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Desalination plants (reverse osmosis) to improve thermal power station. Yield and life cycle

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ABSTRACT

Nowadays, the most important problems that affect the world are carbon footprint decrease, fossil fuel use, and climate change. As proof of that, all environmental international agencies impose different laws and rules related to greenhouse effect. European Union policy is a clear example, which is explained in the document "2020 Strategies (COM/2010/2020 final)" [1]. Water deficit is another question that produces a lot of problems around the World. About 1,100 million people lack access to safe drinking water, which represents 18% of the world population. Approximately 42% of the population is not able to access basic sanitation. The project raised different problems related to water and energy production. The primary goal is to achieve low carbon emissions. Moreover, these dual plants (desalination and thermal power plants) should be more efficient and flexible. The project's main goal is to study water and energy cogeneration in half power thermal power plants through different docking ways. The system is approached to be installed in areas where water is not sufficient.

Keywords: Desalination; Reverse osmosis; Dual plants; Thermal power station; Environment; Water; Energy; Greenhouse gases

1. Introduction

At first, the water and energy resources are disconnected. However, science and technology's development have demonstrated the strong link between the two resources, caused by the substantial increase in current population.

In the Horizon 2020 objectives is included the European greenhouse gases' emissions reduction in a 40% in 2030 with respect to 1990s values. The meeting took place on 24 October 2014 in Brussels (Belgium) [1]. The study suggests energy problems related to the extraction process. One of its objectives will be the eradication of carbon emissions increased.

Also, the increasing problem with the water shortage in Europe has been underscored in a study made by the DGMA of the IEEP [2]. Many members of the European Union that there are and there will be

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shortage problems from here to 2030, so this deficiency will be replaced by desalination process.

This project tries to analyze the possibilities that Reverse Osmosis (RO) plants and electric energy generator groups possess to function together. It evaluates as well the advantages they would obtain by this union in energetic savings as in operation costs and lessen pollution produced by these systems.

2. Objective

The project aims to create new and cost-effective solutions for the desalination and thermal power plants that work with fossil fuel (or bio-fuel). Because of the implementation of RO plants, the thermal power plants can satisfy peak demand and renewable production reductions. These plants consume less fuel and can reduce greenhouse gases' emissions. Moreover, the project seeks to mitigate effects that are produced by operation cycle, minimizing costs [3].

The RO dual plants are designed to reduce operation costs. They raise a substantial flexibility in water and energy production.

The water and energy production can be changed independently, thus it might achieve different water/power installed ratios, without significant loss in yields [4].

This proposal introduces a new concept supported by the construction of pilot plants that no other energy generator plant has nowadays. This offers the possibility for RO plants and electric energy generator groups to work together using water-electricity cogeneration based on electricity in alternator terminals. To achieve this, water must be considered as energy. To obtain fresh water, 5–7 kWh of energy are necessary. So, energy deficient zones use water as energy. Therefore, brackish and seawater desalination technology is needed.

3. Records

Southern Europe and a series of similar zones around the World are typified by energy fluctuations during yearly seasons (winter-summer) likewise; the majority of these zones are short of hydrological resources due to aquifer drainage. This implies a progressive increase in energy consumption. These sectors are explained with more retail below.

3.1. Energy

Nowadays, thermal power plants are very inefficient and they work under their optimal operation point. As mentioned in Enel's Environment Report (2013), a huge difference between the net capacity installed in different countries and the annual generation obtained is observed. As an example, mentioning Belgium and Italy. Belgium has a thermal power plant with a 406 MW of net power installed, which would suppose 3,556,560 MWh if the plant worked 100% capacity. However, it generates 1,373,000 MWh, in other words, the plant is working at 38.6% total capacity. Enel Italy has 43 plants, with different energy obtaining ways (steam, combined cycle, gas turbine, and so on). The installed net capacity is 24,723 MW, which suppose 216,573,480 MWh. The annual generation in Italian thermal plants is 48,440,000 MWh, that is 22.4% total capacity.

The inefficiency of plants is due to the peculiarities of the power grids in different countries, since the share of energy produced from renewable resources is increasing. Wind and solar energy are highly variable and fluctuating. Because of that, they have priority access to the grid. Fossil fuel power plants are responsible to support renewable energy fluctuations in order to control and stabilize the network [5]. Plants should be able to run either in partial load as low and high efficiency as possible. Moreover, plants must operate throughout the load range, all possible speed; start/stop operates with full coverage and they spend less fuel as possible. These conditions force to operate very close to design limits of plants. The extreme conditions force the system to the maximum, which increases the rate of wear of components. Therefore, flexibility in fossil fuel plants presents a major challenge [6].

