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Long-term optimization of Egypt's power sector: Policy implications

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ABSTRACT

This paper presents an evaluation of energy supply strategies for Egypt's power sector and identifies prospects to meet rising electricity demand while addressing energy security and low-carbon development issues. We apply the TIMES energy system model to examine Egypt's energy policy goals as reflected in *Egypt's Vision 2030*, and specifically: (a) targeted power generation based on renewable energy under two different scenarios; (b) targeted carbon dioxide (CO_2) emissions' mitigation toward low-carbon society development; and (c) constraints on natural gas production for power generation. The quantitative results from the model suggest a need for diversification from predominantly natural gas to a mix of renewable and conventional energy sources in order to improve energy security, reduce dependency on fossil fuels, and reduce carbon dioxide emissions, with the level of diversification changing with different policy options. Although total energy system cost is projected to increase the effects on fossil-fuel dependency, diversity of energy supply-mix, marginal electricity generation price, and GHG mitigation indicate that it may be wise to target promotion of renewable energy for power generation and develop a low-carbon society.

1. Introduction

Energy is a key determinant of socioeconomic development [1], in part, because energy consumption and economic growth are interrelated [2]. Energy is a vital commodity in modern living and a necessary intermediate input in all productive sectors. Moreover, energy access helps to improve conditions that, in turn, can alleviate poverty and contribute to sustainable development [3], [4]. While energy security is essential for economic growth and development, the power sector is responsible for 41% of global CO_2 emissions. Without addressing emissions levels, countries cannot meet CO_2 mitigation targets, as laid out in the Paris Climate Agreement and nationally determined contributions (NDCs) [5]. Thus, policies targeting increased energy efficiency as well as promotion of renewable energy technologies are key for sustainable energy development [6]. In this context, Egypt's energy sector faces the dual challenges of heavy reliance on fossil fuels and increased energy demand in all sectors [6], [7]. The country's new energy strategy aims to ensure energy security by increasing energy efficiency as well as through diversification [8].

Studies show that the current energy mix and trend in Egypt is similar to that of other emerging economies, where the share of renewable energy in power generation is declining despite the increase in renewable energy diffusion and investments overtime, due to higher growth in overall energy demand [9], [10]. Current power generation in Egypt is dominated by natural gas, which contributes more than three quarters of total generation [11]. The power sector consumes more than 50% of all natural gas, with the share of renewable energy declining from 13% in 2010 to 10% in 2014 [11]. Although Egypt is the twenty-fifth largest oil producer in the world and has 4.5 billion barrels of crude oil reserves [12], resources have been declining rapidly; it is projected that only about 1.5 billion barrels of oil reserves will be available by 2030 [13]. Natural gas reserves are favorable for power generation, and the new strategy also aims to accelerate gas field exploration and development [8]. However, the current policy to expand natural gas use in all sectors (in place of petroleum products) will lead to a rapid decline in natural gas reserves, which is further fueled by exports.

Although electricity generation has seen impressive growth, it

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still falls short compared to rapidly increasing energy demand. Total electricity generation in Egypt increased from 95 TWh in 2003–04 to 131 TWh in 2009–10 and 168 TWh in 2013–14 which presents an average annual growth rate of 5.8% [14]. Installed capacity of power plants increased from 23.5 GW (GW) in 2008–09 to 32 GW in 2013–14 [15], [16]. Renewables (solar and wind) contributed about 2% of total capacity share in 2013–14. Hydropower capacity has not increased in recent years; and stagnates at 2.8 GW, contributing 9% of total capacity in 2013–14, down from 12% in 2008–09.

In contrast to sluggish changes on the supply side, energy use through the electric grid increased from 64.3 TWh in 2000–01 to 147.5 TWh in 2013–14, which represents an annual growth of about 6.5% [17]. About 43% of total electricity was consumed by the growing residential sector in 2013–04—an increase from 38% in 2007–08. The industrial sector follows as the second largest consumer (26%) of electricity [11], [14–16].

The potential for renewable energy production is relatively high in Egypt. Specifically, wind and solar could continuously supply energy services thereby improving energy security [6], [18]. Moreover, diversification of energy production from a system dominated by fossil-fuel and natural gas to a system involving greater use of renewable energy resources could help improving Egypt's energy security while maintaining gas exports and foreign exchange income, minimizing environmental impacts, and contributing to the development of a "green economy" (or a low-carbon development society).

The feasibility of diversifying the energy supply-mix and integrating renewable energy into the existing system along with any policy implications for the development of long-term sustainable energy strategies can be assessed by applying bottom-up energy optimization models such as MESSAGE, MARKAL, WASP and TIMES. The MARKAL (MARKet Allocation) and TIMES (The Integrated MARKAL-EFOM System) models are widely used to evaluate the impact of national, regional and global energy and environment policies as well as to perform techno-economic assessments. Selected national-scale applications of these models include: long-term energy and emissions forecast for China [19], electricity supply industry for South Africa [20], technology selection for Bangladesh power sector development [21], carbon emission control strategies for China [22], GHG mitigation and associated cost assessment of the French biofuel sector [23], residential heat system planning for Germany [24], electricity decarbonization pathways for Portugal [25], integration of household preferences for heating technologies in the UK [26], the Canadian energy outlook 2050 [27], and multi-pollutant policies for the United States' power sector [28]. Salient regional applications include: energy-economic scenario analysis of alternative fuels for personal transport [29], assessment of policy and technology mixes required to achieve long-term energy security and environmental sustainability growth of Sub-Saharan Africa [30], assessment of clean technologies for selected ASEAN countries [31]. Finally, selected global studies include: shale gas supply curves for 15 world regions [32], waste heat management at power plants and water conservation [33], and climate mitigation options under uncertain technology futures of the world energy system [34]. The application of such an energy model for Egypt can provide important insights into the implications of prospective conversion technologies and energy supply options that can be pursued by the government of Egypt in a cost-efficient and effective way.

