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Design optimization model for the integration of renewable and nuclear energy in the United Arab Emirates' power system

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HIGHLIGHTS

- A design optimization model for the power sector has been developed.
- We examine the influence of exogenous variables in the UAE power infrastructure.
- Subsidizing fuel prices will stimulate fossil-based electricity generation.
- Carbon tax and higher fuel prices are suitable options to decrease air emissions.
- Accounting the social benefits of emissions avoidance incentivizes diversification.

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ABSTRACT

A Mixed Integer Linear Programming (MILP) formulation is presented for the optimal design of the United Arab Emirates' (UAE) power system. The model was formulated in the General Algebraic Modeling System (GAMS), which is a mathematical modeling language for programming and optimization. Previous studies have either focused on the estimation of the UAE's energy demands or the simulation of the operation of power technologies to plan future electricity supply. However, these studies have used international simulation tools such as "MARKAL" and "MESSAGE"; whereas the present work presents an optimization model. The proposed design optimization model can be used to estimate the most suitable combination of power plants under CO_2 emission and alternative energy targets, carbon tax, and social benefits of air emissions avoidance. Although the proposed model was used to estimate the future power infrastructure in the UAE, the model includes several standard power technologies; thus, it can be extended to other countries. The proposed optimization model was verified using historical data of the UAE power sector operation in the year 2011. Likewise, the proposed model was used to study the 2020 UAE power sector operations under three scenarios: domestic vs. international natural gas prices (considering different carbon tax levels), social benefits of using low emission power technologies (e.g., renewable and nuclear), and CO_2 emission constraints. The results show that the optimization model is a practical tool for designing the UAE power infrastructure, evaluating future production technologies and scenarios, and identifying key parameters affecting the UAE power sector.

1. Introduction

The current increasing social pressures on global warming issues and high oil prices have attracted the international attention. Social pressure aims to prevent serious impacts on both the environment and economic growth. According to the International Energy Agency (IEA), in 2009 approximately 68% of the electricity generated originated from fossil fuels such as: coal (40.6%), natural gas (21.4%) and oil (5.1%). The remaining share of electricity was produced from hydro (16.2%), nuclear (13.4%) and renewable sources (3.3%) [1,2]. The production of electricity from fossil fuels is higher in the developing world. Thus, the use of renewable and cleaner energy sources is needed to secure electricity supply in developing regions, including the United Arab Emirates (UAE).

The UAE's power sector completely depends on conventional fossil fuels. For example, in 2009 approximately 98% of the electricity was generated using natural gas-based power plants [3]. On the other hand, electricity demand growth has accelerated in recent years to 9% [4]. Although the country holds one of the largest energy endowments in the world [5]; it became a net importer of natural gas in 2007 [6]. The increasing gas requirements result,

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Nomenclature

Model variables

$AEA_{e,p}$	emission *e* avoided using plant *p* (tonne/h)
Cap_p	capital cost of the power plant *p* ($/yr)
CC_p	CO_2 captured by plant *p* (tonne/h)
CE_p	CO_2 eq. produced by plant *p* (tonne CO_2/h)
CF	objective cost function ($/yr)
$EC_{c,p}$	external cost *c* associated to the air emissions of the power plant *p* ($/yr)
EF	electricity produced by fossil sources (kW)
$EG_{e,p}$	emission *e* generated by the plant *p* (tonne/h)
ER	electricity produced by renewable sources (kW)
EN	electricity produced by nuclear sources (kW)
EP_p	electricity produced by the power plant *p* (kW)
FC_p	fuel cost of the plant *p* ($/yr)
NG_p	natural gas consumed by the plant *p* (Nm^3/h)
OM_p	operating and maintenance cost of *p* ($/yr)
PC_p	total annual power production cost ($/yr)
PPC_p	cost associated to the public perception on the deployment of the *p*th power plant ($/yr)
TCC	total CO_2 captured in the power fleet (tonne CO_2/h)
TCE	CO_2 eq. produced in the fleet (tonne CO_2/h)
TCP	total compression power used to transport the captured CO_2 to the sequestration sites (kW)
TCS	total CO_2 sequestration cost ($/yr)
TCT	total CO_2 transport cost ($/yr)
TEP	total electricity produced by the fleet (kW)
TNG	natural gas consumed by the plants (Nm^3/h)