3.2. Water

Member states of the European Union emphasize that in recent years the concern for seasonal and longer droughts in many European countries has increased. Droughts are not limited only in the South. Among the options to tackle the scarcity of safe water for domestic, industrial, and agriculture consumption is to use desalination technology.

Using the aforementioned countries example, both countries will have water shortages in 2030, which is observed that the European report data previously named. In this report, water deficit starts to accumulate in a watershed when extraction exceeds a threshold of 20% water exploitation. Belgium case, the rate is at 27.2%, while for Italy can reach 251.7% in the extreme case of Sicily. According to this report, almost all European countries will have trouble getting water supply in 15 years. Desalination becomes one of the solutions for supply to avoid any problems that may occur in the future [5].

4. Cogeneration

In order to save energy and improve the use of it, cogeneration is used. Because of its characteristics, this process contributes significantly to the security of energy supply and sustainable development [7]. The approaches followed, mainly due to the oil crisis of 1973, led to two objectives which are: Diversify sources of energy supply and improving energy efficiency of processes.

Firstly, diversification aims to reduce as far as possible, dependence existent with oil as an energy source. It will get regular upgrading of facilities for performance improvement processes; On the other hand, application control techniques and unification processes in the production of primary energy will achieve that different processes use the same energy source. For example, cogeneration is defined as cogeneration electricity-heat and electricity-desalination [8].

In the same train of thought, energy consumption and brine generation are the major environmental problems of desalination plants [9]. Different possibilities to minimize these drawbacks are being worked and studied at the moment. In these analyzes again the concept of cogeneration appear, this time applied to electricity and desalination.

At present, hybrid desalination systems, which combine thermal desalination and membrane modules with power generation plants, obtain the best technical and economics results in this sector. For example, to obtain pure water by evaporating seawater is necessary 2,258 kJ/kg at atmospheric pressure [10,11]. Evaporation is one of the most inefficient methods that exist. The production by evaporation represents 0.627 kWh/kg, (which is around €0.094 per liter of desalinated water, taking the price like €0.15/kWh). Consequently, excess thermal energy, which may exist in these plants, is used for seawater desalination.

Efficiency and cost of water have improved as a product of desalination plants combining two or more desalination systems [12]. Fundamentally these systems are:

(1) RO and distillation processes.
(2) Steam compression and distillation processes.
(3) RO and steam compression processes.

Most cogeneration plants are installed in the Persian Gulf countries, where winter to summer electricity demand could change between 25 and 100% and water consumption is about 60–100%. In summer, electricity demand increases very much. These plants are typified like multistage flash (MSF) and RO cogeneration. There are vapor compression processes and multiple effect distillation (MED) too. About 77% of the total water production in these regions is produced by thermal desalination processes [12–15].

The multi-effect process (MSF) is simpler and safer than any of the other processes. During the 60s, MSF plants produced 500 m^3/d, but this amount increased in 10 years up to 32.000 m^3/d. This process requires a minimum pretreatment and it has low chance of fouling and lime. However, MSF process consumes large amounts of energy (as it is explained above) and requires large investment costs. MED process presents problems about fouling in high salt concentrations. As a consequence, these plants need frequent stop of the process [13]. Currently, MED process has not a large installed capacity compared to MSF, especially in the Persian Gulf countries.

Different commercially available alternatives in cogeneration exist to provide the necessary electricity and steam. Alternatives for desalination processes are:

(1) GT-HRSG, gas cycle with gas turbines connected to heat recovery steam generators (with or without supplementary firing) is use energy from the exhaust gases to generate steam for the desalination process.
(2) BP-ST, steam cycle with back pressure steam turbines where the exhaust steam from the steam turbine is used in desalination process where it condenses and returns back to the steam cycle.
(3) EC-ST, steam cycle with extraction/condensing steam turbines where the steam for the desalination process is extracted from the steam turbine at the appropriate pressures (and temperatures) needed for the desalination process.
(4) CC-BP, combined gas and steam cycle where a heat recovery steam generator (with or without supplementary firing) is used to produce steam at medium or high pressure that is supplied to a back-pressure steam turbine discharging into the thermal desalination plant.
(5) CC-EC, combined gas and steam cycle that is similar to the previous one except that an extraction/condensing steam turbine is used [12,13].

