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Multi-period optimization model for the UAE power sector

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Abstract

A multi-period power optimization model for the UAE's electricity sector is presented. The model aims to minimize the cumulative costs and CO_2 emission of the UAE's power sector during the planning horizon. The optimization problem was formulated as a multi-period MILP model in the GAMS modelling system. Previous studies have analyzed the UAE power infrastructure using standard simulation software such as MARKAL and MESSAGE. The present work's novelty consists of determining the optimal evolution of the power generation infrastructure during different time periods under operational and environmental constraints. The optimization model was used to study the UAE's power system for the time periods comprised between the years 2015 and 2040. The simulation results show that the mathematical model is a valuable tool for planning the optimal evolution of the power plants' fleet in the country, reduce levelized electricity costs and emissions, meet energy targets, and evaluate new power technologies.

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Keywords: Multi-period, Power system, Optimization, Renewables, Nuclear, UAE.

1. Introduction

The United Arab Emirates (UAE) is one of the 10 largest oil and natural gas producers in the world. The fast economic and demographic growth over the last decade has put a lot of pressure on the country's electricity grid. Accordingly, the annual electricity consumption rate has experienced an increase of approximately 8 to 9% over the past years [1]. The majority of the electricity produced in the UAE (approximately 98%) is generated using gas-fed thermal generation [2, 3]. Accordingly, despite holding one of the largest reserves in the world, the UAE became a net importer of natural gas in the year 2007 [4]. Regardless of the abundance of energy resources in the country, the UAE is planning to diversify its domestic energy mix outside fossil-based electricity generation. The plans include targeting a share of 25% of nuclear and 7% of renewable in Abu Dhabi's power installed capacity by 2020. Additionally, the Gulf Cooperation Council (GCC) countries interconnected grid can be used to transfer power from members with an excess in electricity production to those with an undersupply. The expansion of the UAE's electricity sector is fundamental to ensure the country's energy security and economic growth.

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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 while mitigating environmental damages. Many pathways of different scales and from different considerations have been previously proposed for the UAE's power sector [5-7]. However, all of the aforementioned studies are based on standard simulation software (e.g., MESSAGE, MARKAL) and they can be considered more as simulation tools instead of optimization models.

In this work, a novel Mixed Integer Linear Program (MILP) model is presented for the optimal planning of the UAE electricity sector for multi-period operation. The optimization model was developed using the GAMS® modelling system. The paper is presented as follows: Section 2 presents the problem definition. Section 3 shows the formulation of the multi-period model. Section 4 shows two case studies for the optimal planning of Abu Dhabi's power sector over the timeframe 2015-2040. Concluding remarks are presented at the end of this work.

2. Problem Definition

Given are a set of power generation plants with their corresponding operating capacities and air emissions. Additionally, natural gas supply sources and electricity import options for the UAE's electricity system are set. A multi-period picture is considered, where the electricity demand is changing over each time period *t*. Also, given are the capital, fuel and operating costs for the power technologies; in addition to the power imports and carbon capture and storage costs for each time period *t*. The operational planning problem consists of determining the choice of operating units, type of fuels, and power imports for each time period that minimizes the cumulative cost over the entire planning horizon. The optimization process is subjected to meeting the electricity demand at each time period over the planning horizon under technical and environmental constraints.

3. Optimization Model

The conceptual formulation of the optimization problem is presented as follows:

$$\min_{\eta} \; CF = \sum_t CAP_t + OM_t + CHF_t + CNF_t + CA_t + CTC_t + CSC_t + CIE_t \qquad (1)$$

subject to

Feedstock fuel prices per time period t	(4)-(5)
Power Demand per time period t	(10)
Alternative Energy Targets per time period t	(11)
Import Power Capacity from neighboring countries per time period t	(12)
Natural Gas Supply Sources and Availability per time period t	(13)
Decommission Generation Capacity per time period t	(14)
Power Plant Technologies (fossil, wind, solar and nuclear)	(15)

