Energy Conversion and Management 100 (2015) 177–190

Contents lists available at ScienceDirect

Energy Conversion and Management

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

Design multiperiod optimization model for the electricity sector under uncertainty – A case study of the Emirate of Abu Dhabi

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ARTICLE INFO

Article history:
Received 1 February 2015
Accepted 1 May 2015
Available online 17 May 2015

Keywords:
Multiperiod
Uncertainty
UAE
Power system
Nuclear power
Renewables

ABSTRACT

In this study, a multiperiod model that considers uncertainty in the gas feedstock fuel price is developed for the optimal design of electric power systems. The optimization problem was formulated as a multiperiod stochastic programming model using the GAMS® modeling system. Previous studies have analyzed the United Arab Emirates' (UAE) power infrastructure either using a deterministic point of view or simulation tools (e.g., MESSAGE and MARKAL). These previous research has demonstrated that natural gas will remain playing a significant role as key feedstock fuel in the UAE's power sector. However, the present work is designed to be the first to consider different supply options for the natural gas feedstock (i.e., domestic, pipeline imports, and LNG imports) and electricity imports in the UAE power sector. Moreover, the natural gas supply and electricity import options are considered to be decision variables in the problem's formulation. Additionally, the considered case studies assumed a realistically existing power infrastructure for the UAE, whereas previous works considered the planning of the UAE power infrastructure as a Greenfield project. Also, to the authors' knowledge this is the first work to consider a robust optimization model for planning the UAE power infrastructure under uncertainty in the long term horizon. The model was used to study the planning of the power plant infrastructure in the UAE between 2015 and 2040 under uncertainty in the natural gas price. The optimization results show that the model is a valuable tool for planning the optimal power plant infrastructure of the country, reducing levelized electricity costs, and mitigating social and environmental damages.

1. Introduction

The majority of the electricity produced in the United Arab Emirates (UAE) is generated using gas-fed thermal generation plants [1,2]. Accordingly, despite holding one of the largest hydrocarbon reserves in the world, the UAE became a net importer of natural gas in the year 2007 [3]. The UAE is planning to diversify its domestic energy mix outside fossil-based electricity generation. The plans include the deployment of nuclear and renewable energy plants [2,4,5]. Additionally, an international electricity grid connecting the Gulf Cooperation Council (GCC) countries is currently under construction. Natural gas represents approximately 81% of the overall primary energy supply in the UAE. Thus, the country heavily relies on natural gas, particularly in the electricity sector where 99% of the generation is gas-based [2].

As the consumption of electricity increases at an accelerating rate, the generation capacity of the country needs to be expanded. The expansion of the UAE's electricity sector is fundamental to ensure the country's energy security and economic growth. This process will have to be planned well in advance in order to implement the optimal strategy over a period of time that allows securing the UAE's electricity supply at the lowest cost and mitigating environmental damages. The use of mathematical modeling approaches is a suitable tool for planning the expansion of electric power systems. Also, they can be used to study the operation of the system, and evaluate techno-economic and environmental constraints in the network.

Previously, many efforts have been made to develop mathematical models for effectively addressing the planning of electric power systems. For example, Almansoori et al. [6] developed a deterministic mixed integer linear programming (MILP) model for the optimal design of the UAE's power system. The model was used to analyze the UAE's power system considering different gas price levels, social benefits of air emission avoidance, and CO_2 emission constraints in the year 2020. However, the model did not account for different gas/electricity import supply options, and only considered a single period in the analysis. Avetisyan et al. [7] presented a model for the optimal expansion of a developing power system. The problem's goal was to find the optimal

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http://dx.doi.org/10.1016/j.enconman.2015.05.001
0196-8904/

Nomenclature

Indices

c	GCC country
e	type of air emission
f	gas supply source
p	power plant type
s	scenario or realization
t	time period (years)
t'	any previous time period (years)

Sets

CCS	{gas power plants with carbon capture and storage}
$Exist$	{existing power plants}
Gas	{gas – based power plants}
New	{new power plants}
Nu	{nuclear power plants}
$Oper$	{operating power plants}
Re	{renewable power plants}
η	{set of decision variables}