In all of these different cogeneration plants, some high-pressure steam is required to activate a steam ejector to purge the system during start-up and to remove non-condensable gases [14]. The temperature and pressure of the steam required for the desalination process differs according to the desalination process.

Typical temperature and pressure ranges are shown in Table 1.

However, all configurations described have something in common. Traditionally, when trying to produce two complementary elements, it always comes to enhancing one and relegating the other as a byproduct or complementary.

5. Hybrid systems

The hybrid concept is the combination of two or more processes. In desalination, these types of systems are classified by Awerburch in three different options [16].

5.1. Simple hybrid

In the simple hybrid MSF/RO desalination power process, a seawater RO plant is combined with either a new or existing dual-purpose MSF/power plant to offer some advantages. Several plants currently installed are using some of these advantages. Examples are in Jeddah RO, Jubail and Madina-Yanbu II in Saudi Arabia, and Fujairah in UAE.

5.2. Integrated hybrid

The fully integrated MSF/RO desalination power process, which is particularly suitable for new seawater desalting complexes, takes additional advantage of integration features.

5.3. Power/water hybrid

Integration of the power and water cycle aims to obtain the optimum cost for both water and power. Important parameters in the design of these systems include:

(1) Seasonal demands for electricity and water.
(2) Power-to-water ratio.
(3) Minimization of fuel consumption and increase in the power plant efficiency.
(4) Minimization of the environmental impact of carbon dioxide including potential consideration of CO2 tax credit.

6. Research

Water and electricity cogeneration can be classified in two modalities.

In the first place, the electric company transfers low-pressure steam to the water company. The water company uses the steam like energetic source. This method involves a direct relationship between electricity and desalination. An energy company must commit to produce the steam required by another company and it must have availability too. For this reason, when steam output and cost are evaluated, disputes arise.

In the second mode, the desalination company has its own steam and electricity generator. The disadvantage is that, the produced electricity not used must be sold to the electricity company. It is not of interest to the electrical company that the desalination plant produces electricity on a continuous way, and empty out exceeds to the electricity grid.

The proposal showed in this paper introduces a new concept, which does not exist in any power plant. It is the possibility to work together an RO and an electric power generator plant. It would be considered cogeneration of electricity and water according to electricity on the alternator terminals. To get this goal, water is considered as energy carrier. To produce 1 m^3 of drinking water between 5 and 7 kWh of energy are needed, so water is energy in deficit areas of it, because to get it, it is necessary desalination of seawater or brackish [4].

Dual RO plants offer a great flexibility. Water and energy can be change independently, so they get different possibilities in relation to water/energy ratio. This fact does not mean an efficiency loss in the operation yields. The three configurations that can be taken:

(1) RO plant-steam turbine.
(2) RO-gas turbine plant.
(3) RO plant-combined cycle [10].

The schemes are shown in Figs. 1–3.

From the electrical point of view, dual RO plants amount to a use that it has not been analyzed or implemented. Electric demand in a system of any size

Table 1
Steam conditions

Process	Steam temperature (˚C)	Steam pressure (kP_a)	TBT (Top brine temperature)
MSF	100–130	250–350	90–120
MED-TVC	120–150	250–350	70–80
LT-MED	70–90	20–40	60–80

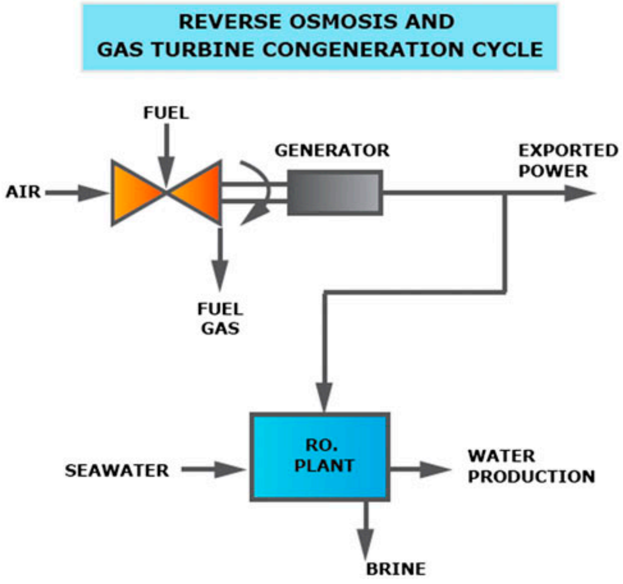

Fig. 1. RO-gas turbine plant.

