Decarbonizing Egypt's energy sector: pathways for an accelerated energy transition

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Abstract

Purpose – This study aims to identify decarbonization pathways and energy mix scenarios of least global warming potential that address Egypt's growing energy demand, while transitioning away from reliance on fossil fuel towards a more sustainable energy landscape.

Design/methodology/approach – The study utilized an integrated modelling approach, namely the Long-range Energy Alternatives Planning system, to simulate Egypt's energy demand and supply from 2010 to 2050. Four alternative scenarios were examined. The reference scenario, RS1, replicates the energy demand and supply change patterns of the model's baseline until 2050. The reference scenario, RS2, considers 5% yearly growth in energy demand alongside integrating nuclear technology into the generation mix. In addition to two renewables-promotion scenarios, RE1 and RE2, wherein renewables contribute 42 and 75% to the energy mix by 2030 and 2050, respectively.

Findings – Results revealed that greenhouse gas emissions are expected to peak in RS1 in 2050. Yet, RE2 demonstrates the lowest global warming potential. Energy generation costs are anticipated to be the highest in RS2 by 2050 and in RE2 between 2022 and 2030, reaching its lowermost point in RE2 by 2050. Moreover, natural gas is anticipated to contribute the largest share of energy generated in RS1 but the smallest share in RE2, wherein wind energy dominates energy production by 2050. Among all other scenarios, RE2 had the greatest potential to enable the achievement of net zero emissions in the long term.

Research limitations/implications – The findings of this research have significant implications as they provide valuable data-driven insights into identifying mitigation scenarios that align best with Egypt's economic development plans while also promoting sustainable energy planning. Moreover, the results hold important implications for energy policymaking in Egypt. Policymakers can utilize these insights to prioritize and channel investments towards renewable energy sources, energy efficiency measures and the adoption of clean technologies.

Originality/value – This study addresses a gap in the existing literature on Egypt's energy landscape by introducing an integrated analysis that combines both energy demand and supply. Previous studies focused solely on demand or supply in isolation, overlooking the interconnected nature of these factors and the specific determinants of Egypt's energy demand profile. Using a modelling approach, this study is the first in Egypt to comprehensively consider both aspects. By identifying key factors influencing Egypt's energy demand until 2050, it provides valuable insights into the future energy landscape, evaluates economic costs, examines potential environmental impacts and presents empirical evidence on energy generation scenarios aligned with future demand and climatic factors.

Keywords Egypt, Climate change, LEAP, Energy modelling

Paper type Research paper

1. Introduction

Climate change is a subject of global concern that marks the shifting dynamics of the earth's climate system, characterized by new weather patterns over extended periods. Many scientists propose that human activities, primarily related to burning fossil fuels, have markedly amplified these changes, resulting in what is often called global warming, the primary factor contributing to climate change. This phenomenon has led to drastic alterations influencing not

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only atmospheric and oceanic temperatures but also affecting precipitation, wind patterns and more. The consequences of such large-scale transformations are enormous, impacting biodiversity, food and water security and posing many existential threats (United Nations, 2023). In this context, the Paris Agreement is a significant global treaty that provides a framework for countries to control their emissions, promote sustainable development and improve their ability to withstand the impacts of climate change by committing to the long-term objective of upholding global temperature to a level significantly below 2 degrees Celsius above pre-industrial levels, with an ambitious aim to strive for 1.5 degrees Celsius (United Nations Framework Convention on Climate Change (UNFCCC), 2015).

Energy is a central element of sustainable development, which is dealt with primarily by the seventh sustainable development goal, affordable and clean energy. The fundamental aim of sustainable development goal (SDG)-7 is ensuring that everyone has access to energy that is affordable, reliable, sustainable and aligned with modern standards (McCollum *et al.*, 2018). Considering this background, the global state of clean energy practice is entering a critical phase, owing its attributes to the significant growth of global greenhouse gas (GHG) emissions specifically from the energy sector as a primary contributor to global emissions, accounting for more than 75% of global emissions, where fossil fuels including oil and natural gas, dominate energy production and emit large amounts of carbon dioxide when burnt (International Energy Agency, 2023).

Egypt is confronted with a multitude of challenges stemming from the changing climate, compounded by its geographical location in a region already burdened by arid conditions and scarce water resources. In recent years, climate change has had a considerable impact on Egypt, demonstrated by rising temperatures and changing precipitation patterns that have led to an increase in the intensity and frequency of extreme weather events. These impacts also had substantial effects on vital aspects of the country's infrastructure, coastal areas and the fertile lands of the Nile Delta and imposed many consequences on critical sectors such as energy, industry and transport (World Bank, 2021, 2022). Demonstrating its unwavering commitment to the Paris Agreement, Egypt submitted its second updated Nationally Determined Contributions to the UNFCCC in 2023, which outlined a fifteen-year working plan from 2015 to 2030 that aims to reduce GHG emissions by 37% from the electricity sector (generation, transmission and distribution), 65% from oil and gas sector and 7% from the transportation sector, compared to 2015 levels (Arab Republic of Egypt, 2023). However, given the country's ambitions for economic expansion and the expected increase in energy consumption needed to achieve these goals, it is likely that some challenges will arise, particularly within the energy sector. It is therefore important for Egypt to explore alternative approaches to address current energy challenges, prioritizing sustainable practices that ensure long-term energy security and mitigate the adverse effects of climate change.

