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Utilisation of the exergy method for the cost evaluation of integrated nuclear desalination systems

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ABSTRACT

At present, the DEEP code, developed by the IAEA is being used internationally for the cost evaluation of integrated nuclear desalination systems. However, economic models in DEEP are often criticised because they are based on the power credit method in which the allocation of the benefits from the sale of one product (electricity) are arbitrarily attributed to the second product (desalted water). To determine the costs of the two products in an integrated nuclear desalination system, we thus used the exergy method which determines the useful work done by the two products in a more equitable manner, using the second and the third laws of thermodynamics. This paper summarises the first results of an economic evaluation of three integrated systems based on the utilisation of the French PWR900, the AP-600 (Westinghouse) and the gas turbine, combined cycle plant (CC900), all coupled to an MED process, and operating in a co-generation mode, producing about 288,000 m^3/day of desalted water. These results are compared with those obtained with the help of the modified IAEA code, DEEP3.1, based on the power credit method. It is observed that the application of the exergy principle leads to water and electricity costs which are at most within about 27% of those obtained by the power credit method. Since this error is about the same order of magnitude as that in the economic data and the models used in DEEP, the comparison allows to have reasonable confidence in DEEP results.

Keywords: Nuclear desalination; Economics of desalination

1. Introduction

There are no specific nuclear reactors for desalination. Any reactor, capable of providing electrical and/or thermal energy can be coupled to an appropriate desalination process. The reactors can operate as dedicated (or single-purpose) systems, producing only desalted water or as co-generation (or dual purpose) systems, producing both water and electricity.

Single-purpose nuclear desalination systems are considered more suitable for remote, isolated regions.

The fundamental role of the economic evaluation of any engineering project is to enable coherent and just comparisons with alternative options, to prepare the financing details for the implementation of the project, to fix tariffs and finally to furnish a clear choice of techno-economic options to decision makers.

The cost economics of single-purpose nuclear (or fossil fuelled) desalination plants can be evaluated and compared, using the well-known constant money, levelized cost methodology. This methodology is described in detail in [1].

The most useful parameter to assess the economics of a given single-purpose system, comprising of an energy source and a desalination system is that of the life-time levelized unit cost of the desalted water produced, expressed in $/$m^3$.

This levelized desalination cost is the ratio of the sum of all the annual expenses related to the production of water (annual required revenue) and the total amount of water produced per year.

The methodology to determine the above costs is similar to that used for the determination of energy (electricity) production cost.

However, determining the water costs for dual-purpose systems, with two products: water and electricity, is relatively more complex since it requires an *a priori* knowledge of the allocation of benefits of at least one product to the other.

Several methodologies have thus been evolved to permit this allocation in a representative manner. These methodologies are discussed in detail in [2]. Only the most commonly used methodologies will, therefore, be briefly recalled here.

2. Conventional water cost evaluation methods

2.1. The power credit method

A value for the electricity generation cost by the dual-purpose plant is the key point of this method. In actual cases, power credit is calculated on the basis of the least-cost alternative, i.e. the least cost of producing the same amount of electricity in a power-only plant. In the following paragraph, it is shown that the amounts of power credit can be varied by the power unit cost to be adopted.

The power credit method of cost allocation first determines the cost of one product (e.g. heat or electricity) based on the cost of that product from an alternative method (an existing or imaginary single-purpose plant, for example). Using this value as an upper limit to the cost of the selected product, in the dual-purpose system, the cost of the second product is obtained by crediting the product with all the economic benefits of the first product.

In the single-purpose plant, the levelized cost of energy is the discounted cost of all expenditures associated with the design, construction, operation, maintenance and fuel cycle costs divided by the discounted values of the quantities of energy produced.

In most industrial organisations this cost is obtained by the present value concept that takes into account the time value of the money.

Water cost is similarly obtained by charging to water all water plant investments (plus energy production costs) and dividing by total water production.

Thus in the power credit method, the energy cost is set to be the cost obtained from an imaginary single-purpose power plant, generating net energy E with total expenses, C.

One can thus determine the net levelized power cost, $C_{\mathrm{kWh}} = C/E$.

One then calculates the amounts of desalted water (W) and the net saleable power $E2$ produced by the plant at a total expense $C2$ ($E2 < E$; $C2 > C$).

Then the desalted water is credited by the net saleable power cost $= C2 - E2 * C_{\mathrm{kWh}}$.

And the water cost is obtained by

$C_{\mathrm{water}} = (C2 - E2 * C_{\mathrm{kWh}})/W$.

2.2. Water credit method

Contrary to the power credit method, the principle of water credit is to evaluate a water value produced and to determine the cost of the power generation by difference. The water credit depends on the water cost, C_{water} to be adopted.

Using the water cost of the optimum single-purpose desalination plant producing the same amount of water as the dual-purpose plant. The single-purpose plant can be conceptual or an existing plant. Its basic requirement is to produce the same amount of water at least cost, independent of the energy source or desalination method:

$$\text{Water credit} = C_{\mathrm{water}} \times E_{\mathrm{water}}$$

The whole benefit of co-production is then assigned to the cost of electricity.

