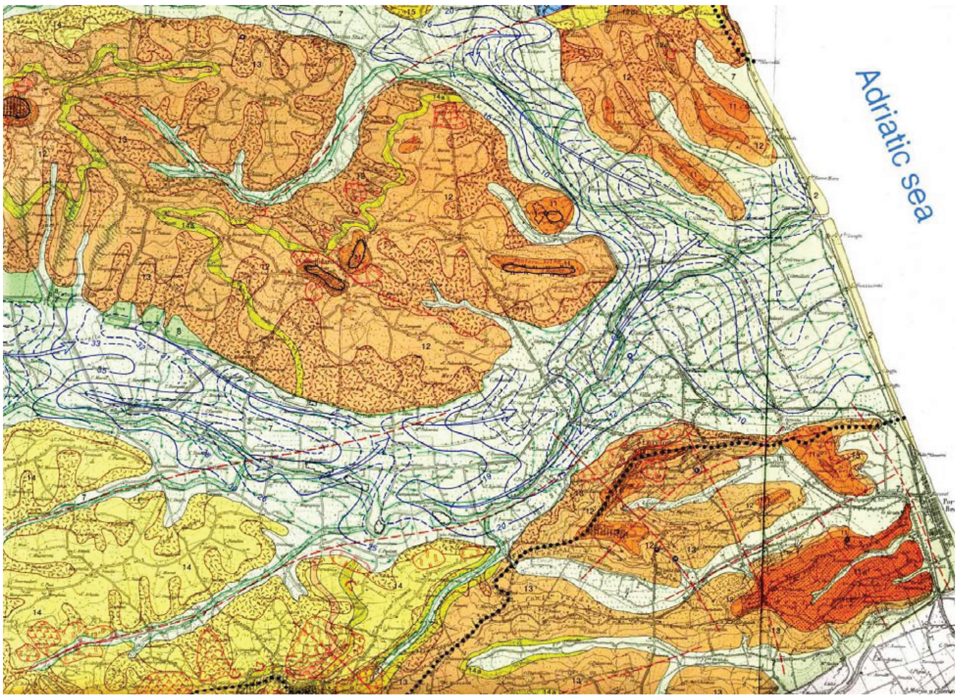

Fig. 4. Geological map and iso-phreatic lines in a representative coastal area. Alluvial aquifers of rivers Musone, Aspio, and Potenza [7].

Table 4
Electrical conductivity (*EC*) and temperature (*T*) of the main alluvial aquifers

River	Metauro	Esino	Musone	Potenza	Chienti	Tenna	Aso	Tronto
Districts	3, 11	2, 4, 6	7	8, 10	9	8, 10	1, 5	5
Minimum *EC* (μS·cm^{-1})	500	500	900	500	600	600	600	800
Maximum *EC* (μS·cm^{-1})	8,000	10,000	4,500	2,500	3,000	2,400	1,500	7,500
Yearly average *EC* (μS·cm^{-1})	1,100	1,200	1,200	1,000	950	950	900	1,500
Minimum *T* (°C)	9	11	12	11	13	8	8	—
Maximum *T* (°C)	20	19	27	19.5	18	17	20	—
Yearly average *T* (°C)	13.5	13.5	16.5	13.5	14	13	13.5	—

intrusion of saltwater, due to heavy ground-water pumping near the shore.

4. Distributed generation of water and power

The aim of the present work is to explore the scope for recovering the thermal energy discharged by power plants and use it to heat the desalination plant feedwater. This reduces aquifer pumping, improves groundwater quality and at the same time mitigates the hydrological risk.

We hypothesized meeting the freshwater demand of Marches using both thermal desalination units (where large power plants are already available) and RO units coupled to new distributed small or medium-sized power plants (in areas where local power production is very small). Notably, both solutions allow heat recovery throughout the year, especially in the summer, when water is scarcer and the demand for electrical energy and freshwater increases.

Selection of one or the other option depends on factors such as user demand, feedwater quality, and plant cost.

