Energy xxx (2016) 1–12

Contents lists available at ScienceDirect

Energy

journal homepage: www.elsevier.com/locate/energy

CHP (combined heat and power) retrofit for a large MED-TVC (multiple effect distillation along with thermal vapour compression) desalination plant: high efficiency assessment for different design options under the current legislative EU framework

A. Tamburini [a], A. Cipollina [a], G. Micale [a,*], A. Piacentino [b]

[a] DICGIM – Department of Chemical, Management, Information and Mechanical Engineering, University of Palermo, Palermo, Italy
[b] DEIM – Department of Energy, Information Engineering and Mathematical Models, University of Palermo, Palermo, Italy

ARTICLE INFO

Article history:
Received 13 November 2015
Received in revised form
2 February 2016
Accepted 14 March 2016
Available online xxx

Keywords:
Cogeneration
Desalination
Thermal vapour compression
Multiple effect distillation
High efficiency CHP
Primary energy saving

ABSTRACT

Integrated power plants in “dual purpose” configuration may represent a viable option for energy cost abatement of desalted water produced by MED-TVC (Multiple Effect Distillation along with Thermal Vapour Compression).

In this paper an existing large MED-TVC plant with a 36,000 m^3/day capacity is studied: a plant retrofit is designed, based on a steam power plant with condensation and steam extraction used to drive the steam ejector. As the plant operates in CHP (Combined Heat and Power) mode, the possibility to assess the integrated “CHP + MED-TVC” as *high efficiency cogeneration* according to Directive 2004/8/EC is discussed. Based on a model developed in Engineering Equation Solver, a sensitivity analysis is performed: the influence of several design and operation parameters on the fraction of energy outputs assessed as “from efficient cogeneration” is investigated. This fraction was found to increase almost linearly with the number of MED units supplied with steam. Also, when all the MED units are supplied and the steam extraction pressure is decreased from 4.89 MPa down to 0.29 MPa, the CHP fraction increased from ~54% to ~77%. The assessment of the plant as “high efficiency CHP” was found highly dependent on the specific fuel adopted.

1. Introduction

Thermal desalination systems represent a well consolidated technological option to face fresh water scarcity in disadvantaged areas. However, the growing concerns for the minimization of desalted water production costs and the high consumption of low grade heat per m^3 of fresh water have stimulated the efforts of desalination industry towards more efficient solutions. Thanks to the continuous improvement of membrane technologies, in the last few years reverse osmosis plants have been covering the largest share of the new installed capacity and, as concerns the thermal desalination plants, the adoption of TVC (Thermal Vapour Compression) and the adoption of dual-purpose “power + water” plants operating in CHP mode has been increasingly considered.

Several works available in literature analyse dual-purpose configurations. Faibish and Ettouney [1] investigated possible arrangements of integrated MSF (Multi Stage Flash) plants supplied with heat released from nuclear plants, with ejectors driven by 800 kPa – 170 °C motive steam. In the work by Najafi et al. [2] a MSF unit is integrated with a hybrid SOFC-GT (Solid Oxide Fuel Cell – Gas Turbine) system, leading to calculate an extremely high 58.8% exergetic efficiency, mainly due to the high efficiency of the Fuel Cell. Li et al. [3] proposed a new combined power and desalination system driven by low-grade heat. The plant, that included a Supercritical Organic Rankine Cycle and a MED-TVC unit, achieved quite low heat conversion efficiency, provoked by both the low temperature of heat input (assumed to be 150 °C) and the low exergetic efficiency (with the MED section representing, as usual, the main source of exergy destruction). However, most of the integrated schemes available in literature are based on the use of CC (Combined Cycles) or steam cycles. Sanaye and Asgari [4]

* Corresponding author. Tel.: +39 091 23863780; fax: +39 091 23860841.
E-mail addresses: alessandro.tamburini@unipa.it (A. Tamburini), andrea.cipollina@unipa.it (A. Cipollina), giorgiod.maria.micale@unipa.it (G. Micale), antonio.piacentino@unipa.it (A. Piacentino).

http://dx.doi.org/10.1016/j.energy.2016.03.066
0360-5442/

performed a "FourE" (energy, exergy, economic and environmental) analysis for a combined cycle, carrying out multi-objective optimization and identifying Pareto optimal frontiers to allow the analyst for an easier evaluation of trade-offs between alternative objectives. Luo et al. [5] proposed an innovative dual-purpose configuration, with a Chemically Recuperated Gas Turbine coupled with a MED-TVC unit; the inclusion of a desalination section allowed to face the high water consumption (23 t/d per MW power output), also producing surplus fresh water for sale. In the work by Wu et al. [6] an optimization of a dual-purpose "steam cycle + MSF" plant was performed by adopting genetic algorithms; the analysis, however, is based on a rather simplified modelling of the steam cycle, which adopts a "hot condenser" to drive the desalination unit. Calise et al. proposed an analysis for a polygeneration system based on solar and geothermal energy, whose performance resulted highly variable throughout the year, as a consequence of the fluctuating irradiation levels [7]. Palenzuela et al. investigated via process modelling the combination of desalination technologies (i.e. reverse osmosis, RO and multi effect distillation, MED) into parabolic-trough (PT) solar power plants (PT-CSP) [8]. Their data indicate that, under certain conditions, the integration of a MED unit into a PT-CSP plant is more efficient than the independent fresh water and power production with a RO unit connected to a PT-CSP plant [9].