The objective function of the deterministic multi-period MILP model is to minimize the cumulative discounted present value of the power generation costs over a specified planning horizon (*CF*). The subindex *t* denotes the time period, CAP_t is the capital costs of the power plants in period *t*, OM_t is the operating and maintenance costs for the plants; CHF_t is the cost of the hydrocarbon fuels, CNF_t is the cost of nuclear fuel, CA_t are the plants' additional costs (e.g, waste disposal, risks), CTC_t and CSC_t are the carbon capture transport and storage costs, respectively; whereas CIE_t is the cost of electricity import. Additionally, the problem's set of decision variables η includes: the type and number of power plants, operating capacities, quantity and supply source of the feedstock fuels and imported power. The International System of Units (SI) was used in this model.

3.1. Power Costs

The power plants' capital costs can be calculated as follows:

$$CAP_t = \sum_{p \in New \cup Exist} Y_{p,t}\ \mathrm{IC_p}\ \mathrm{CAPF_{p,t}}\ \mathrm{CF_p}, \quad \forall t = 1,..., P \tag{2}$$

where the subindex p denotes the type of power plant, the sets *New* and *Exist* represent the new and existing plants, respectively; $Y_{p,t}$ is an integer variable denoting the number of plants p in period t, $\mathrm{IC_p}$ is the installed capacity of plant p, $\mathrm{CAPF_{p,t}}$ is the capital factor of plant p in period t, and $\mathrm{CF_p}$ is the annual capital amortization factor associated to the p^{th} plant. The operating and maintenance (O&M) costs associated to the power plants can be calculated as follows:

$$OM_t = \sum_{p \in New \cup Exist} Y_{p,t}\ \mathrm{OMF_{p,t}}, \quad \forall t = 1,.., P \tag{3}$$

where $\mathrm{OMF_{p,t}}$ is the operating and maintenance cost factor of plant p in period t. The hydrocarbon fuels h used in the power plants are: gas (g), diesel (d), and crude oil (c). These fuels' costs are calculated as:

$$CHF_t = \sum_f \sum_h \mathrm{HC_{h,f,t}}\ HS_{h,f,t}\ \mathrm{OT}, \quad \forall t = 1,..., P \tag{4}$$

where $\mathrm{HC_{h,f,t}}$ is the price of the hydrocarbon fuel h from source f in period t, $HS_{h,f,t}$ is the amount of hydrocarbon fuel h from f in period t, and OT is the annual operating time. The cost of nuclear fuel (CNF_t) consumed by the power reactors is given as:

$$CNF_t = \sum_{p \in Nu} Y_{p,t}\ \mathrm{IC_p}\ \mathrm{CF_p}\ \mathrm{UC_p}\ \mathrm{OT}, \quad \forall t = 1,..., P \tag{5}$$

where the set *Nu* represents the nuclear plants, $\mathrm{CF_p}$ is the plant's p capacity factor and $\mathrm{UC_p}$ is the uranium fuel price used by nuclear plant p. The power plant's additional associated costs (CA_t) are given as:

$$CA_t = \sum_p Y_{p,t}\ \mathrm{IC_p}\ \mathrm{CF_p} \left(\mathrm{WD_p} + \mathrm{CD_p} + \mathrm{CS_p} + \mathrm{CR_p}\right) \mathrm{OT}, \quad \forall t = 1,..., P \tag{6}$$

where $\mathrm{WD_p}$, $\mathrm{CD_p}$, $\mathrm{CS_p}$, and $\mathrm{CR_p}$ denote costs related to waste disposal, plants' decommissioning, plant's system, and public perception risks, respectively. The carbon capture transport cost (CTC_t) associated to the fossil-based power plants with CCS methods can be calculated as follows:

$$CTC_t = \sum_{p \in CCS} CC_{p,t} \left(\mathrm{CTF}\right) \mathrm{PL_p} \left(\mathrm{OT}\right), \quad \forall t = 1,..., P \tag{7}$$