2.3. Apportioning methods

The apportioning methods divide the total integrated plant costs between two products (electricity and desalted water) in a certain ratio, selected in theory on the basis of certain criteria. In practice however, the ratio is quite arbirary.

3. The exergy method

3.1. Background

It so happens that developing countries, which are facing or which will face acute water shortages are or will also be those whose electricity demands would grow at about twice the rate of that in the developed countries. It is thus not surprising that apart from a few exceptions (e.g. China), a majority of the IAEA Member States is, or has been, studying dual-purpose (co-generation) nuclear power plants whose main objective would be to produce electricity and use about 10% of the power for desalination purposes.

For a dual-purpose plant in which electricity production dominates, the power credit method would be the natural choice. A large nuclear reactor acting as a heat source or electricity supply for RO would use only a fraction of its total electrical production for desalination. It is thus closer to being approximated as equivalent to a single-purpose plant.

However, the power credit or other cost allocating methods implicitly contain the seeds of arbitrariness. These include:

- Difficulties in accurately determining equivalent cost of a single-purpose plant.
- Distortion of either of the outputs by local market conditions (direct or hidden subventions, disproportional profits, arbitrary taxing conditions, etc.).
- The very fact that the benefit of one product is arbitrarily allocated to the other, whereas ideally both the products should benefit from each other.
- The practical difficulty in extending the power (or water) credit methods to yet another third product (e.g. the benefits from the extraction of useful materials from the concentrated brine rejected by desalination plants).

To circumvent these difficulties, Breidenbach [2] first proposed the application of the exergy method. In what follows, the principle of the method and the fundamental equations involved will be recalled briefly from [2].

In the cost allocation methods for an integrated plant, the overall expenditure C_0 can be expressed as a linear function of the annual electricity output, E_a (e.g. kWh) and the annual water production, W (e.g. m^3/year). We thus have,

$$C_0 = C_E \times E_a + C_w \times W \tag{1}$$

Eq. (1) is graphically represented by Fig. 1 [2]. The slope of the line is a direct function of the water to power ratio.

Obviously, if all the benefits of the combined production are assigned to the cost of water, without penalising electricity production (power credit method using generation cost of electricity from the imaginary single-purpose plant), then the situation on the curve will be represented by the point A.

The point B can similarly be placed on the curve by supposing that all benefits from water go to electricity production. The points on the curve outside the segment AB will represent some form of subsidization of either water or electricity.

The real situation would be one corresponding to the point E, in which the combined benefits are allocated to both products in an equitable manner. This is the main objective of the exergy method.

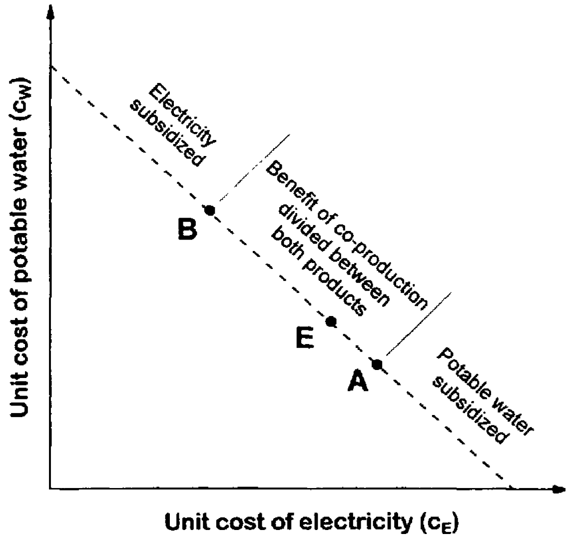

Fig. 1. Allocation of overall expenditures in an integrated desalination system [2].

In this method, the real maximum achievable energy (exergy) is calculated from the thermodynamic principles for each part of the integrated plant. Assessment is then done to determine the quality of energy and hence the useful work done by each product, which then enables the respective allocations in a more accurate manner.

3.2. The exergy method

For a given thermodynamic process,

$$\sum_{\text{process}} dE \leq 0. \tag{2}$$

In other words the above equation implies that the amount of exergy loss, E_l, is directly related to the irreversible entropy generation:

$$E_l = T_0 \times S_p, \tag{3}$$

where T_0 is the surrounding temperature and S_p is the entropy of the system.

By definition exergy is the maximum useful work which can be derived from a system until it is brought in complete, stable equilibrium with the reference surroundings. This can be stated as:

$$E = H - T_0 \times S - \sum_i \mu_{io} \times m_i, \tag{4}$$

where H is the system enthalpy, S is the entropy, m is the mass and μ is the energetic potential of the surroundings.

Exergy is thus the variable that accurately determines the performance of a given system.

