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Exergy analysis and thermoeconomic cost accounting of a Combined Heat and Power steam cycle integrated with a Multi Effect Distillation-Thermal Vapour Compression desalination plant

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In this paper an exergy analysis and thermoeconomic cost accounting of a Combined Heat and Power steam cycle integrated with Multi Effect Distillation-Thermal Vapour Compression plant is performed; the goal of the study is to show how these methodologies provide a rational criterion to allocate production costs on electricity and freshwater in such a dual purpose system. After a brief overview on the methodology and a description of reference plant, exergy analysis is carried out to calculate exergy flows and exergy efficiencies at component level. A detailed description of the adopted thermoeconomic model is given. In a first scenario, cost accounting is performed assuming that the concentrated brine is disposed back to sea, thus being its exergy content definitively wasted; furthermore, a sensitivity analysis is carried out in order to assess the changes in the unit cost of electricity and freshwater with several design and operation parameters. In a second scenario, conversely, part of brine exergy is used in a Reverse Electrodialysis unit to produce further electricity. In both cases results show that high unit costs are obtained for the material streams or energy flows which involve major exergy destruction along their production process, particularly freshwater in the former configuration and Reverse Electrodialysis electric output in the latter one.

1. Introduction

Fresh water consumption has been continuously increasing along the last decades, due to different factors such as population growth, improvement of living standards and economic development [1]. Nowadays seawater desalination technologies are frequently adopted in countries experiencing potable water shortage. Among the available desalination technologies, reverse osmosis is the most widely adopted, accounting for almost 50% of the installed worldwide desalination capacity; conversely, the remaining capacity is shared between the different thermal desalination processes [2]. One of the main barriers to the spread of Thermal Desalination plants lies in their high-energy consumption per m^3 of freshwater product; for this reason, the current researches have being paying growing attention to the design dual purpose systems for simultaneous production of electricity and fresh water. Several studies may be found in literature, that are focused on this topic and discuss the economic feasibility of different technological solutions. In [3] the potential integration of renewable sources and either thermal or mechanical desalination processes is discussed, focusing the attention on solar stills, multi-stage flash, multiple-effects boiling, reverse osmosis and electrodyalisis. An analysis of the potential for highly integrated solar energy systems to supply the requests from isolated communities is presented in [4]. In [5] the attractiveness of Concentrating Solar Power schemes integrated with thermal or mechanical desalination systems was investigated, in terms of levelized water cost and for possible application in Middle East and North Africa countries. Also, geothermal energy represents a possible source to drive water desalination units, as testified by the comprehensive review of technologies presented in [6].

Another solution could be represented by coupling thermal desalination processes with fossil-fuel or nuclear power plants [7]; with regards to fossil fuel-based plant, further opportunities could arise from the possibility of Combined Heat and Power (CHP) plants to be supported, according to the current legislative framework at European Union level, by incentive mechanisms pro-

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Nomenclature

b specific exergy (kJ_{ex}/kg)
$\dot{B}$ exergy flow (kW_{ex})
$\dot{B}_{ji}$ exergy flow "produced" by component "j" and "consumed" by component "i" (kW_{ex})
$C_{P,i}$ cost of the product of component "i" (€)
$C_{R,i}$ cost of the residue allocated on component "i" (€)
$\dot{C}_{P,i}$ cost flow of the product of component "i" (€/h)
$\dot{C}_{R,i}$ cost flow of the residue allocated on component "i" (€/h)
CHP Combined Heat and Power
CRF capital recovery factor (dimensionless)
CND condenser
c_p thermoeconomic unit cost (€/kW h_{ex})
F_i fuel of component "i" (kW_{ex})
f_r residue exergoeconomic factor (dimensionless)
f_z capital exergoeconomic factor (dimensionless)
FWH feed water heater
GEN electric generator
h specific enthalpy (kJ/kg)
k_i overall unit exergy consumption of component "i" (dimensionless)
I_i exergy destruction in component "i" due to irreversibility (kW_{ex})
p pressure (kPa)
P_i product of component "i" (kW_{ex})
MED multi effect distillation
n plant economic life (y)
N number of component
$\dot{N}$ molar flowrate (mol/s)
R_{ji} "Residue" exergy flow produced in component "i" and allocated on component "j" (kW_{ex})
R_u universal constant of gases (kJ/(kmol K))
RED reverse electrodialysis
RH referred to reheater section of steam generator
s specific entropy (kJ/(kg K))
Eco-Vap-SH economizer-vaporizer-superheater section of steam generator
T temperature (°C or K)
TVC thermal vapour compressor
y_{ij} product distribution ratio (dimensionless)
$\dot{W}$ electrical or mechanical power (kW)
x_s salt molar fraction (dimensionless)
X solution molarity (mol/l)
Z_i capital cost of component "i" (€)
$\dot{Z}_i$ capital cost flow of component "i" (€/h)