where the set *CCS* represents the power plants with carbon capture and storage methods, $CC_{p,t}$ is the quantity of CO_2 capture in plant p, CTF is the CO_2 unit transport cost factor, and $\mathrm{PL_p}$ is the pipeline length travelled by the CO_2. Similarly, the CO_2 storage cost (CSC_t) can be estimated as:

$$CSC_t = \sum_{p \in CCS} CC_{p,t} \left(\mathrm{CSF}\right) \mathrm{OT}, \quad \forall t = 1,..., P \tag{8}$$

where CSF denotes the CO_2 unit storage cost factor. On the other hand, the import electricity cost (CIE_t) from the interconnected GCC regional grid to the country is given as follows:

$$CIE_t = \sum_{c \in GCC} ET_{c,t}\ \mathrm{ECF_{c,t}}\ \mathrm{OT}, \quad \forall t = 1,..., P \tag{9}$$

where the set *GCC* denotes the GCC countries, $ET_{c,t}$ is the electricity transferred from the c country to the UAE in period t whereas $\mathrm{ECF_{c,t}}$ is the unit electricity import cost from country c in time period t.

3.2. Model Constraints, Power Generation and Air Emissions

In this section the key model's input are presented. Accordingly, the total electricity demand ($\mathrm{ED_t}$) in the country can be formulated as follows:

$$TE_t\left(1-\varepsilon_t\right)+TI_t-TC_t \geq \mathrm{ED}_t, \quad \forall t=1,\ldots,P \tag{10}$$

where TE_t is the total electricity generated, ε_t denotes the generation losses, TI_t is the imported electricity, and TC_t is the CO_2 compression power. The alternative energy targets ($\mathrm{ET}_{p,t}$) are given as follows:

$$\sum_p E_{p,t} \geq \mathrm{ET}_{p,t}, \quad p=\mathrm{Ren},Nuc, \forall t=1,\ldots,P \tag{11}$$

where the set *Ren* represents the renewable power plants, and $E_{p,t}$ is amount of electricity generated by plant type *p* in time period *t*. The power imports are given as follows:

$$TI_t \leq \mathrm{MI}_t, \quad \forall t=1,\ldots,P \tag{12}$$

where MI_t is the maximum grid capacity for the UAE in period *t*. Additionally, the natural gas supply constraints from different sources *f* (e.g., domestic, pipeline imports, and LNG cargoes) is given as:

$$HS_{h,f,t} \leq \mathrm{MG}_{h,f,t}, \quad h=g, \forall f, \forall t=1,\ldots,P \tag{13}$$

where $\mathrm{MG}_{h,f,t}$ is the maximum gas volume available from source *f* in period *t*. Furthermore, the loss of generation capacity in the fleet ($DE_{p,t}$) due to the decommissioning of power units is defined as follows:

$$DE_{p,t}=X_{p,t}\,\mathrm{IC}_p\,\mathrm{CF}_p, \quad \forall p, \forall t=1,\ldots,P \tag{14}$$

where $X_{p,t}$ is an integer variable denoting the number of power plants *p* decommissioned by time period *t*. The electricity generated by type of power plant *p* in each time period *t* can be estimated as follows:

$$E_{p,t}=Y_{p,t}\,\mathrm{IC}_p\,\mathrm{CF}_p, \quad \forall p, \forall t=1,\ldots,P \tag{15}$$

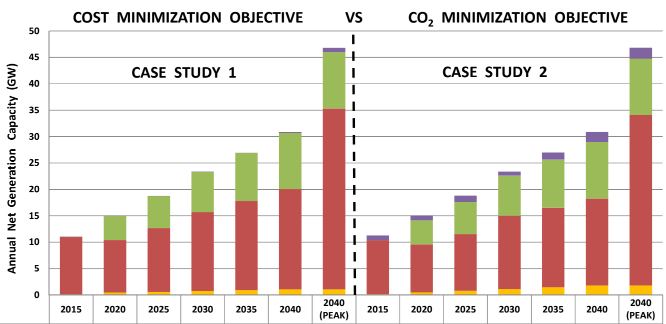
The cumulative CO_2 emission from the power fleet in the planning horizon (*CO2E*) is estimated as:

$$CO2E=\sum_t \sum_{e\in CO_2} \sum_{p\in Fossil} E_{p,t}\,\mathrm{EF}_{p,e,t} \tag{16}$$

where the subindex *e* denotes the type of emission (e.g., CO_2), the set *Fossil* represents the fossil-based power plants, and $\mathrm{EF}_{p,e,t}$ is the factor for emission *e* associated to power plant *p* in the t^{th} time period.