Continuous variables

$AE_{e,t}^{(s)}$	amount of air emission e avoided by using alternative energy sources (tonne/h)
$AP_{p,t}^{(s)}$	total installed power capacity from plants type p in the sth scenario of period t (kW)
$CC_{p,t}^{(s)}$	amount of CO_2 avoided in the pth plant by using CCS methods (tonne/h)
$CE_t^{(s)}$	annual external nuclear power plants' costs in the sth scenario of time period t ($/yr)
CF	problem's objective cost function ($/yr)
$CIE_t^{(s)}$	annual cost of the imported electricity to the country ($/yr)
$CNF_t^{(s)}$	annual cost of the nuclear fuel in time period t ($/yr)
$CNG_t^{(s)}$	cost of the natural gas consumed in the sth scenario of period t ($/yr)
$CP_{p,t}^{(s)}$	compression power required to transport the CO_2 capture (kW)
$CSC_t^{(s)}$	annual captured CO_2 storage cost ($/yr)
$CTC_t^{(s)}$	annual captured CO_2 transport cost from gas-based plants with CCS methods ($/yr)
$DE_{p,t}$	generation capacity loss by decommissioned units in period t (kW)
$ECAP_t^{(s)}$	annualized capital cost of existing plants p in time period t ($/yr)
$EE_{p,t}^{(s)}$	amount of energy generated by existing plants p in period t (kW)
$EG_{p,t}^{(s)}$	total amount of electricity produced by power plants p in period t (kW)
$EM_{e,t}^{(s)}$	emission e produced by the gas-based power fleet in time period t (tonne/h)
$EOM_t^{(s)}$	annual operating and maintenance cost for plant p in time period t ($/yr)
$ET_{c,t}^{(s)}$	electricity transferred from country c to the UAE in period t via international grid (kW)
$GS_{f,t}^{(s)}$	gas supply from source f in time period t (Nm^3/h)
$NCAP_t^{(s)}$	annual capital cost for power plants p built during period t ($/yr)
$NE_{p,t}^{(s)}$	amount of energy generated by new power plants p in period t (kW)
$NOM_t^{(s)}$	annual operating and maintenance cost for new power plants p in time period t ($/yr)
$SB_t^{(s)}$	social benefit related to the air emissions avoided in the sth scenario of period t ($/yr)
$TC_t^{(s)}$	compression power required in CCS (kW)
$TE_t^{(s)}$	total electricity generated by the power fleet in scenario s and period t (kW)
$TI_t^{(s)}$	total electricity imported from the GCC interconnected grid in period t (kW)
$TFC_{i,t}^{(s)}$	total amount of fuel i consumed by the power fleet in period t (Nm^3/h) (kg/h)
$TNG_t^{(s)}$	total amount of natural gas consumed by the power sector in period t (Nm^3/h)

Integer variables

$X_{p,t}$	number of power plants p decommissioned in time period t
$y_{p,t}^{(s)}$	number of new power plants p built during time period t
$z_{p,t',t}^{(s)}$	number of existing plants p built in a previous period t' and available during period t

Parameters

AF_e	air emission e avoidance factor (tonne/kW h)
AD_e	avoided damage of emission e ($/tonne)
CAD	CO_2 emission avoided damage ($/tonne CO_2)
$CAPF_{p,t}$	power plant's p capital factor for time period t ($/kW)
CCF_p	carbon capture factor associated to the p plant (tonne/kW h)
CD_p	nuclear unit p decommissioning cost ($/kW h)
CF_p	power plant's p capacity factor (%)
CPF	compression power required to transport the captured CO_2 (kW h/(tonne·km))
CS_p	nuclear power plants' system costs ($/kW h)
CSF	captured CO_2 storage cost factor ($/tonne)
CTF	captured CO_2 transport cost factor ($/tonne·km)
$ECF_{c,t}$	electricity import cost factor from country c in time period t ($/kW h)
ED_t	Country's electricity demand in period t (kW)
$EF_{p,e}$	air emission factor associated to the pth plant (tonne/kW h)
$HV_{p,i}$	average heating value of fuel i used in the pth power plant (MJ/Nm^3) (MJ/kg)
HR_p	power plant's p heat rate (MJ/kW h)
IC_p	power plant's p installed capacity (kW)
IR	annual real debt interest rate (%/yr)
LT_p	lifetime which is assumed as the depreciation time of the pth power plant (yr)
$MG_{f,t}$	maximum gas volume available for delivery from source f in time period t (Nm^3/h)
MI_t	maximum grid transferred capacity in the UAE in period t (kW)
$OMF_{p,t}$	operating and maintenance cost factor for plant p in time period t ($/yr)
OT	annual operating time (h/yr)
PL_p	pipeline length travelled by the CO_2 captured at the pth plant (km)
$PT_{p,t}$	installed power capacity target for plants type p in period t (kW)
RF_p	annual capital recovery factor (%/yr)
UC_p	uranium fuel cost per type of power plant p ($/kW h)
$w_t^{(s)}$	weight or probability of scenario s at the time period t (%)
WD_p	nuclear waste disposal cost ($/kW h)
$\Omega_{p,t}$	bound for the new power plants p built in period t
$\Phi_{p,t}$	bound for the decommissioned power capacity of plant p in period t
ε_t	power generation losses (%)
$\sigma_{f,t}^{(s)}$	price of natural gas from source f in the sth scenario of period t ($/$Nm^3$)