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Nuclear Air Brayton Combined Cycle and Mark 1 Pebble Bed Fluoride-Salt-Cooled High-Temperature Reactor economic performance in a regulated electricity market

Charalampos Andreades [a,*], Per Peterson [b]

[a] University of California, Berkeley, 4118 Etcheverry Hall, Berkeley, CA 94720, United States
[b] University of California, Berkeley, 4167 Etcheverry Hall, Berkeley, CA 94720, United States

HIGHLIGHTS

- Mk1 FHR performs favorably compared to both utility and IPP built NGCCs.
- Mk1 FHR main performance drivers: electricity price, NG price, and the discount rate.
- Mk1 is much more attractive in markets where NG prices are high compared to NGCCs.

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ABSTRACT

Understanding the financial performance of an engineered system is a key step to its commercialization. In this study, the economic performance of the Mk1 PB-FHR using a nuclear air combined cycle to produce base load nuclear power, and highly efficient peaking power with gas co-firing, was estimated for a regulated electricity market structure. Initially, a survey of major U.S. nuclear utility holding companies' financials was performed to estimate a credible range of input parameters. In combination with the main cost parameters of the Mk1 estimated in a companion paper, a base case analysis was performed, demonstrating the economic attractiveness of the Mk1. A sensitivity study demonstrated that the main metrics of concern were electricity price, natural gas price, and the discount rate. These all pointed to possible ways to further reduce the Mk1's investment risk, such as long term fuel contracts and improved construction management, in order to further increase the attractiveness of Mk1 deployment. Finally, a comparison between the Mk1 and two different natural gas combined cycle (NGCC) plants was made. The Mk1 performance lies in between a utility built and an independent power producer built NGCC. The Mk1 becomes a much more attractive investment than conventional NGCCs in markets where natural gas prices are high.

1. Introduction

One of the most important aspects of designing a new commercial technology is understanding its revenues and long term economic viability. There are certain instances where an investor or business is willing to accept a loss on a specific product (e.g. loss leaders, technical displays), but in general the aim is to create value and generate profit in the long term. The profit of a product depends on two specific components, namely cost and revenue, the difference between the two being the profit/loss. This paper assesses revenues for Mark-1 Pebble Bed, Fluoride Salt Cooled Reactors (Mk1 PB-FHRs) coupled to nuclear air combined cycle (NACC) power conversion (Andreades et al., 2014a, 2016).

Narrowing our focus to the electricity sector, the main market of the FHR and NACC (Mk1), it is important to understand the fundamentals of this sector's operation and the ways in which it has evolved over its lifetime. Here we focus on the U.S. electricity sector, although the conclusions can be generalized to other countries. During the nascent years of the electricity industry at the turn of the 20th century, U.S. electric utilities operated in a fiercely competitive environment, competing primarily in price with gas lighting and self-generation. There was discussion of appropriate rate structures, such as time-of-use and block pricing, however the need for stability and investor attractiveness pushed industry pioneers, such as Samuel Insull, to promote demand charges and government regulation of utilities as protected monopolies. This

* Corresponding author.
E-mail addresses: charalampos@berkeley.edu (C. Andreades), peterson@nuc.berkeley.edu (P. Peterson).

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structure, in which utilities are guaranteed cost recovery at a regulated rate – cost plus x – allowed them to be shielded from competition, take advantage of economies of scale, and expand. Thus was the status quo for the next seven decades. Around the 1990s, an interest in electricity market liberalization and deregulation took shape due to success in deregulating other industries, such as telecommunications, trucking and commercial aviation, and a resurgence in competitive pricing in electricity markets was in vogue. This shifted electricity pricing away from average cost (AC) based to marginal cost (MC) based. The changing nature of modern electricity markets was and remains compounded by the large scale introduction of intermittent renewable energy sources. Flexible and quickly ramping capacity is needed to maintain grid stability, since traditional fossil fuel sources have physical ramp constraints and battery reserves are not well suited to utility scale capacities and demands.

The Mark 1 (Mk1) NACC is a novel power conversion system based on a modified General Electric (GE) 7FB natural gas (NG) turbine. The turbine is retrofitted to accept external heating from a heat source in the range of 600–700 °C, in this application an FHR, while also maintaining its ability to combust NG or other combustible fuel. When coupled to the 232 MW_t Mk1 PB-FHR, NACC provides 100 MW_e of baseload electricity with a 42% efficiency, and a boosted power output of 240MW_e under NG co-firing with a NG-to-electricity conversion efficiency of 66%, well above current state of the art NGCCs. A full technical description of the NACC can be found in Andreades et al. (2014b, 2014c). The NACC, with its ability to peak on-demand and provide flexible capacity make it an attractive and well suited candidate for the current and future low carbon electricity markets, with high penetration of intermittent renewable energy sources. To assess the Mk1 economic allure vis-à-vis its operating and physical benefits, this study aimed at initially quantifying the Mk1's revenue under certain hypotheses and constraints in a regulated electricity market. A description of the methodology used to perform the revenue estimation is given, followed by a summary of the relevant operating and cost inputs from a companion paper (Andreades, 2015). The revenue and profitability results are then presented, followed by discussion of the Mk1 results and a comparison made to its main competitors.