When exergy is converted from one form to another, only part of the exergy is transferred to the new form; the remainder being lost in order to cause the change. Thus an exergy evaluation implies how a system's potential of providing useful work is being used and where the losses of that potential occur. Naturally one thus identifies the sub-systems where the losses could be minimised.

3.2.1. Exergetic allocation of the overall production cost

The key parameter which determines the costs in an integrated desalination system is the annual revenue ($/year) that is required to produce the two final products: electricity and water.

As in any engineering venture, the overall expenditures can be subdivided into fixed and variable charges. Fixed charges include all costs that are independent of the quantities of the final products: capital charge, personnel costs, insurance and preventive maintenance costs, etc. Variable charges include expenses that are proportional to the amounts of the final products: fuel costs, consumables costs, etc.

If the exergy principle is applied then the overall expenditures C_0 of the integrated plant would comprise:

- Electricity generation expenditures, C_{eq}.
- Steam production costs to provide heat to the distillation plant, C_{sq}, allocated exclusively to potable water production.
- Common electricity and steam production expenditures, C_c
- Remaining water production expenditures, C_w.

We thus have,

$$C_0 = C_{eq} + C_{sq} + C_c + C_w \tag{5}$$

The common electricity and steam expenditures are proportional to the exergy loss flows $\dot{E}_E$ and $\dot{E}_s$, that are required to produce these two forms. Hence the electricity generation expenditure C_{E*} and the steam generation expenditure C_{s*} are given by:

$$C_{E*} = C_E + \frac{\dot{E}_E}{\dot{E}_E + \dot{E}_s}.C_c \quad \text{(electricity)}, \tag{6}$$

$$C_{s*} = C_E + \frac{\dot{E}_s}{\dot{E}_E + \dot{E}_s}.C_c \quad \text{(steam)}. \tag{7}$$

Here C_c is the remaining capital charge of say, the nuclear power plant, including fuel cycle, decommissioning, and fixed and variable O & M costs.

C_{E^*} can be further subdivided into the expenditures for the generation of saleable power C_E and the generation of electricity required for the desalination plant, C_{EW}.

If P_E is the net saleable power, P_W the power supplied to the desalination plant and P_{net} is the total electrical output of the plant, then:

$$C_E = C_{E*}.\frac{P_E}{P_{net}}, \tag{8}$$

$$C_{EW} = C_{E*}.\frac{P_W}{P_{net}}. \tag{9}$$

The total water production expenditures are then calculated as

$$C_W = C_{W*} + C_{EW} + C_S. \tag{10}$$

C_{W*} is the capital charge of desalination plant (and the backup heat source), fixed and variable O & M costs of desalination plant and backup heat source and fuel costs for the backup heat source.

The kWh cost C_{kwh} is then obtained by

$$C_{kWh} = \frac{C_E}{P_{net}}. \tag{11}$$

And,

$$C_w = \frac{C_{Ew}}{W} \tag{12}$$

where W is the total desalination plant production (m^3).

3.3. PWR case

The exergy loss flows $\dot{E}_E$ and $\dot{E}_s$ will be the share of the total exergetic potential of the system (also called exergy of the fuel), $\dot{E}_F$.

The exergy analysis of the system is given in Table 1.

It is shown that $\dot{E}_E$ and $\dot{E}_s$ are determined by the exergy loss analysis in different components of the PWR.

The exergy loss flows as summarised under $\dot{E}_c$, which can be assigned to the generation of electricity as well as to the production of steam, are proportional to $\dot{E}_{Ee}$ and $\dot{E}_{sd}$. $\dot{E}_{Ee}$ is allocated exclusively to electricity.

$\dot{E}_E$ and $\dot{E}_s$ can thus be calculated as

$$\dot{E}_E = \dot{E}_{Ee} + \dot{E}_c \cdot \frac{\dot{E}_{Ee}}{\dot{E}_{Ee} + \dot{E}_{sd}} \tag{13}$$

Table 1
Exergy analysis of a PWR plant as the energy source [2]

	$\dot{E}_{\mathrm{F}}$	Total exergetic potential from the core fissions
=		
	$\dot{E}_{\mathrm{sg}}$	Exergy losses in the primary circuit (reactor + steam generator + coolant pumps)
	+	
	$\dot{E}_{\mathrm{MSR}}$	Exergy losses in moisture separators and steam reheaters
$\dot{E}_c$	+	
	$\dot{E}_{\mathrm{aux}}$	Exergy losses due to electrical auxiliary loads
	+	
	$\dot{E}_{\mathrm{FH}}$	Exergy losses in feed-water heaters
+		
	$\dot{E}_{\mathrm{FP}}$	Exergy losses in feed-water pumps
+		
	E_{T}	Exergy losses in turbines
	+	
$\dot{E}_{\mathrm{Ee}}$	E_{con}	Exergy losses in condenser
	+	
	E_{G}	Exergy loss in the generator and other mechanical losses
	+	
	P_{net}	Net electrical output
+		
	$\dot{E}_{\mathrm{sd}}$	Exergy of steam provided to the distillation plant

And,

$$\dot{E}_{\mathrm{s}} = \dot{E}_{\mathrm{sd}} + \dot{E}_{\mathrm{c}} \cdot \frac{\dot{E}_{\mathrm{sd}}}{\dot{E}_{\mathrm{Ee}} + \dot{E}_{\mathrm{sd}}} \tag{14}$$

The electrical power requirements of feed-water pumps and reactor coolant pumps are not analysed separately but they are covered in individual exergy flows of Table 1.