Most of the aforementioned configurations have in common the "Combined Heat and Power" principle of operation, which could make them eligible for dedicated public support mechanisms or incentives, where available. In many contributions [10] the energy saving achieved by dual-purpose "power + desalination" plants has been calculated on the basis of well-established indicators, such as the Fuel Energy Saving Ratio. In Europe, however, some recent legislative provisions [11] have established a harmonized framework for the assessment of the electricity produced in CHP mode and the assignment of "high efficiency CHP" labels. It is worthwhile discussing whether dual-purpose "power + water" plants may easily fulfil the requirements of Directive 2004/8/EC and be thus eligible for the support mechanisms; in most of the EU member states, the support mechanisms essentially involve attribution of *white certificates*, dispatching priority of CHP electricity, guarantee of origin and partial tax exemption for the consumed fuel. The problem of "high efficiency CHP" assessment is not trivial: such dual purpose plants, in fact, often operate in different conditions throughout the year, depending on the variable fresh water production rates required to face requests. Then, it is hardly predictable whether or not a dual-purpose plant fulfils all the legislative requirements [12] in terms of:

- total energy conversion efficiency higher than a threshold value, in order to have the whole amount of electricity assessed as "from CHP";
- primary energy saving higher than a threshold value, in order to have the plant assessed as "high efficiency CHP".

The verification of both the above conditions, in fact, may create serious difficulties and, in some cases, it could be argued that the evaluation method does not appear completely rational from a thermodynamic viewpoint [13]. Also, the energy saving indicators may highly change depending on the technological solutions adopted as concerns, for instance, the power generation unit (either back-pressure turbine steam cycle or condensing cycle with steam extraction) and the desalination unit (either MED or MSF).

In order to perform a detailed analysis, a reference case study is assumed [14], consisting of a MED-TVC plant with 20 years of operation, which has been accurately described in previous works [15]. A retrofit design based on the inclusion of a topping steam cycle is considered.

The analysis is aimed at assessing, for a real world application, whether (and to what extent) the current legislative framework may influence the plant designer/owner to converge toward specific design or operating strategies. This result will be achieved by critically discussing the relation between the design and operating options and the possibility to have the plant (or a fraction of it) qualified as "high efficiency cogeneration" and thus eligible for access to support mechanisms.

According to the above declared goal, the paper attempts to provide answers to some critical questions often arisen in literature, such as:

- (i) how does the current framework created by the so-called "CHP Directive" [11] influence the optimal design criteria and operation strategies for industrial plant?
- (ii) what kind of modifications should be introduced in the current framework, to make the CHP Directive more efficient in leading the private (ie. plant-owner's) perspective and the "social-collective" viewpoint to converge towards the simultaneous maximization of their objectives?

These questions have been posed in a number of contributions and are still open in researchers community. Verbruggen [16] has underlined that "EU Directive is very incomplete in its treatment" and "additional improvements are needed to yield a better-founded, more transparent methodology" for the measurement of cogenerated electricity, especially in large scale CHP plants. Badami et al. [17] performed an energetic and economic assessment of cogeneration plants, comparing the results achievable under theoretical/design conditions with those obtained under real/experimental ones. They observed that the primary energy saving index and the simple payback time can significantly differ, also implying large discrepancies to occur between the expected and actual numbers of Tradable White Certificates. Unfortunately, the referenced paper only performs CHP technology-based analyses, not posing any focus (as made in this paper, conversely) on the influence of the specific industrial or civil user supplied with heat and power. Colmenar-Santos et al. analysed the barriers to the growth of CHP-based district heating in Europe [18], under the current framework determined by provisions of Directive 2004/8/EC and the support mechanisms in force at EU level. Finally, Piacentino et al. [19] analysed the feasibility of sector- and user-oriented settings to "calibrate" the formulas proposed by Directive 2004/8/EC, in order to achieve the aforementioned convergence between the conditions maximizing the "private" and "social-collective" benefits; however, the analysis covered only three particular applications in the civil sector (i.e. hospitals, hotels and office buildings).

To the authors' knowledge, no critical analysis of the influence of the CHP Directive provisions on the optimal design and operation strategies for industrial users has been proposed in literature, thus making the present paper to represent an innovative contribution. Also, the specific focus here posed on a dual purpose "CHP + MED desalination" plant makes the approach even more innovative, since the largest share of the currently installed thermal desalination capacity is located in Middle East, where (due to the easy and cheap access to fossil fuels) there is a lack of normative instruments aimed at regulating specific targets for the energy saving to be achieved by CHP plants.

2. Description of the MED-TVC plant and the retrofit scheme

The examined Multi-Effect Distillation plant consists of 4 units, with 12 effects each, which can be operated independently according to the water requests of the served community. Each module has got a capacity of 9,000 m^3/d capacity, for a total plant