2. Methodology

In order to create a regulated market revenue model, an industry standard commercial software package, THERMOFLEX/PEACE®, was used (Thermoflow). Once a baseline NACC configuration was established based on the Mk1 PB-FHR commercial point design (Andreades et al., 2014a, 2016), and as detailed in Andreades et al. (2014b, 2014c), relevant cost estimates were given. A market survey of major U.S. nuclear utilities was performed to obtain a plausible range of financing and electricity market data. A base case was run with average values to establish a baseline reference, followed by a sensitivity study on each parameter separately. Two additional cases were run, an 'optimistic' and a 'pessimistic' one, in order to bound the results. Finally, a comparison was carried out between the NACC and a NGCC power plant based on the GE 7FB of similar power output, in order to establish how well the proposed design performed against its assumed main competitor. All currency units are set to 2014 USD.

3. Input data

The first step to performing a profitability analysis is assessing costs of the system in question, as given by Eq. (1).

$$Profit(Loss) = Revenue - Cost \quad (1)$$

The relevant costs for the Mk1 were estimated in a companion paper and a summarized version is presented in Table 1.

The next step is to appropriately identify and estimate financing numbers and structures that fit such a project and as required for input by THERMOFLEX/PEACE®'s, '*Economic and regional costs*' tab.

Some basic operating assumptions were made. The Mk1 is anticipated to have a 60 year lifespan; however, THERMOFLEX/PEACE® is limited to a 40 year assessment. In lieu, one can simply extrapolate the 40 year results to a 60 year lifetime. For the purposes of this study and for added conservatism a 40 year lifetime was assumed.

The first year of plant operation was assumed to be 2021, following an assumed 5-year construction period, for a 12-unit plant. THERMOFLEX/PEACE® does not account for staggered construction/operation which would provide added realism and thus results are conservative as initial revenue is generated at a later date, rather than as individual units come online. Such a modeling approach can be considered as a counterbalance to potential construction delays.

The NACC is anticipated to operate in a load-following mode due to its flexible capacity provided by its ability to produce peaking power by injecting NG or other liquid and gaseous fuels when quick ramping is needed by the electricity grid. For this study it was assumed that the 12-unit Mk1 NACC station ran at either 1200 MW_e nuclear capacity or at a full 2832 MW_e co-fired capacity. The capacity factor of the plant was assumed to be the 10-year nuclear industry average of 90%, with range between 80% and 95% (Nuclear Energy Institute, 2014). The Mk1's online refueling capability might enable a higher capacity factor, but current industry average was used for the base case instead for conservatism.

Typically, nuclear installation depreciation terms are set at 15 years (Department of Commerce Bureau of Economic Analysis, 2004). The Nuclear Energy Institute is proposing lowering this term to 7 years, as it affects a plant owner's tax expense (Fertel, 2004). A shorter depreciation term allows for a larger accounting expense each year and therefore reduced taxes in earlier years. A 30 year high was used for the depreciation range.

Debt terms for nuclear facilities are typically set at 15 years (OECD-NEA, 2009; IAEA, 1993). Longer terms allow for longer periods to repay and service the debt and are therefore more attractive. A 30 year maturity date was used on the high side, while the 15 year term was used as the base and lower range.

The following three financing components, namely debt percentage, debt interest rate, and discount rate, are usually highly project specific and in many cases confidential to the parties

Table 1
Overview of Mk1 costs.

Description	Single unit	12 Unit	
Capital construction costs			
Preconstruction costs	80,484,991	263,622,515	$
Total direct cost	214,846,727	2,578,160,727	$
Indirect cost	142,462,635	1,709,551,614	$
Total contingency	71,461,872	857,542,468	$
Total capital investment	509,256,225	5,408,877,325	$
Specific capital investment (nuclear)	**5093**	**4507**	$/kW
Specific capital investment (CF)	**2133**	**1870**	$/kW
Production Costs			
Total annual O&M	62,086,683	311,631,799	$
Fuel cost (annual)	7,750,516	93,006,192	$
Decommissioning cost (annual)	1,165,920	13,991,046	$
Overall production cost	71,003,119	418,629,037	$
Marginal production cost	**81.05**	**39.82**	$/MW h

Bolded numbers are the key comparison metrics used to compare electricity generation technologies.