3.4. The gas turbine, combined cycle plant (CC)

For the gas turbine combined cycle plant, the exergy calculations are more complex as compared to that for the nuclear reactor since the former plant has two sources of energy production. In [2] it is proposed to perform exergy analysis separately for the gas turbine part and for the steam cycle part. These are presented in Tables 2 and 3.

As for the PWR cases, the exergy of fuel $\dot{E}_F$ is allocated to the exergy flows $\dot{E}_{\mathrm{E_{GT}}}$ – required to generate electricity in the gas turbine- and $\dot{E}_{\mathrm{HRSG}}$ to provide heat in the heat recovery steam generator.

In Table 3, the terms represented by $\dot{E}_{\mathrm{E_{e,GT}}}$ are allocated to $\dot{E}_{\mathrm{E_{GT}}}$, whereas the terms represented by $\dot{E}_{\mathrm{CGT}}$ may be allocated to both $\dot{E}_{\mathrm{EGT}}$ and $\dot{E}_{\mathrm{HRSG}}$. Obviously $\dot{E}_{\mathrm{HRSG_e}}$ is allocated exclusively to $\dot{E}_{\mathrm{HRSG}}$

We thus have

$$\dot{E}_{\mathrm{E_{GT}}} = \dot{E}_{\mathrm{E_{e,GT}}} + E_{\mathrm{C_{GT}}} \times \frac{\dot{E}_{\mathrm{E_{e,GT}}}}{\dot{E}_{\mathrm{E_{e,GT}}} + E_{\mathrm{HRSG_e}}} \tag{15}$$

And,

$$\dot{E}_{\mathrm{HRSG}} = E_{\mathrm{HRSG_e}} + E_{\mathrm{C_{GT}}} \times \frac{\dot{E}_{\mathrm{HRSG_e}}}{\dot{E}_{\mathrm{E_{e,GT}}} + E_{\mathrm{HRSG_e}}}\,. \tag{16}$$

In the same way, the exergy analysis of the steam cycle is performed (Table 3) and we have

$$E_{\mathrm{E_{ST*}}} = \dot{E}_{\mathrm{E_{e,ST}}} + E_{\mathrm{C_{ST}}} \times \frac{\dot{E}_{\mathrm{E_{e,ST}}}}{\dot{E}_{\mathrm{E_{e,ST}}} + E_{\mathrm{S_e}}}\,. \tag{17}$$

And,

$$E_{\mathrm{S*}} = \dot{E}_{\mathrm{S_e}} + E_{\mathrm{C_{ST}}} \times \frac{\dot{E}_{\mathrm{S_e}}}{\dot{E}_{\mathrm{E_{e,ST}}} + \dot{E}_{\mathrm{S_e}}}\,. \tag{18}$$

Finally, the allocation of $\dot{E}_{\mathrm{HRSG}}$ to $E_{\mathrm{E_{ST}}}$ and E_{S} is obtained through

Table 2
Exergy analysis of the gas turbine cycle of a combined cycle plant [2]

	$\dot{E}_{\mathrm{F}}$	Total exergy of fuel
$=$		
	$\dot{E}_{\mathrm{CC}}$	Exergy losses in the combustion chamber
	$+$	
$\dot{E}_{\mathrm{CGT}}$	$\dot{E}_{\mathrm{EG}}$	Exergy of exhaust gas leaving the heat recovery steam generator
	$+$	
	P_{auxGT}	Electrical auxiliary loads
$+$		
	E_{TGT}	Exergy losses in the gas turbine (+ cooling losses)
	$+$	
	E_{Co}	Exergy losses in the compressor
	$+$	
$\dot{E}_{\mathrm{E_{e,GT}}}$	$E_{\mathrm{G_{GT}}}$	Exergy loss in the generator and other mechanical losses of the gas turbine
	$+$	
	P_{netGT}	Net electrical output
	$+$	
	$\dot{E}_{\mathrm{HRSG_e}}$	Exergy transferred in heat recovery steam generator

Table 3
Exergy analysis of the steam cycle of a combined cycle plant [2]