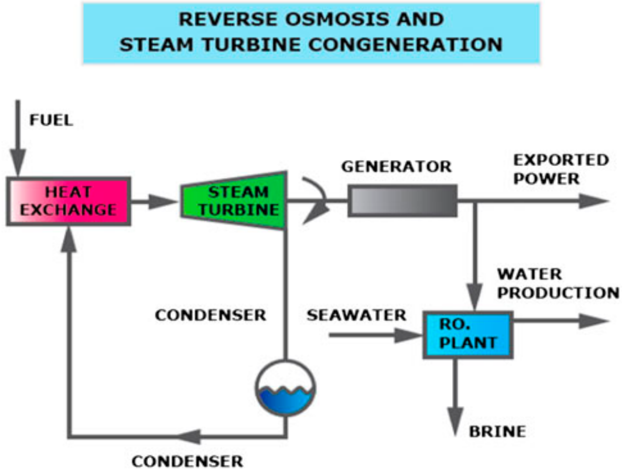

Fig. 2. RO-steam turbine plant.

fluctuates significantly on a daily basis. Besides, the electric load varies between a minimum load level, which electricity demand never falls from below; and a maximum o peak load level, which only occurs for a couple hours a year. For example, For US utility systems the minimum annual load is 27–33% of the peak annual load. Generally, the load level exceeds 90% of the peak value 1–5% of the time, exceeds 80% of the peak value 5–30% of the time, and exceeds 33–45% of the peak 95% of the time. Annual load factors ((average/load/peak annual load) × 100) typically range from 55 to 65%.

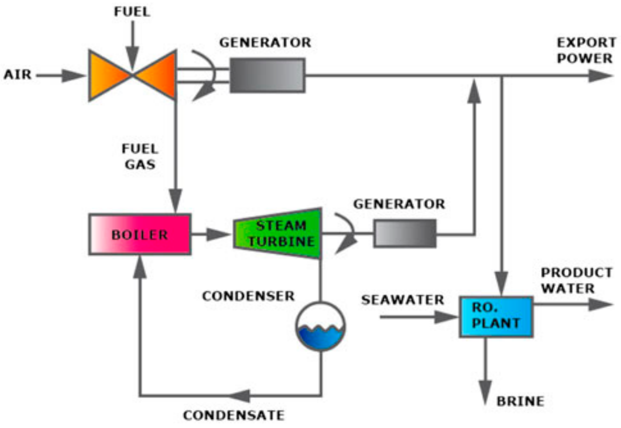

Fig. 3. RO-combined cycle plant.

It can be considered two different relationships between the power plant and the RO installation. The electrical and osmosis plant are working together, like only one plant. In other words, it is managed by the same consortium or company. Another possibility is that the power plant is independent from the RO plant, so to supply the power required is necessary for a relationship between two companies.

Both options would lead to the production of water not considered as the main basis. As much production electricity as water should conform, in order to obtain a reduction in capital costs and operating.

Another innovative approach involved in this system is to regulate the operation of the RO plant. Up to date, the majority of plants have been designed with a constant operating point. Therefore, it is always operated in a defined way, with constant operating parameters.

The dual plants formed by thermal power and RO plants have an important challenge, because it is necessary that the RO plant is adapted to the power fluctuation.

Flexibility in RO plant sizing together with lower energy consumption has seen RO become the system with the greatest potential for the immediate future. Improvements in membranes and enhanced energy recovery have led to RO becoming highly competitive, and some may say indispensable, desalination technology [4].

Different projects (including OPRODES project) [18–20] have undertaken a detailed analysis of the membranes and the response offered by an RO plant operating under discontinuous regime, with constant shut downs and successive fluctuations in pressure and flow, without the need to acquire more energy production equipment.