Integer variables

IE_p	number of power plants *p*

Sets

c	set of external cost associated to the air emissions
e	set of gaseous air emissions
p	set of power plants
η	set of decision variables in the design optimization model

Sub-sets

g	subset of natural gas-based power plants
n	subset of nuclear power plants
s	subset of solar-based power plants
w	subset of wind turbine farms

Sets and subsets elements

cc	Natural Gas Combined Cycle (NGCC) plants
cs	concentrating solar power (CSP) plants
dis	cost discount due to emission abatements
gt	power gas turbines
ot	ocean thermal energy conversion (OTEC) plants
ox	oxyfuel power plants
pv	photovoltaic power plants
sp	solar land pond power plants
st	power steam turbines
tax	toll paid due to the generation of air emissions

Model parameters

A	surface covered by the photovoltaic cells (m^2)
$AEF_{e,p}$	emission *e* from the plant *p* (tonne/kW h)
AF_p	capital amortization factor of plant *p* (%/yr)
AI	annual capital interest rate (%)
AN	total array number of wind turbines in the farm (units)
BOS_p	balance of the system cost for PV ($/$m^2$)
CCF_p	CO_2 capture factor of plant *p* (tonne CO_2/kW h)
CET	maximum allowable CO_2 emission from the country's power infrastructure (tonne CO_2/h)
CF_p	capacity factor of power plant *p* (%)
CPF	power consumed per unit of CO_2 and traveled distance (kW h/(tonne) (km))
CSF	CO_2 sequestration cost ($/tonne CO_2)
CTAX	CO_2 tax cost ($/tonne CO_2)
CTF	CO_2 transport cost ($/tonne km)
DT_p	depreciation time of plant *p* (yr)
ED	total electricity demand input (kW)
ENG_e	average emission *e* generated by the conventional NGCC fleet in the UAE (tonne/kW h)
ESC_e	avoided social cost associated to the emission *e* by using alternative energy plants ($/tonne)
FCF_p	fuel cost factor ($/MJ)
FLH	full load hours for wind turbines in a given geographic location (%)
HR_p	heat rate of the power plant *p* (MJ/kW h)
IC_p	installed capacity of power plant *p* (kW)
Ins_p	installation cost for photovoltaic plants ($/$m^2$)
E_p^L	minimum allowable number of plants *p* (units)
E_p^U	maximum available number of plants *p* that can take part in the power infrastructure (units)
OMF_p	operating and maintenance cost factor (%), ($/kW h) or ($/yr)
PCF_p	power plant *p* capital factor ($/kW) or ($/m^2)
PL_p	distance traveled by the CO_2 captured at *p* (km)
AE_p	minimum installed generation capacity expected of power plants type *p* (kW)
RET	minimum overall installed capacity expected from renewable sources (kW)
RRF_p	repair and replacement cost factor (%)
SCC	avoided social cost of CO_2 emitted to the atmosphere ($/tonne)
SE_p	share of electricity produced by *p* (%)
t	total operating time of the infrastructure (h/yr)
UCF_p	unit capacity factor of plant *p* (units)
WT	number of wind turbines in the farm's arrays (units)

Acronyms

ADWEC	Abu Dhabi Water and Electricity Company
BAU	business-as-usual
CAC	criteria air contaminants (e.g., NOx, SO_2 and PM_{10})
CCS	carbon capture and storage
CH_4	methane emissions
CO_2	carbon dioxide emissions
CO_2 eq.	carbon dioxide equivalent
CSP	concentrating solar power
GHG	greenhouse gases (e.g., CO_2, CH_4 and N_2O)
MILP	mixed integer linear program
N_2O	nitrous oxide emissions
NGCC	Natural Gas Combined Cycle
NOx	nitrogen oxides emissions
OTEC	ocean thermal energy conversion
RSB	Regulation and Supervisory Bureau of the Emirate of Abu Dhabi
SO_2	sulfur dioxide emissions
UAE	United Arab Emirates
yr	year