4. Case Study: Abu Dhabi's power sector planning for the timeframe 2015-2040

The modelling and optimization framework presented in the previous section has been applied to two case studies for the planning of Abu Dhabi's power sector over the timeframe 2015-2040, considering a time span of five years between studied periods. The first case study considers the minimization of the cumulative cost (1) as optimization objective whereas the second considers the minimization of the cumulative CO_2 emission (16) as objective. The initial power fleet (t=0) according to the literature [2, 3] was assumed to be composed of gas generation (99%) whereas renewable made up the remaining (1%).



	2015	2020	2025	2030	2035	2040	2040 (PEAK)	2015	2020	2025	2030	2035	2040	2040 (PEAK)
GCC grid Power (GW)	0.05	0.01	0.07	0.09	0.03	0.16	0.83	0.90	0.90	1.20	0.77	1.31	1.95	2.09
Nuclear Power (GW)	0.00	4.55	6.07	7.59	9.11	10.63	10.63	0.00	4.55	6.07	7.59	9.11	10.63	10.63
Gas-based Power (GW)	10.88	9.96	12.03	14.93	16.89	18.97	34.26	10.19	9.05	10.76	13.91	15.09	16.50	32.34
Renewable Power (GW)	0.13	0.47	0.62	0.77	0.93	1.08	1.08	0.18	0.53	0.80	1.13	1.46	1.79	1.79

Fig. 1. Annual net power generation capacity in Abu Dhabi for the timeframe 2015-2040.

Fig. 1 illustrates the power generation optimization results for the two case studies (separated by a black dashed line). The cost objective and CO_2 reduction objective results are shown on the left-hand and right-hand side of the figure, respectively. As shown in Fig. 1, for the two case studies the overall power generation picture for 2015 is similar to that of the initial fleet since no major changes are expected to take place for this time period. However, some differences can be observed comparing both cases. For example, the predominance of gas power is higher in the first case study (98.4%) compared with the second case (90.4%). Also, imported power from the GCC interconnected grid represents an important resource in the second case study whereas its share in the first case study is practically negligible. This is the result of no considering the CO_2 emissions generated by the imported power (in its source country) as part of the Emirate’s power sector lifecycle emission. Thus, the substitution of domestic fossil-based generated power by imported power is found to be the most suitable option in the second case study to reduce the CO_2 emissions compared with the first case in 2015. Moreover, the share of renewable power is greater in the second case study since renewables are considered to be carbon-free technologies.

Furthermore, the energy mix increases after the year 2015 as a result of the emirate’s commitments on alternative energy options for the year 2020 and onward due to energy security reasons. Consequently, for the second period (year 2020) mainly due to the introduction of nuclear energy, the net gas power generation capacity decreases to 67% (first case study) and 60% (second case study) of the overall capacity. Nuclear power accounts for approximately 30% of the net generation capacity in both case studies given its high annual capacity factor whereas renewable contributes with over 3% given its low annual capacity factor. Additionally, power imports account for 0.1% and 6% of the capacity in the first and second case study, respectively. The previous power generation capacities remain at similar levels throughout the planning horizon (see Fig. 1) since new deployments of nuclear and renewable energies can be expected, but a slower pace than that experienced in the year 2020. Furthermore, fossil-based power generation is expected to remain as the main electricity source. Nonetheless, in the second case study all the new fossil-based plants deployed include CCS methods for CO_2 abatement (additional costs) whereas in the first case study none of the new gas plants include CCS methods. Moreover, although a CO_2 pipeline network is currently under development, the capacity of the pipeline would have to be greatly expanded (compared with the originally envisioned capacity) in order to transport the levels of CO_2 suggested in the second case study.