However, the development and application of a comprehensive bottom-up energy optimization models for the assessment of long-term energy policies and low-carbon development strategies for Egypt is currently lacking. Shaaban (2017) developed a prototype model (an approach of integrating multi-criteria decision analysis, geographic information system data analysis and agent-based modelling) for Egypt to assess an energy security roadmap for Egypt [35]. In the study, future energy-mix for Egypt according to actors' priorities are assessed and presented, but as suggested by the authors, the study lacks precision. Other energy studies for Egypt include: solar and wind power for economic development [6], sustainable development indicators for the assessment of electricity production [36], an assessment of Egypt's concentrated solar power components [37], a sustainability assessment of electricity generation technologies [38], and a further road map for renewable energy research and development [39].

This study is using the TIMES optimization modelling framework in order to identify the most cost-efficient energy development pathways that meet Egypt's rising electricity demand while improving energy security, promoting indigenous energy use, and mitigating GHG emissions. Moreover, sensitivity analysis is performed to account for variations in discount rates, energy prices, investment costs (of renewable energy technologies), and impacts of nuclear power plants.

2. TIMES model

The TIMES model is a successor of MARKAL discussed in Ref. [10] and has been promoted by the executive committee of the International Energy Agency's Energy Technology Systems Analysis Program (IEA-ETSAP) since 2008. About 70 countries and approximately 250 institutes have applied the TIMES/MARKAL model to assess long-term energy supply alternatives [40]. The model determines the energy and technology mix needed to meet the energy demand of an energy system, given specific limitations regarding available technologies and energy sources. It then determines an optimal energy supply mix (in economic terms) based on technological and economic parameters, such as the minimum cost for the technologies selected [41].

TIMES is a bottom-up energy system optimization model [42]. It computes an economic equilibrium for energy markets, from supply to end-use energy services. The model is demand-driven and computes both energy flows and prices so that supply meets demand. The main building blocks of the model are processes (for example, the types of power plants or technologies) and commodities (for example, the energy carrier, cost, emissions level, etc.), which are connected by commodity flows in a network called the reference energy system (RES). The RES approach facilitates graphical analysis of the whole energy system—from primary energy resources to sector-wide energy services—through different conversion processes.

The objective function is usually chosen to minimize the long-term discounted cost of the energy system. The objective function is the sum of all region objectives, all discounted to the same modeler-selected base year. The formulations of the objective function and related basic equations are presented in Ref. [10]. The constraints (equations or inequalities) and objective function (criteria to be minimized or maximized) are expressed by decision variables and parameters, where decision variables are unknown or endogenous quantities, which TIMES solves for, and parameters that are specified by the modeler. Details of the TIMES objective function, equations, variables, and parameters are discussed in the IEA-ETSAP documentation in Ref. [42]. The configuration of the supplied RES is dynamically adjusted by TIMES in such a way that all model equations are satisfied, and long-term system cost is minimized.

The model determines the volume of energy and investment needed to meet projected energy demand. It fixes technological capacity by year, the level of utilization of selected technologies, and environmental impacts. The environment is an important restriction for any energy conversion process, and this issue is explicitly considered in the TIMES model. The model finds an optimal energy supply-mix (in economic terms) based on technological and economic parameters, such as the minimum cost for the technologies selected.

The TIMES database includes technologies ranging from primary energy extraction, energy processing and conversion, energy transportation, and end-use. A typical TIMES model's main input and output parameters are presented in Fig. 1 (without showing the constraints). The model solves for a series of constraints, such as renewable production targets, CO_2 emissions mitigation targets, and resource availability (not shown in Fig. 1). Model results include the most cost-efficient electricity generation, fuel requirements, emissions, energy imports/exports, electricity production by fuel type, marginal price of electricity, and other criteria.

3. Egypt-TIMES development

The Egypt-TIMES model is composed of four modules: (1) primary energy, (2) process and conversion technologies, (3) electricity demand, and (4) GHG emissions.

The primary energy supply in the Egypt-TIMES model includes mining of indigenous conventional resources (including natural gas and crude oil), renewable energy resources (including solar, wind, hydro, and geothermal), imported heavy fuel oil (HFO), and diesel. The model allows the export and import of electricity. Fuel prices used for 2014, 2015, and 2016 are based on national reports and international data, presented in Table 1 [43–46]. An annual increase of 1.50% and 1.45% is assumed from 2017 onward for natural gas and oil prices, respectively, over the study period [47]. The electricity price is assumed to increase by 2.5% per year [47]. Natural gas consumption for power generation increased from 18,270 million cubic meters (m^3) in 2009–10 to 29,332 million m^3 in 2013–14. An annual growth of 4% is therefore applied for use of natural gas for power generation [11].

Egypt aims to interconnect with regional and international electricity networks by 2020 [7]. The National Democratic Party Congress decreed in 2007 to implement a unified Arab electricity network, interconnect it with Arab-Maghreb countries and the European network across Mediterranean countries, and to invest in water resources in African countries for electricity generation [7]. In 2013–14, Egypt imported 61 GWh and exported 460 GWh of electricity [16]. A maximum of 1000 GWh for importing and 5000 GWh for exporting electricity is assumed by 2050.

Primary fuels are converted to secondary energy and electricity through conversion technologies. The power generation sector considers 57 existing power plants, twelve types of new power generation technologies, and five government-planned gas-based combined cycle plants (including steam turbine, solar PV, concentrated solar power (CSP), and wind power) that are expected to be installed within the next five years. Among fossil-fuel based new conversion technologies, this study considers efficient gas-based combined cycle (CC), HFO-based steam turbine, diesel-based gas turbine, and dual fuel-fired (gas and HFO) technologies. Renewable technologies considered are solar PV, CSP, wind, hydro, and geothermal; we consider two technologies for each type of technology with an introduction in 2020 and 2030, depending on the technology "learning cost effect." In addition to the investment cost of the new Damanhour power plant, the Suez steam power plant and the Gulf of Suez wind power plant data, techno-economic parameters for fossil-fuel based power plants are reviewed and incorporated in the modelling based on a series of national and international studies [48–51]. Renewable technologies are also reviewed and incorporated in the modelling based on additional studies [50, 52–55]. Table 2 provides an overview of selected key conversion technologies. Due to limited technical know-how in nuclear and fuel cell technologies in Egypt, these technologies are not considered in the reference case. In addition, Egypt has no coal power plants and limited coal reserves (18 million tons [35]) and the technology does not support mitigation goals; coal-based power plants are therefore not incorporated in this study.