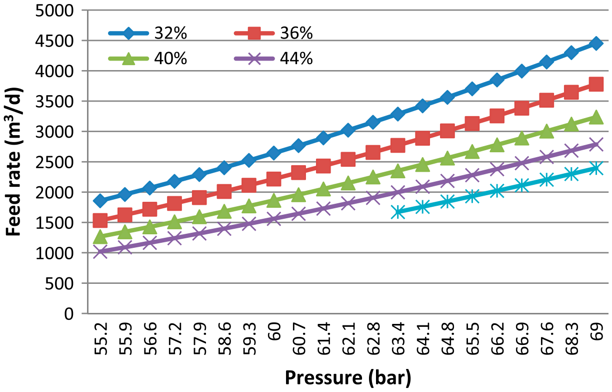

Fig. 4. Pressure vs. feed rate to different conversion.

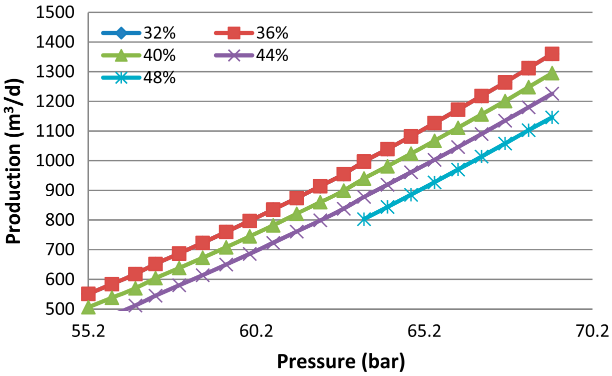

Fig. 5. Pressure vs. production to different conversion.

A simulation has been undertaken to prove the performance of the RO plant to different pressures and recovery. The analysis data obtained from the simulation are calculated for a one stage RO plant with 15 high pressure tubes and 6 membranes each one, 90 elements SW30-8040-HR from Filmtec. This plant produces 1,500 m^3/d. Feedwater has 35,000 ppm in total solids dissolved, the temperature is 25℃, and the fouling factor considered is 20% [10].

The program simulates the plant behaviour in different recovery ranging from 30 to 50%. The program calculates design parameters with pressures ranging from 69 to 51.7 bar.

The results of the simulation have allowed establishing the graphs shown in Figs. 4–8.

6.1. Analysis of feed flow rate

The graphs shown below describe the behavior of RO plant, when its conditions differ. In Figs. 4 and 5 can be seen that at a fixed recovery, the curve increases, and the slope is maintained practically constant. At fixed pressure, the production decreases with the conversion. On the other hand, when operating pressure decreases, the production and feed rate decrease too.

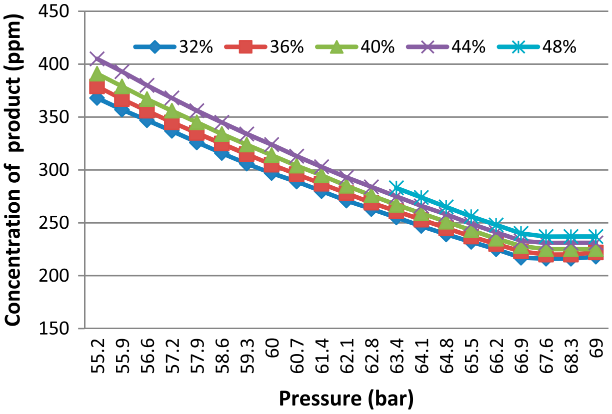

Fig. 6. Pressure vs. concentration of product to different conversion.

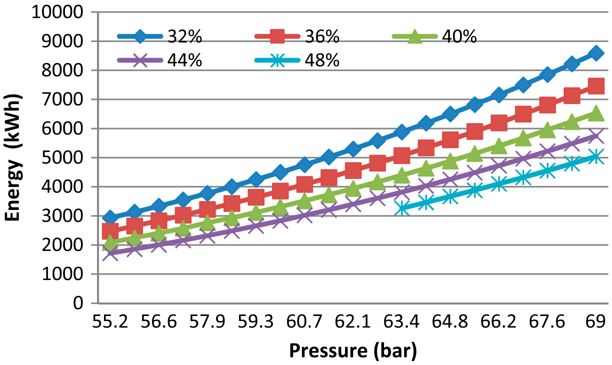

Fig. 7. Pressure vs. energy to different conversion.