	$\dot{E}_{\mathrm{HRSG_e}}$	Exergy transferred in heat recovery steam generator
$=$		
	$\dot{E}_{\mathrm{L_{HRSG}}}$	Exergy losses in the heat recovery steam generator
	$+$	
$\dot{E}_{\mathrm{CST}}$	$\dot{E}_{\mathrm{O_{ST}}}$	Other exergy losses in the steam cycle
	$+$	
	P_{auxST}	Electrical auxiliary loads
$+$		
$\dot{E}_{\mathrm{E_{e,ST}}}$	E_{TST}	Exergy losses in the steam turbine
	$+$	
	E_{Con}	Exergy losses in the condenser
	$+$	
	$E_{\mathrm{G_{ST}}}$	Exergy loss in the generator and other mechanical losses of the steam turbine
	$+$	
	$P_{\mathrm{net}}\mathrm{ST}$	Net electrical output of steam turbines
$+$		
	$\dot{E}_{\mathrm{se}}$	Exergy of steam for the distillation plant

$$\dot{E}_{\mathrm{E_{ST}}} = \dot{E}_{\mathrm{HRSG}} \times \frac{\dot{E}_{\mathrm{E_{ST^*}}}}{\dot{E}_{\mathrm{E_{ST^*}}} + E_{\mathrm{S^*}}} \quad (19)$$

and,

$$\dot{E}_{\mathrm{S}} = \dot{E}_{\mathrm{HRSG}} \times \frac{\dot{E}_{\mathrm{S^*}}}{\dot{E}_{\mathrm{E_{ST^*}}} + E_{\mathrm{S^*}}} \quad (20)$$

with,

$$\dot{E}_{\mathrm{E}} = \dot{E}_{\mathrm{E_{GT}}} + \dot{E}_{\mathrm{E_{ST}}}\,.$$

4. The development approach

Our basic interest is to compare the power and water production costs by the exergy method to those already evaluated with the help of the DEEP code (power credit method) for energy sources such as the PWR-900, AP-600, GT-MHR, PBMR, CC-900 and the

Table 4
Comparison of first degree polynomial correlations with the simulation results

Parameter	Minimum error, %	Maximum error, %
Site cold source temperature	2.7	3.0
SG exhaust temperature	1.8	2.1
Temperature of the steam leaving the BP turbine to the MED water plant	3.2	4.9
Flow-rate of the steam leaving the BP turbine to the MED water plant	0.6	1.3

coal fired plant CFB-900, all coupled to MED and RO systems, as reported in [3].

As Sections 3.3 and 3.4 show, following steps would be required to achieve this goal:

- Compilation of the complete operational characteristics of various systems (temperature, pressure, flow rates at different points of the involved components).
- Exergetic analyses of the systems and sub-systems according to the principles outlined above.
- Integration of the exergy analysis in an EXCEL format along with some of the calculated characteristics by the DEEP code.
- Comparison of the electricity and water costs as calculated by the exergy method and the power credit method (DEEP 3.1).

A special software programme was then developed for detailed exergy analysis of the components in each system.

4.1. Methodology

An integrated water and power system consists of a number of components in which fluids undergo (irreversible) transformations.

The physical models of the nuclear desalination systems derive from basic macroscopic mass, energy and momentum conservation equations, exergy analysis formulas and supplementary correlation for heat transfer and physical properties.

These laws were applied to system components such as steam generators (SG), turbines, pumps, ducts, heat exchangers (reactor energy conversion system), MED effects, flash tank and condenser (intermediate loop and desalination system).

A simulation study was performed using the software tool, engineering equation solver (EES). The simulation results were used to build an empirical model describing exergy destruction in different process components as a function of:

- the site cold source temperature,
- the SG exhaust temperature,
- the temperature of the steam leaving the BP turbine to the MED water plant,
- the flowrate of the steam leaving the BP turbine to the MED water plant.

In order to obtain empirical relations for each of the above variables, a regression analysis was performed using a 6-degree polynomial of the form:$y = a_0 + a_1x^1 + a_2x^2 + a_3x^3 + a_4x^4 + a_5x^5 + a_6x^6$

The data obtained were then compared to the simulation results as given by EES.

It was observed that terms a_2 to a_6 could be neglected since, as shown in Table 4, maximum error was 4.9%. We thus only retained the first degree polynomial for final calculations.

4.1. Application to the case of a 600 MWe PWR, the AP600

The PWR is assumed to be coupled to a low-temperature MED plant using an extraction coupling scheme. This coupling scheme is shown in Fig. 2. In this scheme, the nominal water production capacity is 288,000 m^3/day. A backup heat source (gas turbine system of equivalent capacity) has also been used.

Calculations were made with the hypotheses presented in Table 5.

The exergy loss decomposition, as calculated by the software described in Section 4, is presented in Table 6.