The Gulf of Elzait region has an excellent wind power potential of about 20 GW [18]. Other areas such as Owaynat, Sinai, and the north coast have significant potential for wind power. Power generation from solar has particularly high potential in Egypt, at about 74,000 TWh per year [18]. The maximum potential of renewable energy technologies is based on findings from Refs. [56], [57]. Geothermal is also included although there is a very limited potential of about 20 MW [58]. Technology learning cost effects for wind, solar PV, and CSP power plants are considered in this

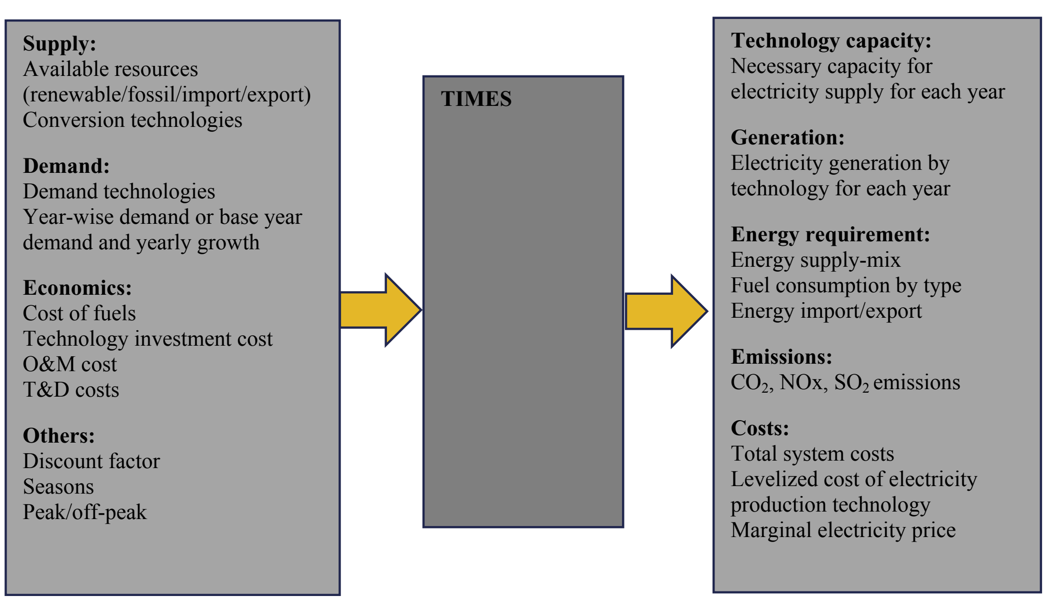

Fig. 1. Key inputs and outputs parameters for a typical TIMES model for power system.

Table 1
Energy prices and limits applied in modelling.

	2016	2020	2025	2030	2040	2050
Mined natural gas:						
Cost (US$/GJ)	2.84	3.01	3.25	3.5	4.06	4.71
Mined crude oil:						
Cost (US$/GJ)	6.06	6.42	6.90	7.42	8.56	9.89
Imported heavy fuel oil:						
Cost (US$/GJ)	7.09	7.51	8.07	8.67	10.02	11.57
Electricity cost[a]:						
Imported (US$/GJ)	13.15	14.84	16.79	19.00	24.32	31.14
Exported (US$/GJ)	21.01	23.2	26.24	29.69	38.00	48.65
Solar, wind, hydro, geothermal and biomass	Resource bound for biomass: 350 PJ by 2050. New wind bound: 30 GW, solar (including solar PV and CSP): 50 GW, geothermal: 0.02 GW and hydro: 10 GW by 2050					

[a] Imported electricity is expected to increase from 0.22 PJ in 2014 to 3.6 PJ by 2050 and exported electricity increases from 1.66 PJ in 2014 to 18 PJ by 2050.

Table 2
Overview of selected key conversion technologies.

Technology	Year of introduction	Efficiency (thermal plants)	Availability factor	Investment cost (US$/kW)	Fixed O&M cost (US$/kW/yr)
Government planned:					
Gas combined cycle	2016	0.55	0.95	947	18.9
Gas steam turbine	2015	0.42	0.90	676	30
Solar PV	2015	–	0.33	4800	60
Concentrated solar power	2016	–	0.40	5056	67
Wind	2015	–	0.33	2000	60
Expected advanced:					
Duel fired (Gas and HFO)	2020	0.45	0.90	950	15
Fuel-oil steam turbine	2020	0.40	0.90	825	18
Gas combined cycle	2020	0.56	0.95	917	18.3
Hydro	2020	–	0.70	2640	60
Solar PV	2020	–	0.33	4451-3150*	40
CSP	2016	–	0.40	4879-4252*	67.6
Wind	2020	–	0.33	1800-1700*	60
Geothermal	2016	–	0.80	3650	229

Notes: * The later value shows investment cost in 2030 as technology learning cost effects are considered in modelling, i.e. the investment costs for these technologies decrease during the investment periods.

analysis. An annual growth constraint of 30% for wind and solar PV and 20% for CSP is applied [21], [59]. A transmission loss of 4.5% and a distribution loss of 10% is incorporated in the modelling [16]. This study assumes that all existing power plants will continue to be used, given that most power plants in developing countries are not shutdown but instead are retrofitted to allow for continuous operation.

The demand module comprises total economy-wide electricity demand for Egypt, resulting from intermediate demand of production sectors, final demand of consumers and the government, and export demand from abroad. Annual electricity demand for the period 2014 to 2050 is projected by applying a single-country, recursive-dynamic, multi-sectoral computable general equilibrium (DCGE) model. The DCGE model, developed at the International Food Policy Research Institute, has been designed primarily for the analysis of agricultural strategies, income distribution, and household welfare in an open economy facing import and export competition on world commodity markets [60], [61]. However, by including all the demand components mentioned above, the model can be used to quantify the impact of population and income growth etc. on total electricity demand, including indirect demand resulting from general equilibrium effects. The links between the economic DCGE model and the TIMES energy model are described in more detail in Ref. [62].