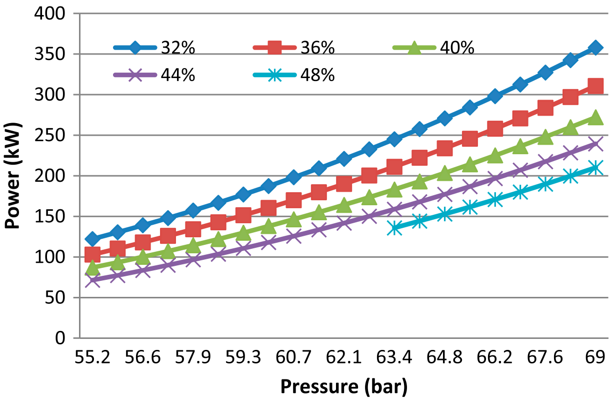

Fig. 8. Pressure vs. power to different conversion.

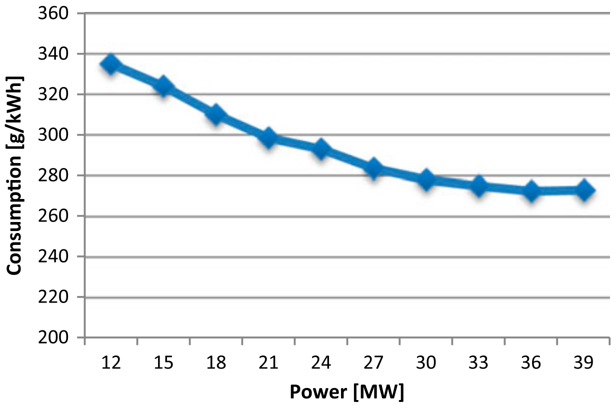

Fig. 9. Consumption vs. power.

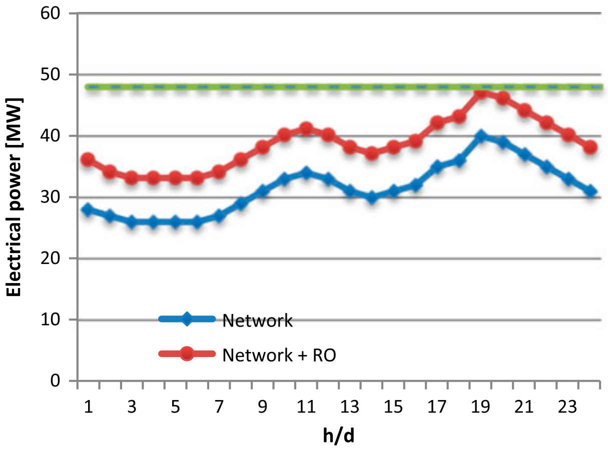

Fig. 10. Steam power plant and RO with continuous operation and constant operating point.

Fig. 6 shows the behaviour between pressure and concentration at different conversion. When recovery increases, more pressure is necessary to obtain fresh water, but the range is acceptable.

Figs. 7 and 8 show how the behavior of energy and power is described, respectively. It is observed that it can work with medium-high pressure obtained acceptable power and energy data. The plant works in a range between 3,200 and 9,000 kWh/d, and its range power between 75 and 360 kW. Therefore, it is an available option for dual plants.

7. Discussion

If it is known, or it can be expected, the daily demand curve of a system, it is necessary to know the impact that takes place in the different groups system. Obviously, the impact in the based groups is minimal because they do not modulate load. The interesting groups are those that modulate its charge during the day. Because of that, their yields have been affected. Usually, these groups are steam turbines, which have middle power respect to base system groups [17–20].

In Figs. 9–12, which are associated to each case, it can be observed how power curves depend on the system. Data used are from a thermal power plant, whose capacity is 40 MW. All figures express power (MW) vs. h. The graphs show the behavior of the system in different cases: work in continuous, intermittent, and varying any operating points. To compare the different cases, it is considered that all of them should produce the same power and conditions demand will be similar.

It should be noted that it is used to the simulation of this system a bolier, whose manufacturer is combustion engineering-Bazan, a turbine and alternator, whose manufacturer are Westinghouse-Bazan, and whose power is 39.9–46.875 kWA, respectively.

Their consumptions are represented in Table 2.

(1) Case 1: Steam power plant and RO with continuous operation and constant operating point. This case corresponds to the normal operation of a power plant in a system where you have installed an RO plant. There is no relationship between the two plants unless the power plant supplies power to osmosis, as if it were another subscriber.