We thus have the following equations:

$$\dot{E}_{\mathrm{E}} + \dot{E}_{\mathrm{s}} = \dot{E}_{\mathrm{F}} = 1961.7\mathrm{MW}$$

From Eqs. (13) and (14), we have

$$\dot{E}_E = 669.234 + 1160.110 \times \frac{669.234}{669.234 + 132.356} = 1637.79$$

and

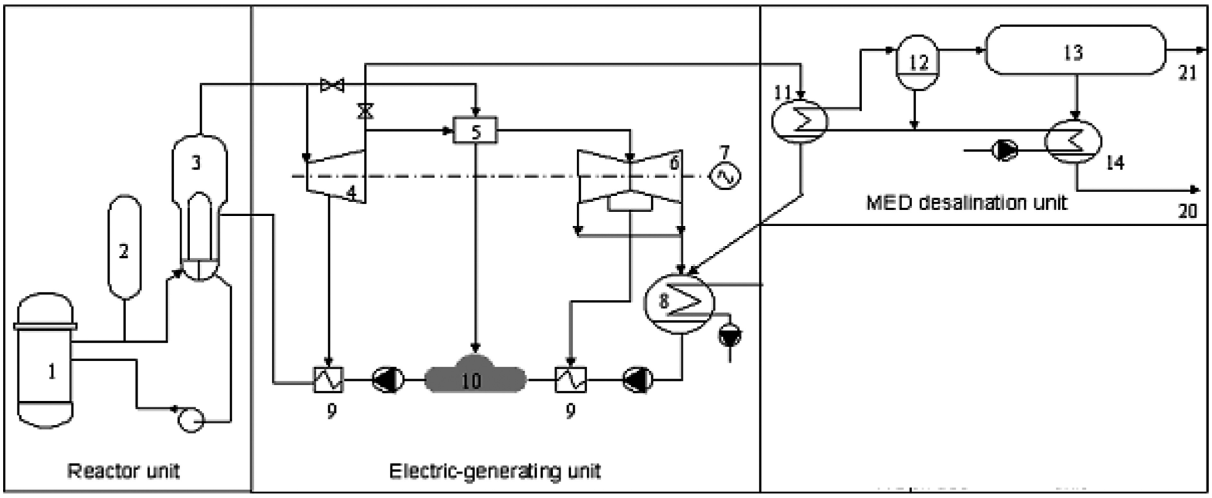

Fig. 2. Schematic diagram of the PWR (AP600) + MED system

$$\dot{E}_{\mathrm{s}}\,. = 132.356 + 1160.110 \times \frac{132.356}{669.234 + 132.356} = 323.909$$

We then updated the CDEE code version as initially developed by [2] to take into account the all the corrections which were made in this code until the issue of DEEP3.1.

The exergy prorated water and electricity costs thus obtained are:

Exergetic perorated levelized water cost ($/m^3)	1.13497
Exergetic perorated levelized electricity cost ($/kWh)	0.0609

We subsequently performed a DEEP3.1 calculation in as similar conditions as was possible.

The DEEP results are:

Levelized water cost ($/m^3)	0.9946
Levelized electricity cost ($/kWh)	0.04446

One observes that the relative errors in the water and electricity costs as calculated by DEEP3.1 and our modified exergy method are[1] −12% and −27%.

From these results one can conclude that either the power credit method is reasonably precise or the exergy method has not been applied as it should be.

To verify this uncertainty, we repeated the calculation for a 900 MWe reactor.

4.2. Application to a 900 MWe PWR

The thermodynamic properties of the Energy Conversion System (ECS) and its layout, as assumed in the calculations for exergy loss determination, are graphically illustrated in Fig. 3.For a 900 MWe French reactor, with open sea cooling, the rated total thermal power produced is 2932 with the electrical power of 910 MWe.

As for the AP600, we obtain the Table 7 for the exergy losses.

And,

$$\dot{E}_{\mathrm{E}} = 998.375 + 1730.674 \times \frac{998.375}{998.375 + 197.451} = 2443.285.$$

And

Table 5
Main calculation assumptions

Parameter	Value
Reference currency (year)	8 (2008)
Year of operation	2015
Sea water temperature	30 °C
Sea water TDS	45,000 ppm
Coupling scheme	Extraction turbine
Water plant capacity	288,000 m^3/day
Reference unit size	36,000 m^3/day
Water plant life-time	30 years
Power plant life-time	40 years for the PWRs, 25 years for the CC900
Calculation with backup heat source	Yes
Fossil fuel price for backup heat source	100 $/bbl

Table 6
Proportional breakdown of exergy flows in the AP600 + MED system. Exergy of fuel = 1965 MW

Exergy losses	%	Value (MW)
Primary circuit, including reactor, steam generator and coolant pumps	55.801	1094.648
Moisture separators and steam re-heaters	1.072	21.029
Auxiliary electrical loads without feed-water and reactor coolant pumps)	1.007	19.754
Feed-water heaters	1.039	20.416
Feed-water pumps	0.219	4.296
Total exergy loss $\dot{E}_c$	59.138	1160.110
Turbines	4.595	90.140
Condenser	1.641	32.191
Generator and other mechanical losses	0.525	10.299
Net electrical output	27.354	536.603
Total exergy losses $\dot{E}_{Ee}$	34.115	669.234
Steam provided to the distillation plant, E_{sd}	6.747	132.356

$$\dot{E}_{s\,.} = 197.451 + 1730.674 \times \frac{197.451}{998.375 + 197.451}$$
$$= 483.214.$$