The model is based on microeconomic theory and uses a competitive economy with flexible prices and market-clearing conditions. Agents represented in the model are (1) consumers, who maximize utility; (2) producers, who maximize profits; and (3) the government. The economy is connected to the rest of the world via trade and capital flows. The dynamic framework of DCGE is "recursively dynamic," meaning that the evolution of the economy over time is described by a sequence of single-period static equilibria connected through capital accumulation, changes in labor supply and agricultural land, and sector-specific technical progress. The economic structure of DCGE is fully specified and covers production, investment, and final consumption by consumers and the government. Policy instruments in DCGE are taxes, subsidies, or quantity constraints in factor markets, product markets, and international trade. The Egypt DCGE is used to project electricity demand that is forwarded to the TIMES model during the analysis period.

The CGE model projected electricity demand is exogenous in the Egypt-TIMES modelling. The economic model projects an average annual growth rate of 4.46% for electricity demand until 2050 starting from a base-year (2014) demand of 144 TWh. As mentioned, the TIMES model then determines the optimum energy supply-mix and technology selection to meet this electricity demand under given constraints regarding renewable production targets, CO_2 emissions mitigation targets, and natural resource availability. The CGE model projected electricity demand of 4.46% is considered for modelling.

Carbon Dioxide (CO_2), nitrogen dioxide (NO_x), and sulfur dioxide (SO_2) emissions from power generation are considered in this modelling. Intergovernmental Panel on Climate Change (IPCC) emissions factors are used for GHG emissions calculations [63–65].

3.1. Other model variables

Additional model variables used in TIMES are summarized in the following. The analysis covers a 36-year period from 2014 to 2050.

The year 2014 is used as the base year in this analysis. The 36-year span is divided into 8 periods: span one for two years (2014–2016), span two for four years (2016–2020) and the remaining time spans cover 5 years each. Considering the years of introduction of technologies (mostly in 2016 and 2020) and to reflect the installation capacities planned by the government by 2020, we shortened the initial span to 2 years (2014–2016) and 4 years (2016–2020), respectively. A discount rate of 10% is applied in this analysis [66]. As this rate is very significant for all financial results, sensitivity analysis is performed considering alternative discount rates to see its impact on technology choices. All costs are presented in terms of 2014 US dollars (USD), where 1 Egyptian pound (LE) = 0.138 USD [45], [67]. Alternative rates are applied in the sensitivity analysis. All power plants are considered to be grid connected and electricity storage is included in this modelling. The model determines how much electricity must be generated to feed to the national grid to meet the specified projected demand. Total electricity losses are estimated at 14.5% (transmission loss: 4.5% and distribution loss: 10%). End-use demand technologies are merged into their respective sector-wise electricity demand that refers to the gross-demand of each sector. An assumption is made that all the existing power plants will continue their operation to work throughout their life time. The electric load profile was differentiated according to three seasons—intermediate, summer and winter—and distinguishes between day and night. The efficiency of thermal power plants and the level of emissions are considered for full-load conditions. This study assumes that sufficient infrastructural support will be available for transportation and installation of new power plants. No constraint is imposed on the availability of financial resources as the private sector is expected to be involved in future power sector development in Egypt.

4. Scenario development

Egypt's Vision 2030, the country's sustainable development strategy, considers energy as the second most important pillar among ten pillars for sustainable development [68]. The vision report highlights optimal and domestic use of energy resources as well as diversification of the energy supply-mix to incorporate renewable energy for power generation. The Ministry of Electricity and Renewable Energy and *Egypt's Vision 2030* have a common strategy to generate 20% of total electricity from renewable energy by 2020 [68], [69]. Moreover, the Egyptian NDC emphasizes mitigation of CO_2 emissions from the energy sector. Drawing on Egypt's sustainable development strategy and its energy and environmental policy goals outlined in different reports [11], [13], [16], [68–71], the following reference and alternative scenarios were developed in the Egypt-TIMES model to assess their feasibility, benefits, and co-benefits:

1. **Reference scenario:** This scenario does not impose any policy intervention and considers a continuance of existing energy-economic dynamics. It serves as a reference for comparing alternative policy options and their technology selection and investments, technology capacity, energy requirement, cost, and GHG emissions.
2. **Renewable energy development (Renewable Target30 and Target40) scenarios:** This is a "what if" scenario, in which a certain share of renewable-based power generation is targeted to meet future electricity demand. Two targets of renewable energy developments were assessed:
   a. Renewable Target30: A minimum of 20% renewable energy-based power generation by 2020 and 30% by 2050 is an alternative policy option based on *Egypt's Vision 2030*, which outlines the government's renewed commitment for substantial renewable energy in total power generation.
   b. Renewable Target40: A minimum of 20% of the total electricity by 2020 and 40% by 2050 from renewable energy is targeted in this alternative energy scenario.
3. **CO_2 mitigation scenario**: This "what if" scenario evaluates technology choices under explicit reductions of CO_2 emissions. We simulate a 5-percent CO_2 emissions mitigation rate by 2020, 10% by 2030, and 25% by 2050.
4. **Limited gas production scenario:** This "what if" scenario evaluates impacts of a reduction in Egypt's natural gas production for power generation. The country's natural gas reserves and production ratio is expected to decline from 37 years to 17 years by 2030 [13]. Statistical data show that natural gas production in Egypt increased from 18.3 million ton of oil equivalent (mtoe) in 2000–01 to 46.68 mtoe in 2009–10, followed by a decrease to 39.24 mtoe in 2013–14 [14]. Production levels decreased further in recent last years. This scenario considers a 2% growth of natural gas production for power generation until 2050 compared to the historic increase of 2.8%.

5. Interpretation of TIMES results

5.1. Technology capacity development and electricity generation

The TIMES model projects a rise of total capacity of power plants from 37.7 GW in 2016 to 126.7 GW in 2050 to meet the electricity demand in the reference scenario (Table 3). New diesel and dual-fired power plants do not get additional selection in the reference scenario, while there are substantial increases in investment in efficient combined cycle natural gas based power plants. The model finds feasibility to invest in HFO-based steam, hydro, and wind power in the end period of the analysis. The electricity generation share from dual and natural gas based power plants increases from 84% in 2016 to 91% in 2050 in the reference scenario. At the same time, the share of renewables in the electricity generation-mix declines from about 15% in 2016 to 6% in 2050. Total electricity generates about 183 TWh in 2016 and 808 TWh in 2050. Fossil-fuel dependency rises from 1588 PJ in 2016–4975 PJ in 2050, an annual average increase of 3.4%. Under the reference scenario, CO_2 emissions jumped about three-fold in 2050 compared to emissions levels in 2016, due to fossil-fuel dependent power generation choices.