4.1. Existing large power plants

We hypothesized adding multiple effect distillation (MED) units to the existing large power plants, since economies of scale make thermal desalination plants more profitable when coupled to large than small plants. However, RO plants can also be used, even though they consume a greater amount of electricity due both to high flow rates and to feedwater salinity. In fact, large feedwater flows are needed to exploit fully the high thermal energy output. Moreover, if aquifer drawing is to be reduced, the plants must use seawater, which entails higher feed pressure and maintenance costs.

Coupling MED units to existing power plants must be carefully considered in terms of plant operating strategies. In particular, coupling the GT power plant to a desalination unit will improve total plant efficiency, since the thermal energy of exhaust gases is not recovered at all. As regards the CCC power plant, it is currently working in non-cogeneration mode because of the closure of the sugar refinery that was the final user of the thermal energy discharged; moreover the thermal output is drained through an air condenser, which significantly limits power production in the summer. Consequently, the plant's total efficiency is currently lower than the nominal operation efficiency. Therefore a MED unit would slightly reduce the amount of electricity produced, but would strongly enhance total efficiency through the use of thermal energy. In contrast, the IGCC power plant condenses the steam using seawater; a thermal desalination plant would therefore involve a higher condensing temperature and consequently a further reduction in electrical power production, even though the plant's total efficiency would be increased.

Table 5 reports the water production potential of the existing large power plants assuming a typical power to water ratio (PWR) according to plant size and technology [8].

MED units coupled to the existing power plants would meet 58% of the water demand in Marches. This level of freshwater production would probably exceed requirements, but the analysis is useful to determine the water production potential of existing power plants and to provide an order of magnitude. This level of production would significantly reduce aquifer pumping, improving groundwater quality and reducing the hydrogeological risk. However, since desalination units consume power and can reduce current electricity production, adding them to the existing power plants would compound the electricity deficit.

4.2. New distributed power plants

Alternatively, the freshwater and electrical demand of Marches could be met by distributed small or medium-sized power plants coupled to RO desalination units. In fact, a capacity significantly lower than the one of the power plants described above makes thermal desalination plants unprofitable, whereas RO systems are less

Table 5
Water production potential of the three existing large power plants

	IGCC	CCC	GT
Power plant size (MWe)	281	150	104
PWR (MED)	10	10	6
Daily water production (MIGD)	28	15	17
Yearly water production (m^3/y)	38,330,367	20,461,050	23,643,880
Water authority demand met (%)	88	47	54

affected by economies of scale. Moreover, since a smaller amount of thermal output would be recovered, lower feedwater flows would be required, enabling the use of ground-water use.

Distributed power plants allow electrical energy production right where it is consumed and a 4–6% reduction in transmission losses. However, distributed generation becomes profitable when the thermal output is recovered and the plant works as long as possible. This means that these plants are not designed for peak loads but for base loads, since plant operation must be ensured. In this work, we estimate the potential power size of each local plant that would allow meeting 75% of the freshwater demand of the energy-intensive districts. In particular, the thermal output of the power plants was assumed to be used to raise feedwater temperature and reduce water dynamic viscosity (to improve RO system performance, since a 1°C increase in feedwater temperature entails a ~3% increase in freshwater production). The yearly average temperature of the Adriatic sea near Ancona is ~18.5°C [9]. We conservatively assumed a feedwater temperature of 20°C and a further temperature increase of 8°C, from thermal output recovery, in order to avoid side effects on the membranes. However, the use of seawater involves a feedwater recovery factor not exceeding 50 % and higher electricity consumption. Groundwater allows better performances, because less saline feedwater is associated with a higher recovery factor and with lower electricity consumption. Moreover, in case of the presence of contaminants in the aquifers, for example due to fertilizers, use of ground-water will further improve aquifer quality.

In this study, we considered:

- daily per capita freshwater consumption of 252 l [10];
- recovery factor equal to 50%;
- desalination plant utilization factor of 50%;
- power plant utilization factor of 90%.

These figures have been calculated for the coastal districts, which are characterized by a summer peak in electricity and water demand related to the tourist season, and for energy-intensive districts nos. 4 and 6, which are under the same water authority as districts nos. 2 and 7.

Table 6 shows the water and electricity production potential of the distributed power plants.