Which leads to

Exergetic perorated levelized water cost (\$/m^3)	1.2501
Exergetic perorated levelized electricity cost (\$/kW.h)	0.0509

The corresponding DEEP3.1 values, calculated with the power credit method are

Levelized water cost (\$/m^3)	0.9629
Levelized electricity cost (\$/kWh)	0.04003

It is observed that the relative error between the two methods are -23 and -21%

4.2. Application to a 900 MWe gas turbine, combined cycle plant (CC900)

Tables 8 and 9 give the exergy loss distributions in various components of the gas turbine and steam cycles.

From Eqs. (15) and (16), and Table 8, we have

$$\dot{E}_{EGT} = 699.957 + 493.259 \times \frac{699.957}{699.957 + 372.68}$$
$$= 1021.837\text{MW}$$

And,

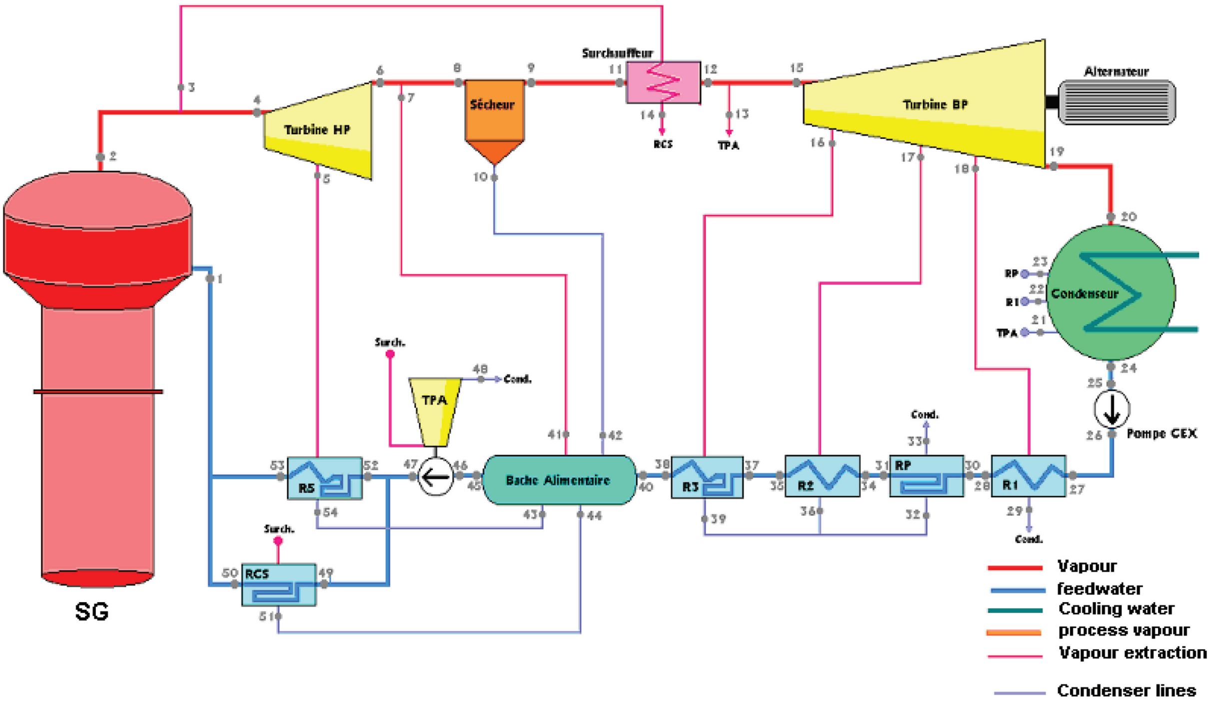

Fig. 3. General layout of the PWR900 secondary system. Abbreviations: SG, steam generator; Surchauffeur, superheater; Bache alimentaire, feed-water tank; Alterbator, generator; Condenseur, condenser.

Table 7
Proportional breakdown of exergy flows in the PWR900 + MED system. Exergy of fuel = 2932 MW

Exergy losses	%	Value (MW)
Primary circuit, including reactor, steam generator and coolant pumps	55.801	1633.016
Moisture separators and steam re-heaters	1.072	31.372
Auxiliary electrical loads without feed-water and reactor coolant pumps)	1.007	29.47
Feed-water heaters	1.039	30.406
Feed-water pumps	0.219	6.409
Total exergy loss $\dot{E}_{\mathrm{c}}$	59.138	1730.674
Turbines	4.595	134.473
Condenser	1.641	48.024
Generator and other mechanical losses	0.525	15.364
Net electrical output	27.354	800.515
Total exergy losses $\dot{E}_{\mathrm{Ee}}$	34.115	998.375
Steam provided to the distillation plant, E_{sd}	6.747	197.451

$$\dot{E}_{\mathrm{HRSG}} = 372.68 + 493.259 \times \frac{372.68}{699.957 + 372.68} = 544.05\mathrm{MW}$$