The results of the analysis show that, in terms of capacity expansion, both the Reference and Limited Gas scenarios are unresponsive in the period of 2014–25. In the subsequent period, out to 2050, more capacity installments are suggested under the optimization approach. Differences in investment results are largest for PV, CSP, and wind from 2030 to 2050 (Fig. 2). In the Renewable Target30 and Renewable Target40 scenarios, the introduction of new wind and geothermal energy begins in 2020. Total generation capacity is expected to be higher than the reference scenario due to the introduction of renewable energy technologies. The model selects a total installed capacity of 161 GW, 166 GW, 176 GW, and 146 GW by 2050 in the CO_2 Mitigation, Renewable Target30, Renewable Target40, and Limited Gas scenarios, respectively (Fig. 2). Investment in expansion of oil-based power plants increases sharply in the Limited Gas scenario as there are no constraints on imported oil for power generation. The model finds feasibility to invest in oil plants rather than renewable-based plants in this scenario.

Scenarios that target renewable energy promotion and restrictions on CO_2 emissions and natural gas increase the competitiveness of renewable energy in Egypt. Under these scenarios,

Table 3
Technology capacity, electricity generation, fuel requirement, and emissions in the reference scenario.

Technology capacity (GW)	2016	2020	2025	2030	2040	2050
Diesel oil	0.31	0.31	0.31	0.31	0.31	0.31
Duel fired	14.24	14.24	14.24	14.24	14.24	14.24
Heavy fuel oil	0.69	0.69	0.69	0.69	0.69	2.57
Natural gas	17.70	28.33	42.04	49.97	72.25	100.53
Geothermal	00	00	00	00	00	0.02
Hydro	2.80	2.80	2.80	2.80	2.80	5.41
Solar	0.62	0.62	0.62	0.62	0.36	0.14
Wind	1.35	1.35	1.35	1.35	0.91	3.55
Total (GW)	**37.71**	**48.34**	**62.05**	**69.98**	**91.56**	**126.77**
Electricity production (TWh)						
Diesel oil	–	–	–	–	–	2.12
Duel fired	79.97	60.50	–	–	–	–
Heavy fuel oil	–	–	–	–	–	19.63
Natural gas	74.58	129.07	243.33	309.84	497.17	737.11
Geothermal	0.00	0.00	0.00	0.00	0.00	0.14
Hydro	22.73	22.73	22.73	22.73	22.73	38.74
Solar	2.24	2.24	2.24	2.24	1.23	0.37
Wind	3.72	3.72	3.72	3.72	2.48	10.07
Total (TWh)	**183.25**	**218.26**	**272.03**	**338.53**	**523.61**	**808.17**
Fuel requirement (PJ)						
Fossil	1588	1532	1679	2108	3313	4975
Renewable	318	318	318	318	287	551
Total	**1906**	**1850**	**1997**	**2426**	**3599**	**5526**
Emissions ("000" ton)						
CO_2	97015	89596	94183	118268	185848	283471
NO_x	623	287	–	–	–	345
SO_2	178	162	168	211	331	508

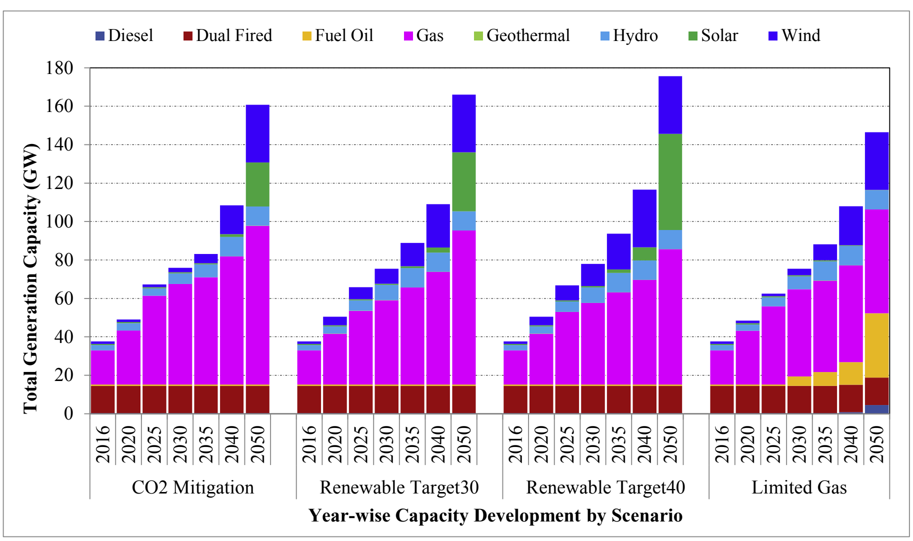

Fig. 2. Power generation capacity (GW) by technology and by policy scenarios.

investment in solar PV and wind started earlier than CSP. Due to the learning cost effects, investments in capacity expansion of CSP only occurs in the CO_2 Mitigation and Renewable Targets scenarios and only toward the end of the time period analyzed.