Table 2
Operating conditions case 2

Recovery	Pressure (bar)	Concentration of product (ppm)	Brine concentration (ppm)	RO production (m^3/d)	Brine flow (m^3/d)	Rated flow (m^3/d)	Power (kW)	Energy (kWh)	Specific energy (kWh)
40	66.9	228	58,169	36,529.6	54,826	91,355.6	7,468	179,233	4.91
41	65.5	244	59,141	33,243.2	47,842.4	81,085.6	6,539.2	156,940	4.72
42	64.1	262	60,143	30,051.6	41,554	71,605.6	5,693.2	136,636.9	4.55
43	62.1	291	61,172	25,754	34,191.2	59,945.2	4,650.5	111,612.1	4.33
44	60	324	62,232	21,677.6	27,618.4	49,296	3,728.3	89,478.8	4.13

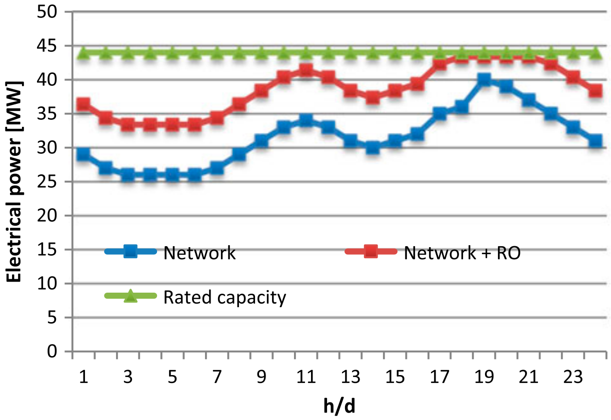

Fig. 11. Steam power plant and RO with continuous operation and variable operating point.

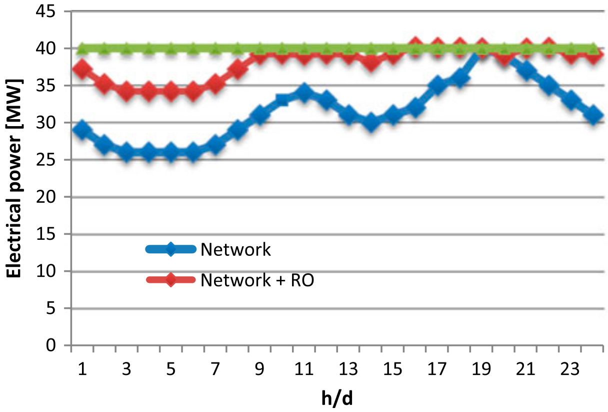

Fig. 12. Steam power plant and RO with discontinuous operation and variable operating point.

It can be seen that the maximum power demanded by the system is 40 MW. The RO plant demand is 7.2 MW. So, the total installed capacity of the power plant is 48 MW. Production of the RO plant is 35,000 m^3/d.

The figure shows that this kind of system does not improve the power plant, because the load curve is only transfer on the demand curve.

(2) Case 2: Steam power plant and RO with continuous operation and variable operating point. This type of operation corresponds to a current dual plant. Electricity and water production aim to decrease operating costs. In Fig. 11, it can be seen how the load regulation at peak times is affected by high demand. The installed capacity of the power plant goes from 48 to 44 MW, because it is necessary to regulate operating power by half at peak times. Production of the RO production plant is 35,000 m^3/d.

Operating conditions:

It is possible to vary the operating conditions, the following parameters are presented.

(3) Case 3: Steam plant and RO with discontinuous operation and variable operating point.

From the point of view of the operation both plants, this case is more complex that the other two cases. The RO plant should vary the operating point modules and stop when it is necessary (mostly to achieve minimum energy consumption in the power plant). It can be seen that the maximum power demanded by the system is 40 MW. Production of the RO plant is 35,000 m^3/d.

The graph shows the versatility RO plant. This versatility allows that the power installed in the power plant will be the maximum power that it is demanded by network. Furthermore, it can be seen the great achievement of the available energy [10].

