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New technology integration approach for energy planning with carbon emission considerations

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ABSTRACT

This paper introduces a systematic methodology and corresponding tools to support the decision-making process for the integration of various improvement options, including new technologies, into existing mature processes. The proposed methodology was applied on a case study focusing on planning the capacity supply to meet the projected electricity demand for the fleet of electric generating stations owned and operated by Ontario Power Generation (OPG). A deterministic mixed integer linear program with a goal to minimize total annualized costs while satisfying various CO_2 emission constraints was developed. The results show that achieving the CO_2 emission mitigation goal while minimizing costs affects the configuration of the OPG fleet in terms of generation mix, capacity, selection of new technologies and optimal configuration with and without new technologies. By using new technologies including integrated gasification combined cycle (IGCC) and natural gas combined cycle (NGCC) with and without carbon capture and sequestration, the optimum electricity cost obtained was 1.1661 ¢/KW h at base caseload demand with 60% CO_2 reduction.

1. Introduction

Technological evolution is a continuous process aiming at improving the efficiency and environmental sustainability of process industries, and it is the main reason for the global competition confronting most businesses. Currently, industries are facing a number of challenges, the most significant of which are energy costs, greenhouse gas emissions, labor costs, and aging plants and infrastructure. New innovative technologies can offer enormous opportunities for profitable economic growth of industries. The integration of a new technology is sometimes far more complicated than a grass-roots design.

Current methodologies implemented for the integration of new technologies into existing processes focus only on state-of-the-art technology with little focus on financial risk. A study combining the process using available methodologies and a study of the technological development of the process and its financial risks allow the generation of a better solution. A new modified process results from the fusion of new and existing knowledge. Novel concepts or concepts novel to the process at hand can contribute to the development of new or modified processes that can be economically attractive. However, to be used effectively, these technologies or concepts must be carefully selected to match the requirements of the existing plant.

Several methodologies for process retrofit and design have been developed during the last three decades. Retrofit implies changes to the structure of a new flowsheet and to some equipment sizes in order to increase profitability of the plant. Fisher et al. [24] proposed a methodology of design retrofitting aiming at improving the cost efficiency of chemical processes. The analysis was based on a grassroot design method composed of hierarchical and heuristic elements, which was later refined and improved by Nelson and Douglas [18]. There are several methods that have been presented for grassroots design that consists of knowledge-based systems, design methods and process synthesis based on heuristic rules, engineering experience, detailed economic evaluation, and optimization methods [19,26,41,43].

Ben-Guang et al. [4] describe a methodology for retrofitting chemical processes that focuses on the bottleneck of a chemical plant. Guinand [28] proposes a broad approach in retrofit design, which includes formulation of retrofit incentive, process analysis, generation of alternatives and selection of the best alternative. Dunn and Halwagi [22] provided an attractive framework for the holistic analysis of process performance and the development of cost-effective and sustainable solution strategies.

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Nomenclature

Subscripts

f	fossil fuel plants
j	type of fuel (i.e., coal and natural gas)
k	CO_2 capture procedure
p	new fossil fuel plants
rn	renewable energy plants
sq	sequestration procedure

Continuous variables

E_f	electricity generation amount for fossil fuel plants
$Ek_{f,k,j}$	amount of electricity required for capture in fossil fuel plants
E_{nic}	electricity generation amount for IGCC station with capture
E_{nig}	electricity generation amount for IGCC station
E_{nnc}	electricity generation amount for NGCC station with capture
E_{nng}	electricity generation amount for NGCC station
E_{ns}	electricity generation amount for solar station
E_{nw}	electricity generation amount for wind station
E_p	electricity generation amount for new fossil fuel plants
E_{rn}	electricity generation amount for renewable energy plants
$\gamma_{f,j,k}$	slack variables for carbon procedure of fossil fuel plants
$\varphi_{f,\mathrm{sq}}$	slack variables for sequestration procedure of fossil fuel plants