Fig. 3 shows electricity generation by fuel type under the alternative scenarios. Electricity generation is expected to increase from 183 TWh in 2014 to 808 TWh in 2050 under all scenarios. The contribution of renewable energy technologies is significant for electricity generation in all alternative policy scenarios. Solar- and wind-based electricity generation account for approximately 1% of the total electricity share in the reference scenario during the analysis period. Solar-based electricity generation is projected to increase from 2.24 TWh in 2025 to 69 TWh in 2050 in the CO_2 Mitigation, 89 TWh in the Renewable Target30, and 170 TWh in the Renewable Target40 scenario (Fig. 3). Due to the absence of clean energy development targets, solar-based electricity generation was negligible (less than 1 TWh) by 2050 in the Reference and Limited Gas scenarios. Wind-based generation reaches the upper bound of production in the alternative policy scenarios. The total renewable generation share would decrease from 15.6% in 2016 to 6.1% by 2050 in the reference scenario but would increase by 2050 in the following scenarios: CO_2 Mitigation (27.5%), Renewable Target30 (30%), Renewable Target40 (40%), and Limited Gas (19%). The TIMES model finds feasibility to export electricity in all scenarios and export levels reach the upper bound. Finally, the share of natural gas and dual-fired plant power generation increases from a share of 84% in 2016 to 91% by 2050 under the Reference scenario and decreases to 44% in the Limited Gas scenario over the same time frame.

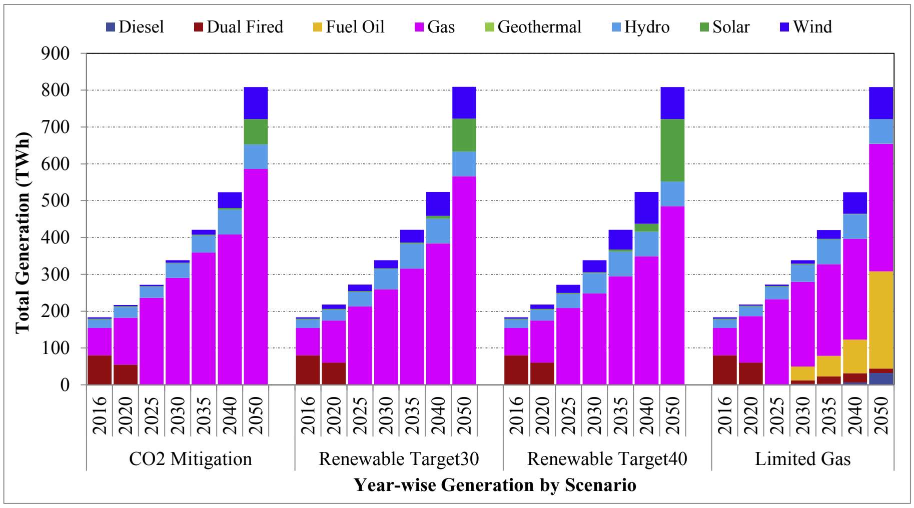

Fig. 3. Electricity generation (TWh) by fuel types in all developed policy scenarios. Note: This figure shows a summary of primary energy supply-mix for 2014 in Reference and 2050 for all scenarios. It also presents the percentage increase of system cost compared to the Reference scenario, cumulative emissions, and renewable-based electricity production in all scenarios.

5.2. Comparison on energy use, renewable generation, emissions, and costs

To summarize the extensive results generated by the TIMES model for each of the alternative scenarios, the principal metric chosen to demonstrate overall outcomes was the energy supply-mix for 2050. Fig. 4 presents the summary of results as well as the energy supply-mix for 2014, which gives an overview of the growth of energy supply to meet both the projected electricity demand in Egypt as well as to support export opportunities. The colored bars (except for the thin yellow bar in the middle) show the type of energy sources. The yellow bar in the middle of four of the scenarios (CO_2 Mitigation, Renewable Target30, Renewable Target40, and Limited Gas) represents the share increase in the total “system cost” over the Reference scenario.[1] The first row at the top of Fig. 4 represents the cumulative power generation from renewable energy technologies between 2014 and 2050, and the second row shows the cumulative CO_2 emissions during the analysis period across all scenarios. The values presented provide insights into the costs and potential of low-carbon development strategies, diversification of energy supply-mix, and the potential to meet NDC targets.

The optimal energy requirement in 2014 is 1976 PJ and this is projected to grow to 5526 PJ in 2050 in the Reference scenario. Primary energy supply increases in the alternative scenarios as a result of the increased use of renewable energy resources: to 6666 PJ in the CO_2 Mitigation scenario, 6526 PJ in the Renewable Target30 scenario, 7445 PJ in the Renewable Target40 scenario, and 7098 PJ in the Limited Gas scenario. No oil consumption is expected in the mitigation and renewable production scenarios in the later period of this analysis. Oil consumption is projected to grow from 389 PJ in 2016 to 2834 PJ in 2050 in the Limited Gas scenario. Due to higher investment costs for solar PV and CSP plants, the model suggests that Egypt will import oil for power generation in the scenario that limits gas production.

The cumulative (2014–50) renewable-based electricity generation is 1270 TWh in the Reference scenario, which increases to 3536 TWh in the CO_2 Mitigation scenario, 4432 TWh in the Renewable Target30, 5465 TWh in Renewable Target40, and to 3448 TWh in the Limited Gas scenario. The growth of renewable energy technologies improves the country’s energy security. Solar-based electricity generation increases from 2.24 TWh in 2016 to 69 TWh, 89 TWh, and 170 TWh in 2050 in the CO_2 Mitigation, Renewable Target30, and Renewable Target40 scenarios, respectively. Solar was not selected by the model in the Reference and Limited Gas scenarios as there was no constraint to use natural gas and oil in Reference scenario and oil in Limited Gas scenario. The cumulative fossil-fuel based electricity generation decreases from 15,961 TWh in the Reference case to 13,670 TWh, 12,803 TWh and 11,764 TWh in the CO_2 Mitigation, Renewable Target30, and Renewable Target40 scenarios, respectively. There are no significant differences of cumulative generation from fossil fuels between the Limited Gas and Reference scenarios.

CO_2 emissions from the power sector increase from 97 million tons (mt) in 2016 to 283 mt in 2050 under the Reference scenario. The growth of CO_2 emissions is significantly higher in the later period of this analysis. The CO_2 emissions in the alternative policy scenarios decrease to 213 mt, 205 mt, and 176 mt by 2050 in the CO_2 Mitigation, Renewable Target30, and Renewable Target40 scenarios, respectively. CO_2 emissions decrease (cumulatively) by 15%, 20%, and 25% in the CO_2 Mitigation, Renewable Target30, and Renewable Target40 scenarios, respectively, when compared with the Reference scenario. On the other hand, CO_2 emissions increase by about 5% in the Limited Gas scenario, due to additional use of HFO and diesel for electricity generation. This clearly shows that the Limited Gas option is not feasible if Egypt strives to reduce CO_2 emissions from in its power sector.