Table 6 clearly shows that coupling distributed power plants to RO desalination units can both reduce the electrical energy deficit and produce large amounts of freshwater, possibly even exceeding the actual water demand, thus meeting the targets of the regional environmental and energy plan and enhancing groundwater quality.

5. Utilization of process water

One of the strengths of this project is the attempt to address both a current problem, i.e. the regional electrical energy deficit, and at the same time a longer-term issue, i.e. groundwater deterioration due to excess salinity or pollution. Some possible uses of process water are affected by factors such as plant location, the proximity of particular industries, and land use in surrounding areas. For instance in predominantly agricultural areas, characterized by contaminated or brackish groundwater, the process water could be used for irrigation. These plants could even (perhaps specially) be operated to clean up contaminated groundwater; in such cases they would have to be provided with an upstream circuit to reduce iron concentrations. The treated water could then be pumped back into the aquifer, cleaned up or even processed, to improve groundwater quality; or it could be pumped into the aqueducts to soften or dilute the drinking water. If distilled water is produced, it could be sold. Near the coastal areas most affected by marine intrusion a multiple-well hydraulic barrier could be realized to remove and treat the saltwater or brackish water and pump it back after treatment, thus lowering the saline wedge. Finally, the concentrated process by-products (salt or highly concentrated brine or water) require proper disposal; this can be achieved through release into the sea if they derive from seawater desalination, or via commercial re-use as mud, salt baths and salts for chemical or pharmaceutical purposes.

6. Conclusions

This works explores the hypothesis of meeting the demand for electrical energy and water by energy-intensive coastal districts in Marches, an Adriatic region in central

Table 6
Water and electricity production potential of each local distributed power plant

District	2 (Ancona)	3 (Fano)	3 (Pesaro)	4 (Fabriano)	5 (San Benedetto del Tronto)	6 (Jesi)	7 (Senigallia)	9 (Civitanova Marche)
Population	100,507	57,529	91,086	30,019	45,054	39,224	41,550	38,299
Daily per capita water consumption (l/d)	252	252	252	252	252	252	252	252
Yearly water consumption (m^3/y)	9,244,634	5,291,517	8,378,090	2,761,148	4,144,067	3,607,824	3,821,769	3,522,742
Yearly electricity consumption (MWh/y)	429,748	266,526	381,157	190,013	188,078	205,331	154,421	189,736
Plant size required to meet 75% of the water demand (MWe)	28	16	25	8	13	11	12	11
Plant electricity production with RO unit on (MWh/y)	122,675	70,218	111,176	36,640	54,991	47,875	50,714	46,746
Yearly RO unit energy consumption (MWh/y)	34,667	19,843	31,418	10,354	15,540	13,529	14,332	13,210
Yearly net energy production with RO unit on (MWh/y)	88,007	50,374	79,758	26,286	39,451	34,346	36,383	33,536
Electrical energy demand met with RO unit on (%)	20	19	21	14	21	17	24	18
Yearly energy produced with RO unit off (MWh/y)	98,140	56,174	88,941	29,312	43,993	38,300	40,571	37,397
Total electrical energy demand met (%)	43 %	40 %	44 %	29 %	44 %	35 %	50 %	37 %

Italy, through distributed generation plants coupled to desalination units. For the districts already endowed with large electrical power plants the proposed solution is to couple them to MED thermal desalination units. Although this solution does not reduce the regional electrical energy deficit, it allows meeting ~58% of the freshwater demand of the region. For those districts lacking large electrical power plants, the study calculates the size of distributed power plants coupled to RO units that would allow meeting the district freshwater demand. In this case, the thermal energy discharged by the power plants is recovered to heat the feedwater, increasing the efficiency of both power plants and RO units. This solution allows meeting 35–50% of the local energy demand, depending on district characteristics. Despite their abundance, the water resources of Marches are increasingly under threat by aquifer pollution, due particularly to fertilizers and to saltwater intrusion near the coast. The solutions advanced in this work address both a current problem, i.e. the regional electrical energy deficit, and a longer-term issue, i.e. ground-water quality deterioration. Local water production reduces freshwater collection from the aquifers and, consequently, saltwater intrusion, improving groundwater quality and reducing the hydrological risk.

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