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Economic analysis of a combined power and desalination plant considering availability changes due to degradation

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HIGHLIGHTS

- The paper presents a new economic analysis method for thermal systems.
- State space method with time-varying failure rate is used to estimate availability changes due to degradation and overhauls.
- The maintenance cost is calculated considering overhaul and number of components repairs.
- A combined gas turbine and multi-stage flash desalination plant is considered as the case study.
- The results are compared with conventional economic analysis method.

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ABSTRACT

In a conventional economic analysis, the availability of system is considered as a constant value. However, some factors such as increasing components' failure rate due to degradation, reducing failure rates by replacement or repairing, and stops in operation because of overhauls change the availability during the lifetime of a system. Furthermore, due to overhauls and degradation, maintenance costs are not identical in different years. This paper presents a new approach for economic analysis of thermal systems in which change in the availability of system during its lifetime is considered. A combined gas turbine cycle and desalination is studied. The instantaneous availability of system is calculated using state space method with time-varying failure rates and considering overhauls. Then, the average availability of producing electricity and fresh water in each year of lifetime is applied to the economic analysis. In addition, maintenance costs are calculated according to the overhauls and the number of components repairs in each year. Finally, some economic indicators are compared in two cases of variable and constant availability, using the life cycle cost analysis method. Considering time-varying availability, increase in payback period is observed by 9 months and reduction in net present value by about $18 million.

1. Introduction

Economic analysis is one of the most important factors in selection and usage of thermal systems, in which indicators such as payback period, net present value, products unit cost, and benefit-cost ratio are studied by different methods. Life cycle cost analysis is one of the most widely used methods.

Performing an economic analysis needs some predictions regarding economic and operational parameters. There are some works which consider uncertainties in various economic parameters. For example, Momen et al. considered uncertainty of economic parameters in the economic optimization of a cogeneration system using Monte Carlo method [1].

There are many researches on the economic analysis and feasibility study of energy systems. An economic analysis was carried out on a cogeneration system, and the present value of incomes and costs, payback period, and internal rate of return were calculated [2]. Petrillo et al. presented a life cycle cost analysis and life cycle assessment for a hybrid renewable system [3]. Rodriguez et al. assessed the performance of several designs of hybrid systems composed of photovoltaic panels, solar thermal collectors, and natural gas internal combustion engines using life cycle cost analysis [4]. Tadros performed an economic study on multi-stage flash (MSF) desalination combined with a variety of steam and gas turbines and discussed the optimum value of performance ratio and its effect on reducing the desalinated water cost in each scheme [5]. Gomar et al. carried out a techno-economic analysis to select the most economic desalination method for Assaluyeh combined cycle power plant [6]. Rautenbach and Arzt demonstrated the superiority of the multiple-

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Nomenclature

$\overline{A}$	Average availability
P	Probability
W	Power (kW)
t	Time
i	Inflation rate (%)
d	Discount rate (%)
n	Year
$\dot{m}_f$	Fuel consumption rate (kg/s)
c_f	Fuel unit cost ($/GJ)
c_w	Fresh water price ($/m^3)
c_e	Electricity price ($/kWh)
N	Plant economic life (year)
Z	Investment cost (M$)

Greek letter

λ	Failure rate
μ	Repair rate
α	Weibull distribution scale parameter
β	Weibull distribution shape parameter

Abbreviation

PV	Present value
OM	Operation and maintenance cost
LHV	Lower heating value (kJ/kg)
MTTR	Mean time to repair
ARC	Average repair cost
O&M	Operation and maintenance
GT	Gas turbine
HRSG	Heat recovery steam generator
MSF	Multi-stage flash

Subscript

TC	Total cost
TB	Total benefit
f	Fuel
e	Electricity
w	Fresh water
G	Gas turbine
H	Heat recovery steam generator
D	Desalination

effect stack (MES) process compared to the standard MSF process for a desalination plant to combine with a 10 MW gas turbine [7]. Sun studied energy efficiency and economic feasibility of a cogeneration system and concluded that using this combined system results in 37% energy saving and payback period reduction of 4.5 to 2.65 years [8].

Operation time of a system during its lifetime and, as a result, the amount of products plays a key role in its economic analysis. Thermal systems cannot operate continuously because of random failures and preventive maintenance at defined intervals which change the availability of a system.

System availability depends on its components' failure and repair rates. However, if they are assumed to be constant with time, degradation of the system is ignored and, as a result, the availability is nearly constant. There are some researches on feasibility study and economic analysis of thermal systems, especially desalination plants coupled with a gas turbine, assuming a constant value for the system availability without any availability analysis [9–12].

There are different methods for reliability and availability analysis; one of the most widely used methods is Markov state space [13–16]. These studies assume constant values for components' failure and repair rates. If time-varying failure rates are considered in the availability analysis, the economic evaluation results will be more accurate. There are few studies on availability analysis with time-varying failure rates [17–23], and the results of these analyses have not been used for economic evaluation.

This paper presents a new method for the economic analysis of thermal systems considering time-varying availability. At first, instantaneous availability at any time is obtained using state space method with time-varying failure rates. Furthermore, periodic overhauls which stop production and decrease failure rates are considered. Then, the average availability in each year of system's lifetime is calculated and used for the economic analysis. The system studied in this research is an MSF desalination plant coupled with a gas turbine (GT) cycle. It is assumed that when the desalination plant or heat recovery steam generator (HRSG) is failed, the gas turbine can generate electricity. So, different availabilities are obtained for the electricity and fresh water production. Furthermore, maintenance costs in each year are calculated due to overhauls and the number of components' repairs.

2. System description

Today, use of cogeneration systems, due to their higher efficiency, is significantly increasing. One kind of these systems is simultaneous production of electricity and desalinated water which is useful in coastal areas. These lands have significant energy sources and need fresh water. One of the most common systems, combining a gas turbine power plant with MSF desalination plant through an HRSG, produces desalinated water by recovering excess heat of gas turbine exhaust. Fig. 1 shows the schematic of this system.

Power generation cycle consists of three main components of compressor, combustion chamber, and gas turbine. The compressor is connected axially to the gas turbine, and its power is provided by turbine during plant operation. After compressing, the fresh air enters the combustion chamber together with fuel. The produced high-temperature gas passes through the gas turbine where it expands to the atmospheric pressure, thus power is produced. Finally, the turbine exhausted gas enters an HRSG to give its heat to the MSF desalination plant.

3. Economic analysis

Economic analysis of a designed system requires estimation of major costs considering various assumptions and predictions (e.g. lifetime, inflation, and discount rate) and use of engineering economics techniques. Life cycle cost analysis is a method commonly used for evaluating the profitability of alternative investments. This method is based on cash flow analysis, while time value of money is taken into account. Considering variable costs and benefits due to changes in the availability and maintenance cost of system during its lifetime, the present value of cash flows is calculated. Then, three common economic indicators including net present value, payback period, and internal rate of return are used to evaluate the GT-MSF combined system.

3.1. Costs

The total cost of a system consists of investment, operation and maintenance costs. The investment costs include purchased equipment and land cost, installation, piping, designing, engineering, construction, and other costs before plant operation. Operation and maintenance (O&M) costs are incurred yearly, consisting of fixed O&M costs, variable O&M costs, and fuel cost [24].