The model estimates that a total of US$131.9 billion of investment are required in the Reference scenario from 2014 to 2050. In comparison, the total system cost increases above the total system cost in the Reference scenario by 5.4% in the CO_2 Mitigation, 9.5% in the Renewable Target30, 13.7% in the Renewable Target40, and 17.7% in the Limited Gas scenarios. The marginal price of electricity generation declines from US$0.054 per kilowatt hour in 2016 to US$0.036/kWh in 2025 and increases from 2025 onward to US$0.10/kWh in 2050 in the Reference scenario. Due to implications of wind, additional hydro, and geothermal in 2050, the marginal electricity price increases to US$0.016/kWh, US$0.07/kWh,

[1] The system cost presents all costs during the analysis period (2014–50) related to investment in technology, fuel, operation and maintenance, import, transmission and distribution, and others.

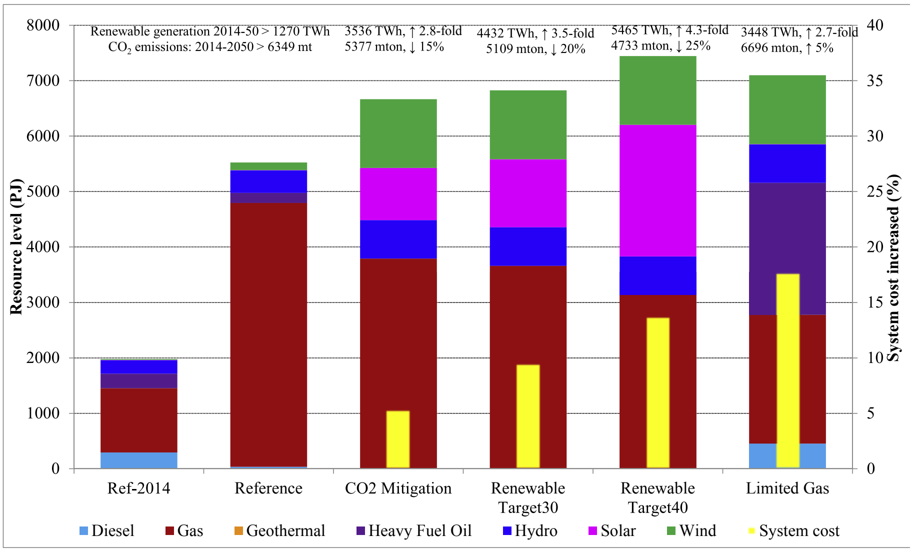

Fig. 4. Egypt energy future between 2014 and 2050.

US$0.11/kWh, and US$0.11/kWh in the CO_2 Mitigation, Renewable Target30, Renewable Target40, and Limited Gas scenarios, respectively, by 2050.

5.3. Energy security

Introduction of renewable energy technologies in the alternative policy scenarios helps to improve Egypt's energy security. Energy security is assessed based on the diversification of the primary energy supply-mix and the dependency on fossil-fuel use for power generation. The Shannon-Wiener Index (SWI) is used for diversification of energy supply-mix. The SWI estimates the scale of diversification of energy resources used for power generation. The minimum index value is zero, which signifies that there is only one source for electricity generation; more energy resources for diversification lead to a higher value of this index [72].

In the Reference scenario, the diversification index decreases from 1.12 in 2016 to 0.20 in 2045, due to reliance mainly on natural gas based power plants (Table 4). Between 2045 and 2050, the index increases due to the selection of wind and geothermal. The SWI for electricity generation declines in all policy scenarios until 2025, due to restrictions on resources, emissions reductions, and promotion of clean technologies. The SWI increases to 0.40, 0.89, 0.94, 1.08, and 1.37 by 2050 in the Reference, CO_2 Mitigation, Renewable Target30, Renewable Target40, and Limited Gas scenarios, respectively. The alternative policy options support higher index scores for diversification of energy resources for electricity generation and support improved energy security.

The second indicator for energy security assessment is dependency on fossil-fuel use for electricity generation and estimates based on consumption of fuel by technology. The modelling analysis shows that the share of fossil-fuel use increases from about 83% in 2016 to 90% in 2050 in the Reference scenario (Table 4). The dependency on fossil fuels decreases from 90% in the Reference scenario to 57%, 53%, 42%, and 73% in 2050 in the CO_2 Mitigation, Renewable Target30, Renewable Target40, and Limited Gas scenarios, respectively. Less dependency on fossil-fuel use for electricity generation would help to improve the energy security of Egypt in the long term.

5.4. Sensitivity analysis

This section presents the sensitivity of results to changes in assumptions. It considers alternative discount rates, investment costs of new renewable energy technologies (solar PV, wind, and CSP), natural gas prices, and gas production growth. As the model's optimization problem is to minimize the total current and future system cost, the discount rate becomes more significant over the life of the study period. Two alternative discount rates of 8% and 14% are applied. The impact of a decrease of 10% of investment costs for renewable energy technologies is also assessed. An annual increase of natural gas prices of 2.5% and a production growth rate of

Table 4
Energy security indicators during 2016 and 2050 in all developed scenarios.

Indicators/Scenario	2016	2020	2025	2030	2035	2040	2045	2050
Shannon-Wiener Index (SWI)								
Reference	1.12	1.02	0.40	0.35	0.29	0.22	0.20	0.40
CO2 Mitigation	1.12	1.05	0.45	0.49	0.52	0.70	0.78	0.89
Renewable Target30	1.12	1.17	0.69	0.71	0.75	0.81	0.89	0.94
Renewable Target40	1.12	1.18	0.73	0.79	0.86	0.96	1.05	1.08
Limited Gas	1.12	1.04	0.49	1.05	1.24	1.36	1.40	1.37
Dependency on fossil fuels (%)								
Reference	83.32	82.82	84.08	86.90	89.25	92.04	92.69	90.03
CO2 Mitigation	83.32	79.29	79.92	78.32	77.49	65.91	61.68	56.85
Renewable Target30	83.32	73.44	67.85	65.76	63.03	59.55	56.59	53.62
Renewable Target40	83.32	73.44	65.38	60.96	56.18	51.04	46.59	42.11
Limited Gas	83.32	81.24	78.86	75.37	68.89	65.43	66.09	72.64

3% were considered, in comparison with the 1.5% rate and 4% rate, respectively, in the Reference case. The impact of including nuclear power plants (4.8 GW by 2024) is also analyzed.