And from Eqs. (17) and (18), and Table 9, we have

$$\dot{E}_{\mathrm{E_{ST^*}}} = 86.0891 + 18.26132 \times \frac{86.0891}{86.0891 + 38.889} = 98.668\mathrm{MW}$$

and

$$\dot{E}_{\mathrm{S^*}} = 38.889 + 18.26132 \times \frac{38.889}{86.0891 + 38.889} = 44.571\mathrm{MW}.$$

From Eqs. (18) and (19), we also have $\dot{E}_{\mathrm{E_{ST}}} = 544.05 \times \frac{98.668}{98.668+44.571} = 374.761\mathrm{MW}$ and,

$$\dot{E}_{\mathrm{s}} = 544.05 \times \frac{44.571}{98.668 + 44.571} = 169.289\mathrm{MW}.$$

This gives,

$$\dot{E}_{\mathrm{E}} = 1021.837 + 374.761 = 1396.598MW.$$

Inserting these values in our modified software leads to:

Exergetic perorated levelized water cost ($/m^3)	2.077
Exergetic perorated levelized electricity cost ($/kWh)	0.1769

Table 8
Exergy breakdown of the gas turbine cycle in CC900 plant. Exergy of fuel = 1565.9 MW

Exergy losses in the combustion chamber	27.4	429.057
Exergy of exhaust gas leaving the heat recovery steam generator	3.8	59.504
Electrical auxiliary loads	0.3	4.698
Total, $\dot{E}_{\mathrm{cGT}}$	31.500	493.259
Exergy losses in the gas turbine (+ cooling losses)	8.8	137.799
Exergy losses in the compressor	2.2	34.450
Exergy loss in the generator and other mechanical losses of the gas turbine	0.8	12.527
Net electrical output	32.9	515.181
Total, $\dot{E}_{\mathrm{E_{e,GT}}}$	44.7	699.957
Exergy transferred in the heat recovery steam generator	23.8	372.68

The corresponding DEEP3.1 values are:

Levelized water cost ($/m^3)	1.6199
Levelized electricity cost ($/kWh)	0.1803

5. Discussion

The water and electricity costs for the three different power sources (900 and 600 MWe PWrs and the

Table 9
Exergetic breakdown of the steam cycle of a combined cycle plant; exergy transferred in heat recovery steam generator =372.68

Item	Proportion (%)	Value (MW)
Exergy losses in the heat recovery steam generator	3.8	14.1618
Other exergy losses in the steam cycle	0.2	0.7454
Electrical auxiliary loads	0.9	3.3541
Total, $\dot{E}_{\mathrm{CST}}$	4.9	18.26132
Exergy losses in the steam turbine	2.7	10.0624
Exergy losses in the condenser	0.5	1.8634
Exergy loss in the generator and other mechanical losses of the steam turbine	0.2	0.7454
Net electrical output of steam turbines	9.9	36.8953
Total, $\dot{E}_{\mathrm{E_{e,ST}}}$	23.1	86.0891
Exergy of steam for the distillation plant	72 or 17.12 of the total exergy of fuel	268.329

900 MW gas turbine combined cycle) can be summarised as in Table 10.

It is observed that for all the three systems considered, the relative errors on water costs as obtained by the power credit method and the exergy method are 12–22%. The corresponding errors on the power costs vary from +1.9 to −27%.

These differences are within the errors of the uncertainties in the economic data as used for all calculations.

Our conclusion is that the power credit method is reasonably correct, at least for the cases considered here since in all systems the amounts of thermal energies used are but a small fraction (6–17%) of the total thermal power. In such cases the dual-purpose systems can be approximated to a single-purpose one.

6. Conclusion

This paper describes the basic formalism for an exergy analysis of integrated desalination systems, which is absolutely essential to develop a software providing precise cost evaluations of the integrated desalination systems based on the utilisation of nuclear and fossil fuelled based energies.

Preliminary comparison seems to indicate that the differences in electricity and water costs, between those calculated from the exergy principle and from the power credit method, are at most of the order of 20% for the two PWRs and the gas turbine combined cycle and are within the uncertainties of the economic data and models used.

We believe that these differences are relative small because the amount of heat used to produce the same quantity of water (288,000 m^3 day) is a smaller fraction of the total power thermal produced in the three sources.

In this case, obviously the power credit method would give quite correct results since the approximation to single-purpose systems would be a correct one. One can thus have reasonable confidence in DEEP3.1 results.

Future detailed calculations for very large desalination systems, including the fossil fuelled based systems, would likely lead to a better understanding and more precise results from the exergy method.

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Note

1. Error (%) = 100 * (DEEP3.1 − exergy)/exergy.

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