Operating conditions:

Assumed the case 3 like optimum and recovery 44%, the table described below shows the energy demand by the grid, the energy consumed in the RO

Table 3
Operating conditions case 3

Recovery	Pressure (bar)	Concentration of product (ppm)	Brine concentration (ppm)	RO production (m^3/d)	Brine flow (m^3/d)	Rated flow (m^3/d)	Power (kW)	Energy (kWh)	Specific energy (kWh)
40	66.9	228	58,169	40,074.6	60,146.7	100,221.3	8,192.8	196,626.9	4.91
41	65.5	244	59,141	36,469.4	52,485.3	88,954.7	7,173.8	172,170.5	4.72
42	64.1	262	60,143	32,968	45,586.7	78,554.7	6,245.7	149,897	4.55
43	62.1	291	61,172	28,253.4	37,509.3	65,762.7	5,101.8	122,443.7	4.33
44	60	324	62,232	23,781.3	30,298.7	54,080	4,090.1	98,162.4	4.13

Table 4
Data of energy demand by the grid, the energy consumed in the RO process, and the total energy generated in a day

Hour	Elec. prod. (MW)	Available energy (MW)	RO consump. (kW)	Grid specific consump. (g/kWhe)	Total (grid + RO) specific consump. (g/kWhe)	Grid total consump. (g/kWhe)	Total (grid + RO) consump. (g/kWhe)	Water obtained (m^3)
1	29	11	8,192.8	278.78	273.34	8,084.5	10,166.44	1,668.59
2	27	13	8,192.8	282.48	274.82	7,627.0	9,671.68	1,668.59
3	26	14	8,192.8	284.65	275.82	7,401.0	9,431.10	1,668.59
4	26	14	8,192.8	284.65	275.82	7,401.0	9,431.10	1,668.59
5	26	14	8,192.8	284.65	275.82	7,401.0	9,431.10	1,668.59
6	26	14	8,192.8	284.65	275.82	7,401.0	9,431.10	1,668.59
7	27	13	8,192.8	282.48	274.82	7,627.0	9,671.68	1,668.59
8	29	11	8,192.8	278.78	273.34	8,084.5	10,166.44	1,668.59
9	31	9	8,192.8	275.92	272.57	8,553.5	10,682.85	1,668.59
10	33	7	6,245.7	273.91	272.56	9,039.2	10,696.84	1,372.68
11	34	6	5,101.8	273.23	272.59	9,289.8	10,658.82	1,178.24
12	33	7	6,245.7	273.91	272.56	9,039.2	10,696.84	1,372.68
13	31	9	8,192.8	275.92	272.57	8,553.5	10,682.85	1,668.59
14	30	10	8,192.8	277.24	272.87	8,317.2	10,421.68	1,668.59
15	31	9	8,192.8	275.92	272.57	8,553.5	10,682.85	1,668.59
16	32	8	8,192.8	274.81	272.45	8,793.9	10,950.48	1,668.59
17	35	5	5,101.8	272.76	272.45	9,546.6	10,925.85	1,178.24
18	36	4	4,090.1	272.50	272.45	9,810.0	10,922.68	990.34
19	40	0	0	273.59	272.46	10,943.7	10,898.35	0
20	39	1	0	273.00	272.62	10,647.0	10,632.01	0
21	37	3	4,090.1	272.45	272.49	1,008.8	11,196.57	990.34
22	35	5	5,101.8	272.76	272.45	9,546.6	10,925.85	1,178.24
23	33	7	6,245.7	273.91	272.56	9,039.2	10,696.84	1,372.68
24	31	9	8,192.8	275.92	272.57	8,553.5	10,682.85	1,668.59
Total	757		156.93 (MW)	277.04	273.35	209.3	249.75	32,993.78

process, and the total energy generated in a day. Besides, it is exposed specific fuel consumption, considered energy demand by the grid and total demand (Tables 3 and 4).

It can be seen how the data about specific consumption decreases in all hours. This means that at every time of the day, a desalinated water quality is obtained at the expense of lower fuel energy consumption. The evolution obtained by the system adapts perfectly to the variability of the energy supplied.

8. Conclusions

This paper discusses the variation of traditional operation systems (defined operation points and continuous operations). Different schemes in operation and design of RO plants, which are connected with thermal power plants, increase the overall performance of both systems.

This new system would be available if the investment and the annual operation ranges were lower than traditional case.

The decrease of the majority of costs will achieve provided that the system reach these objectives:

1. To decrease energy peaks to modulate the RO plant with the load.
2. To decrease fixed cost of the thermal power plant.
3. To improve power curve group.
4. To reduce the cost of kWh, which to reduce to variable costs in the RO plant.

It can be concluded that, the system proposed as optimal (Case 3) achieves the objectives specified above, so the proposed system shows the real possibilities that offer working together RO plants and electric energy generator groups.

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