Vectors and matrices
$\boldsymbol{U}_D$ identity matrix (N × N)
$\langle \boldsymbol{FP} \rangle$ matrix of product distribution ratios (N × N)
$\langle \boldsymbol{RP} \rangle$ matrix of residue distribution ratios (N × N)
$\boldsymbol{C_P}$ vector of product cost (N × 1)
$\boldsymbol{C_e}$ vector of external fuel cost (N × 1)
$\dot{\boldsymbol{C}}_{\boldsymbol{P}}$ vector of product cost flow (N × 1)
$\dot{\boldsymbol{C}}_{\boldsymbol{e}}$ vector of external fuel cost flow (N × 1)
$\boldsymbol{Z}$ vector of capital cost (N × 1)
$\dot{\boldsymbol{Z}}$ vector of capital cost flow (N × 1)

Greek symbols
α coefficient of isoentropic efficiency for steam turbine off-design (dimensionless)
η performance (dimensionless)
ι interest rate (dimensionless)
φ salt dissociation Factor (dimensionless)
ψ_{ij} residue distribution factor (dimensionless)

Superscripts
no,diss not accounting for the ionic dissociation of salts
t related to total pressure

Subscripts
0 related to reference or "dead" state
Cond related to condenser
d related to design working condition
el related to electric power
ex related to exergy
HP related to high pressure steam turbine
k related to downstream pressure of steam extraction section
IP related to intermediate pressure steam turbine
is related to turbine isoentropic efficiency
LP related to low pressure steam turbine
ph related to the total physical, *i.e.*, thermo-mechanical, exergy
u related to upstream pressure of steam extraction section

vided by the different member states. The technical feasibility of small-medium scale integrated schemes including cogeneration and thermal desalination units has been analysed in a recent paper by Salimi and Amidpour [8], where thermodynamic modelling and economic assessment for a reciprocate engine coupled to a multiple effect desalination unit were presented. A completely different configuration, based on an integrated use of a solid oxide fuel cell and a reverse osmosis unit, has been proven economically and technically viable for application in the Arabian Gulf [9].

In order to exploit the potential of dual purpose systems, in [10] a condensing cycle with steam extraction was proposed as an efficient CHP retrofit solution for an existing Multiple Effect Distillation with Thermal Vapour Compression (MED-TVC); the cited paper proposed a sensitivity analysis of design and operation parameters, in order to assess whether or not the produced electricity was eligible for the "high efficiency cogeneration" assessment, according to the current legislative framework.

Referring to the same CHP-MED-TVC plant presented in [10], in the present paper the potential of thermoeconomic cost accounting is investigated, as an instrument to provide a rational criterion to allocate the costs of the consumed resources, either in the form of natural gas and capital investment, on the produced freshwater and electricity. In fact, when dealing with single-output systems, all the sustained costs are easily allocated on the unique product; conversely, when multi-output systems are concerned, as in the case of polygeneration systems [11], it is worthwhile questioning about the contribution of each product on the total production cost. Cost allocation also provides a basis for rational pricing of the different outputs.

The basic idea of thermoeconomic cost accounting is that each output of an energy system impacts differently on the consumption of input resources, due to the different number and quality of processes involved in its production [12]. In this sense, exergy analysis has been proven to provide useful information: in fact, as known from the principles of this method, among the different productive processes that could be designed to obtain a particular product, the process characterized by the lowest exergetic performance obviously requires the highest exergetic input, thus

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