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Original Article

Q1,2 INITIAL ESTIMATES OF THE ECONOMICAL ATTRACTIVENESS OF A NUCLEAR CLOSED BRAYTON COMBINED CYCLE OPERATING WITH FIREBRICK RESISTANCE-HEATED ENERGY STORAGE

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ABSTRACT

The Firebrick Resistance-Heated Energy Storage (FIRES) concept developed by the Massachusetts Institute of Technology aims to enhance profitability of the nuclear power industry in the next decades. Studies carried out at Massachusetts Institute of Technology already provide estimates of the potential revenue from FIRES system when it is applied to industrial heat supply, the likely first application. Here, we investigate the possibility of operating a power plant (PP) with a fluoride-salt-cooled high-temperature reactor and a closed Brayton cycle. This variant offers features such as enhanced nuclear safety as well as flexibility in design of the PP but also radically changes the way of operating the PP. This exploratory study provides estimates of the revenue generated by FIRES in addition to the nominal revenue of the stand-alone fluoride-salt-cooled high-temperature reactor, which are useful for defining an initial design. The electricity price data is based on the day-ahead markets of Germany/Austria and the United States (Iowa). The proposed method derives from the equation of revenue introduced in this study and involves simple computations using MatLab to compute the estimates. Results show variable economic potential depending on the host grid but stress a high profitability in both regions.

1. Introduction

The electricity market in the Western countries is facing changes engendered by market deregulation as well as new environmentally friendly energy policies. Studies show that large penetration of nondispatchable generators, mainly solar and wind generators, in an energy mix induces market volatility and that this is amplified in a deregulated market [1,2]. The variability in electricity price is expected to threaten the profitability of future nuclear power plants (PPs), while most current ones are currently operating in base-load to lower the impact of the investment cost on the electricity price.

Led by Massachusetts Institute of Technology, the project of the Q5 fluoride-salt-cooled high-temperature reactor (FHR) with Nuclear Air-Brayton Combined Cycle (NACC) and Firebrick Resistance-Heated Energy Storage (FIRES) aims to develop a PP that is able to generate profit from a variable electricity price [1,3,4]. This is achieved by operating a nuclear reactor at constant thermal power and using additional heat sources to provide a variable electric power output: natural gas burned with the air used as coolant of the power conversion cycle and the FIRES system in which heat can be charged, stored, and discharged. Both heat sources are added in addition to the nuclear heat when the market prices are sufficiently high. The additional heat from the heat storage system or the combustion of natural gas increases the highest temperature of the conversion cycle and is converted to electricity using the plant turbines. The system is able to convert the additional heat sources to electricity with an efficiency up to 66%, which is above efficiencies of most current PPs [1]. Moreover heat at high temperature can be sold directly to industry, offering an additional option to maximize profit. A supplemental revenue source from ancillary services, using the flexible capacity of such PPs, can also be valuable to a lesser extent [5].

Economically this system generates profit from variable electricity prices as well as from the difference in electricity and natural gas prices. Estimates for such a PP show a high profitability when the PP is implanted in markets in which natural gas price is slightly higher than the average variable electricity price. The case of the Iowa market (US) was studied when the system was applied to industrial heat supply (IHS) [6].

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Nomenclature

Abbreviations

FIRES	Firebrick Resistance Heated Energy Storage
FHR	Fluoride-salt-cooled High temperature Reactor
NACC	Nuclear Air Combined Cycle
IHS	Industrial Heat Supply
NCCC	Nuclear Closed Combined Cycle
PP	Power plant

Variables

R_X	Additional revenue generated by FIRES during X hours [€ or $]
Δt	Cycle duration [h]
$p^{DA}(t)$	Electricity price on the day-ahead market at time t [€/MWh_e or $/$MWh_e$] (simply noted p^{DA})
P_{in}	Electrical power to charge FIRES [MW_e]
$\dot{Q}_{out}$	Thermal discharging power of FIRES [MW_{th}]
$\dot{Q}_{nuclear}$	Thermal nuclear power [MW_{th}]
S_k	State of charge of FIRES after the k^{th} event (charge or discharge) [MWh_{th}]
η^{eh}	Electricity-to-heat efficiency of FIRES′ electrical resistances
K	Incremental heat-to-electricity efficiency related to FIRES
$t^{i,k}_{c,ini}$	Starting time of the i^{th} FIRES charge (k^{th} event, not displayed if unnecessary) [h]
$t^{i,k}_{c,fin}$	Ending time of the i^{th} FIRES charge (k^{th} event, not displayed if unnecessary) [h]
$t^{j,k'}_{c,ini}$	Starting time of the j^{th} FIRES discharge (k'^{th} event, not displayed if unnecessary) [h]
$t^{j,k'}_{c,fin}$	Ending time of the j^{th} FIRES discharge (k'^{th} event, not displayed if unnecessary) [h]
m	Number of FIRES charges during the current cycle
n	Number of FIRES discharges during the current cycle
μ	Yearly average of the amount of heat discharged from FIRES between two charges [MWh_{th}]
σ	Yearly standard deviation of the amount of heat discharged from FIRES between two charges [MWh_{th}]
H	Heat storage capacity of FIRES [MWh_{th}]