Binary variables

$X_{f,j}$	fossil fuel plants selection and fuel type decision
X_{rn}	renewable energy plants selection
X_p	new fossil fuel plants selection
X_{new}	new tech plants selection
$W_{f,\mathrm{sq}}$	CO_2 sequestration procedure selection on fossil fuel plants
$Z_{f,j,k}$	CO_2 capture process selection on fossil fuel plants

Parameters

A_f	amortized factor
Cap	capital investment cost for all power plants
Cc_f	CO_2 capture cost for fossil fuel plants
Ccs	capture cost for fossil fuel plants
C_f	amount of carbon emission from fossil fuel plants
$C_{f,j}$	CO_2 emission from fossil power plants per unit of electricity generated
C_{new}	fixed capital cost for new tech stations
C_{now}	current amount of carbon emission in millions of tonnes per year
C_p	CO_2 emission from new fossil power plants per unit of electricity generated
Cre	CO_2 reduction target
C_{rn}	fixed capital cost for renewable energy plants
E_d	electricity demand
E_{reqf}	electricity required for capture process on fossil fuel plants
F_{max}	maximum electricity generated in fossil fuel plants
F_p	fixed capital cost for new fossil fuel plants
Ge	electricity demand increase
HR_f	heat rate generation for fossil power plants
HR_p	heat rate generation for new fossil power plants
Max$C$	maximum electricity requirement for capture process
O_f	operating cost for fossil power plants
O_{new}	operating cost for new tech station
O_p	operating cost for new fossil power plants
OpC	operating cost for all power plants
O_{rn}	operating cost for renewable energy plants
Per$C$	CO_2 capture factor
P_{max}	maximum electricity generated in new fossil power plants
Pr_j	price for raw materials, coal and natural gas
R_f	retrofit cost factor due to fuel switching for fossil fuel plants
$\mathrm{RN}_{\mathrm{max}}$	maximum electricity generated in renewable energy plants
Seq	sequestration cost for fossil fuel plants with capture
S_f	sequestration cost for fossil fuel plants

Several retrofit design methodologies presented in the literature handle the problem of energy and waste minimization [16,53]. The implementation of process energy integration technology plays a significant role in reducing energy consumption of chemical processes, which was addressed by Huiquan and Pingjing [30]. Several researchers have investigated the use of the pinch technology combined with optimization methods to generate improved heat exchanger network designs and sensitivity analysis approaches [33,35,39,47,54]. Querzoli et al. [42] propose a methodology for increasing the energy efficiency of refining processes. Fisher et al. [25] propose a systematic procedure for developing and screening process retrofit that considers the alteration of the structure of a process flow sheet and the capacities of the incorporated equipments. Their main contribution is the proposition of a systematic approach to identify equipments that cause bottlenecks in process operations. Their main findings indicated that retrofitting chemical processes with the goal of minimizing raw material costs is more beneficial that minimizing energy costs. Halim and Srinivasan [29] introduce a retrofit design methodology for waste minimization.

Alternate solutions are generated when more than one alternative process or technology is identified that can be applied to reduce the cost or improve the efficiency of the process. There are several techniques in the literature in screening of alternatives. Several researchers have used the pinch analysis in screening alternatives in retrofitting various chemical processes [5,48]. The cost diagram is an approach to summarizing cost information at the initial stage of the design [52]. Douglas and Woodcock [20] indicate that the cost diagrams are often useful for checking rules of thumb, for obtaining quick estimates of the economics of process alternatives and for establishing a hierarchy of optimization variables. The mathematical programming techniques have made significant contributions in the screening of alternatives [13]. Bumann et al. [8] developed a systematic retrofit approach to optimize chemical batch processes. The main contribution of their work is the utilization of statistical evaluation of historical process data to generate process performance trends.

The sensitivity analysis, together with a hierarchical method [21] was used as a starting point to identify possible alternatives and to generate the mixed-integer non-linear program (MINLP) superstructure. Jaksland et al. [32] describe a thermodynamic based approach for generating and screening process alternatives. Maechal and Kvalitventzeff (1996) combine pinch analysis and mathematical techniques. A MINLP model is applied in the structural and parameter optimization of utility plants as explained by Bruno et al. [7]. It included combined advantages of