Regarding the CO_2 emissions, Fig. 2 shows the projected Emirate’s power sector CO_2 emissions in the planning horizon 2015-2040 for both case studies. According to the figure, in the year 2015 the CO_2 emissions reached approximately 35 and 33 MT/yr for the first and second case study, respectively. On the other hand, the avoided CO_2 emissions due to the use of renewable energies were 0.43 and 0.59 MT/yr, respectively. Moreover, in the year 2020 the carbon emissions are reduced to 32 and 29 MT/yr in the first and second case study, respectively. This is despite the increase in the net power generation capacity in both case studies. On the other hand, in 2020 the CO_2 emissions avoided grow to around 16 MT/yr for both case studies, which is a very significant increase compared with the previous period. These outcomes are the results of introducing clean alternative energies in the power infrastructure, particularly nuclear power. From the third period (year 2025) onward, the CO_2 emissions for both case studies become increasingly divergent (see Fig. 2). For instance, for the first case study there is a sustained increase (at a medium-to-low slope) in the emission rate; whereas for the second case study there is an increasingly downward trend in the CO_2 emission (at a high slope). Furthermore, although in both case studies the emissions avoided grow with each time period; the rate is much higher in the second case study. The difference is given by the deployment of gas-based plants with CCS methods in the second case study compared with the non-presence of this type of technology in the first case study.

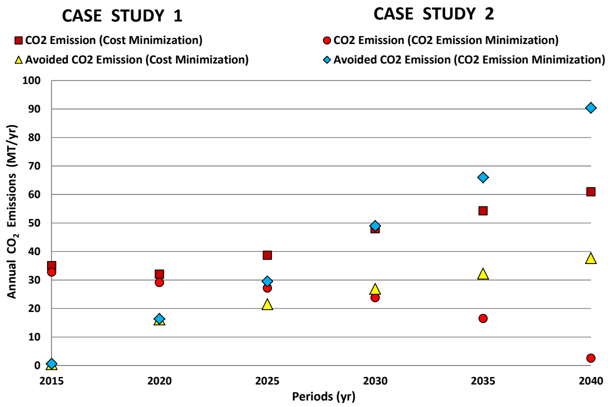


Fig. 2. Abu Dhabi's power sector CO_2 emissions between the year 2015 and 2040.

The use of alternative hydrocarbon fuels, e.g., diesel and crude oil, in the Abu Dhabi's power sector operation was also considered in the present analysis. However, as the gas supply is significantly less expensive and more environmentally friendly than the alternative hydrocarbon fuels; the latter fuels were not selected as part of the optimal power sector operations. Accordingly, the use of alternative hydrocarbon fuels is restricted to gas supply gaps as backup fuels under emergency circumstances.

5. Conclusions

This paper presents a novel multi-period optimization model for the planning of the UAE power sector. A case study showcasing the planning of Abu Dhabi's power infrastructure comprising the timeframe 2015-2040 was analyzed. The results show that nuclear energy will play an important role in the emirate's power mix diversification in the short-to-long term future. Accordingly, nuclear represents around one third (30%) of the total annual net power generation from the year 2020 onward. Renewable energy will also contribute to the power generation capacity at a comparatively smaller scale. Furthermore, the introduction of alternative energy options will decelerate the growing CO_2 emission trend of the emirate's power sector in the cost minimization case study; whereas absolute CO_2 emission reductions are obtained in the emission minimization case study aided by the use of CCS methods.

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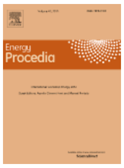

Biography

The biography of the corresponding author. (50 words)

Dr. Almansoori holds a PhD in Chemical Engineering from the Imperial College in London. In August 2006, he joined the Petroleum Institute (PI) in Abu Dhabi, and currently holds the position of Dean of Engineering and Associate Professor. His research interest include: process systems engineering, simulation, optimization, and energy systems.