However closing the Brayton cycle can be of some interests; this is detailed in the first subsection. Instead of focusing on the revenue of the PP from both natural gas price and the electricity price, here the PP makes a profit only on the variable electricity price. This study aims to provide estimates of PP revenue when FIRES operates with FHR and a closed Brayton combined cycle.

First, we introduce the main points of interest of using the nuclear closed Brayton combined cycle with FIRES and describe how it operates. Second, we discuss a methodology to estimate the revenue expected from operating FIRES. Finally, results are given and discussed.

1.1. Main points of interest

The main motivation of using a closed Brayton cycle is a more robust containment against accidents releasing radioactive elements from the nuclear reactor. The closed Brayton cycle acts as an additional containment barrier.

Besides this advantage, the closed Brayton cycle gives more choices for the design of the PP, such as the Brayton cycle working fluid (use of inert gas, noncorrosive fluid, and fluid with high specific heat), the operating pressures (increase of the compactness), etc. The choice of the working fluid is a key factor to enlarge the range of nuclear reactors able to operate with FIRES. This is especially the case for some sodium fast reactors, e.g. the ASTRID project in France. The closed Brayton cycle involved in nuclear PPs is not new and experience already exists, in particular on helium-operated turbomachinery [7]. Table 1 presents some of the concepts of nuclear plants involving a closed Brayton cycle.

Finally, in countries where natural gas is mostly imported and its access is costly compared to the average wholesale electricity market price, the ability to use natural gas for supplemental power production can be less valuable. This has to be tempered by the high economical sustainability of NACC PPs, even in case of high break-even natural gas prices [13]. Hence the advantages of closing the Brayton cycle could surpass the benefits of keeping the cycle opened. The choice is made to perform estimates of revenue on the European market in Germany/Austria. To ensure comparison with estimates done in the previous study in the case of IHS, additional estimates are provided for the Iowa wholesale market [6].

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Table 1
Nonexhaustive list of nuclear plant concepts involving a closed Brayton cycle.

Reactor	Brayton cycle coolant	Projects and references
HTGR	He, $He-N_2$	GT-MHR [8], HTGR-GT [9], PBMR [10]
SFR	N_2	ASTRID Project [11]
GFR	He, $He-N_2$	EM2, ALLEGRO Project [12]

1.2. Operating modes

The PP is built with a high-temperature nuclear reactor, using a combined cycle in which the Brayton cycle is closed and a FIRES-like heat storage unit is installed. A flow-sheet of the simplified power conversion cycle is shown in Fig. 1. More complex nuclear closed Brayton combined cycles have been studied by North-West University (South Africa) [14]. Further studies will have to answer the design issues raised by the need to keep the nuclear reactor in

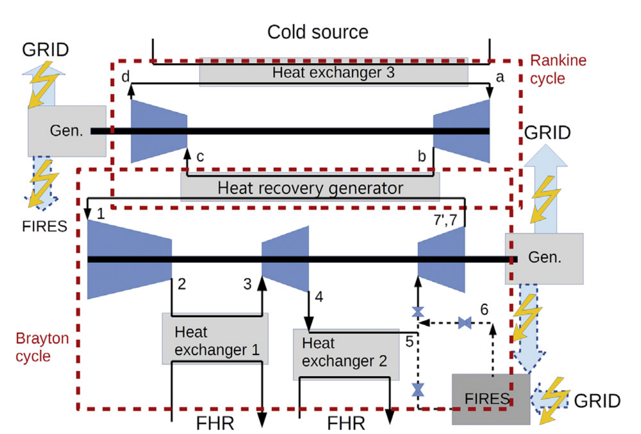

Fig. 1. Flow-sheet of the PP conversion cycle.
FIRES, Firebrick Resistance-Heated Energy Storage; FHR, fluoride-salt-cooled high-temperature reactor; PP, power plant.

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