With a discount rate of 8%, it would be more advantageous to increase investment in hydro and wind power and less in natural-gas-based power plants during 2040–2050. In the Reference scenario, hydropower capacity increases significantly from 5.4 GW to 8 GW in 2050 with an 8% discount rate. With a higher discount rate (14%), the model suggests a switch to more fossil-fuel-based plants. With a 14-percent discount rate, heavy fuel oil (HFO) based plants with a capacity of 3.4 GW are selected in 2050, while investments in hydro and wind power decline in the later period (2040–2050) of this analysis.

A 10-percent decrease of investment into renewable energy technologies would help to increase wind capacity from 3.55 GW in 2050 in the Reference scenario to 8.5 GW. Solar PV and CSP are not selected. Due to the increase of wind capacity in 2050, investments in fuel-oil-based plants decline from 2.6 GW to 0.7 GW in 2050. Total generation capacity reaches 130 GW instead of 126.7 GW in the Reference scenario.

Due to the limited growth of natural gas production for use in power generation, investment in hydro, wind, and oil-based power plants increase from 2030 to the end of the period analyzed in the Limited Gas scenario. Natural-gas-based capacity decreases significantly while the upper bound of wind and hydro are used to generate electricity to meet demand. Investment in fuel-oil based plants leads to a capacity of 2.5 GW in 2040 and 15.5 GW in 2050. Solar technologies are not an option due to high cost. Total generation capacity reaches 145 GW in 2050 due to large investment in wind power. The system cost also increases by about 4% when compared with the Reference scenario during the study period.

The total system cost increases by 6.4% when the natural gas price increases by 2.5% instead of 1.5%, as it does in the Reference scenario. There are no significant changes of technology capacity selection compared to the Reference case. A slight increase in investment occurs between 2045 and 2050 for wind and hydropower. Oil-based generation also increases from 5.3 TWh to 21.7 TWh in 2050, compared with the Reference scenario.

Another sensitivity analysis considers the contribution from nuclear power plants of 4.8 GW. Given that the nuclear power plants are planned and expected to be completed by 2020, it is important to consider them in the Reference case to examine the impacts of costs, emissions, fuel use, and technology selections to meet future electricity demand in Egypt. Including nuclear power plants, the model finds an increase of the total capacity from 126.7 GW to 128.7 GW by 2050. Wind capacity decreases from 3.5 GW to 1.5 GW, and hydro decreases from 5.4 GW to 4.8 GW in 2050 in the Reference scenario. The total system cost slightly increases by 2.3% over the study period. Fossil-fuel use decreases from 111,508 PJ (cumulative, 2014–50) to 101,906 PJ, due to the inclusion of nuclear fuel in the system; nuclear fuel replaces a total of 8% of fossil-fuel use. CO_2 emissions decrease substantially with the inclusion of nuclear during 2020–2025 by about 18%, compared to the Reference case without nuclear power plants.

6. Conclusions

The results outlined in this study have important policy implications for Egypt. The optimal energy supply-mix and technologies selected by the model in all alternative policy scenarios would allow Egypt to its sustainable energy development goals and NDC mitigation targets. The results demonstrate how different power generation technologies and energy supply-mixes can be chosen to adequately address the country's energy demand growth, environmental policy goals, such as mitigation of CO_2 emissions, promotion of renewable energy for power generation and optimal use of indigenous energy resources. Each of these energy development strategies also has implications in terms of total system cost, utilization of the existing energy resource potential and environmental impacts. All of these reflections must be weighed carefully when shaping the path of Egypt's energy sector development.

The quantitative results generated from the TIMES model suggest that the current supply of energy resources for electricity generation needs to diversify from predominantly natural gas to a mix with increased weight of renewable energy sources in order to improve energy security and reduce dependency on fossil fuels. This would support the country to achieve Vision 2030 on energy and sustainable development.

Natural gas still dominates the power generation sector in Egypt during the analysis period, but the sector has significant potential to generate electricity from alternative renewable resources. The CO_2 emission mitigation constraint and renewable-based generation targets influence technology choices—moving from conventional to more efficient conventional and clean renewable energy technology options. Wind and solar PV contribute significantly to meet these constraints and targets. Concentrated solar power and hydropower were also identified as feasible diversification options. Solar PV and CSP were not chosen in the Limited Gas scenario, while oil import is feasible to generate electricity under this scenario. The modelling results show that the scale of variation of total primary energy use and energy supply-mix is expected to grow with the different policy options.

All the alternative policy scenarios involve an increase in the total energy system cost compared to the Reference scenario due to integration of renewable energy technologies in the future years. Dependency on fossil fuels is expected to decrease from 90% in the Reference scenario in 2050 to 42% in the Renewable Target40 scenario with an additional total system cost of 13.8%, thus highlighting to policymakers the trade-offs of promoting renewable energy technologies in Egypt. Long-term benefits from investing in energy diversification include improvement of the country's energy security, reduction of fossil-fuel dependency for power generation and progress toward a low-carbon society. These benefits support investing in alternative technologies such as solar PV, wind, and concentrated solar power due to their learning effects on cost reduction.

This study qualifies as an exploration of Egypt's energy futures under alternative policy options and provides insights into the implications of technologies that can be pursued by the government of Egypt. Future studies might consider expanding this Egypt-TIMES power sector model to include end use technologies from all sectors (such as transport, industry, household, commercial and agriculture); as well as the explicit modelling of energy storage to handle intermittency of some renewable energy resources.

The energy development future chosen by Egypt will not only affect the country, but will also have repercussion on both exporters of energy to Egypt and importers of Egyptian energy sources. With growing trade and inter-connections of electric grids, a stronger and more diversified Egyptian energy sector can support a wider regional economy, in addition to contributing to a better future climate.

Note

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