2. Literature review

Energy modelling and the exploration of alternative energy mix scenarios have captivated the attention of researchers across various disciplines due to their significant implications for energy planning, policy design and sustainable development. Several scholars have undertaken the task of categorizing energy models based on their analytical approach, dividing them into three groups, namely top-down, bottom-up and integrated or hybrid models. Bottom-up models discuss thoroughly energy-generating technologies, but they lack practical details necessary for making final policy decisions. On the other hand, top-down models effectively mitigate this limitation by incorporating macroeconomic feedback. However, they cannot reliably forecast future market responses, mostly attributed to their inherent deficiency in incorporating technology-specific details. The disparity between the two models created the need for an integrated model that combines features from both frameworks (Bhattacharyya and Timilsina, 2010; Herbst *et al.*, 2012; Neshat *et al.*, 2014; Schinko *et al.*, 2017; Subramanian *et al.*, 2018; Hawker and Bell, 2020).

(1) *Integrated (hybrid) energy models:*

Scholarly efforts have therefore been directed towards specific areas that align with this classification in most cases, with a prevailing emphasis on both the integrated and bottom-up approaches. Jacobsen (1998) introduced a comprehensive model that combined the features of both top-down and bottom-up energy models and applied it extensively in the Danish context. Ringkjob *et al.* (2018) utilized the Long-range Energy Alternatives Planning system (LEAP) as an integrated platform for energy analysis and planning spanning a time horizon of 20–50 years. The research conducted by Vieira *et al.* (2020) serves as an illustration of how the integration of bottom-up and top-down approaches can be achieved. In their work, they presented a framework for energy preservation policy, which effectively combined elements from both approaches. Moreover, the study conducted by Yang *et al.* (2021a, b) examined the integration of the top-down Computable General Equilibrium model with the bottom-up pollutant control model to assess the effects of decarbonization on energy, economic and ecological variables in China.

(2) *Bottom-up energy models:*

Other strands of literature investigated the inherent differences among the various energy models to examine the implications of these variations on the accuracy, reliability and policy relevance of the model outputs. Park *et al.* (2016) used a bottom-up model to evaluate the electrical energy production in South Korea. Their study involved calculating the optimal portfolio, considering renewable energy technologies explicitly, up until 2050, with the cost-effectiveness of measures being assessed. Prina *et al.* (2020) performed a comprehensive assessment of the categorization algorithms used in modelling bottom-up energy systems. Their findings showed that the Market Allocation and The Integrated Markal-EFOM System (TIMES) (MARKAL/TIMES) and the Open-Source Energy Modelling Systems (OSeMOSYS) were observed to possess somewhat lower temporal and techno-economic data resolutions while exhibiting moderate spatial resolutions. On the other hand, the LEAP model underwent an evaluation as a long-term energy model characterized by comparatively lower resolutions in terms of temporal, spatial and techno-economic variables. In a similar vein, Perissi *et al.* (2021) conducted a study aiming to evaluate the performance of the Modelling Energy System Development under Environmental and Socioeconomic Constraints model in conjunction with TIMES and LEAP models to examine the dynamics of Austria and Bulgaria's energy transition. According to the findings, the three models effectively simulated scenarios in replicating past patterns; however, a significant discrepancy was detected with the introduction of renewables at certain degrees. Furthermore, Prina *et al.* (2021) conducted a thorough analysis of the available bottom-up models, where they evaluated and compared forty-three different studies that utilized these models for analysis at the national level. Sanchez *et al.* (2021) conducted a study to assess the role of bottom-up energy models in informing policy formulation for enhancing residential building and sector-specific electricity end-use efficiency. The findings showed that models constructed using a bottom-up approach do not afford a wide range of tools for analysis, which plummets their ability to effectively assist in policy formulation.

(3) *Energy system optimization modelling and the pursuit of efficiency in electricity generation:*

Another thread within the realm of the literature centred on the analysis of energy systems' dynamics and the exploration of methodologies aimed at enhancing electricity-generating efficiency while concurrently reducing emissions and promoting the transition to sustainable and eco-friendly energy sources. Decarolis *et al.* (2017) undertook a thorough review of existing literature to establish best practices for optimization modelling of energy systems. Their analysis confirmed that ESOMs have the capability to provide accurate insights that inform national climate targets and environmental and energy policymaking, emphasizing importance of providing guidance on effective application. Kueppers *et al.* (2021) recognized the importance of energy system modelling in identifying the optimal mix of technologies for the most effective carbon mitigation strategies at the national level. They proposed a new method of energy system archetypes that allowed for direct evaluation and categorization of countries based on their similarities, irrespective of their geographical location, in an effort to maximize the number of countries analysed while minimizing the modelling workload. Plazas-Niño *et al.* (2022) conducted a thorough examination of the main ESOMs to find patterns in scenario analyses for national economies' decarbonization pathways. Their findings revealed that ESOMs are valuable tools for developing scenarios that capture the various interactions between energy sources, end uses and transformation technologies and further support decision-making in formulating optimal decarbonization pathways.

(4) *Utilization of LEAP for simulating future scenarios in research studies:*

Several studies utilized LEAP to simulate futuristic scenarios of energy supply and assess their impacts on key variables, such as energy consumption, GHG emissions and economic indicators, at the country level. Huang *et al.* (2011) employed LEAP to simulate the future energy demand, supply and CO_2 emissions in Taiwan. Their study analysed several energy policy scenarios from 2008 to 2030. The findings indicated that under a business-as-usual (BAS) scenario, oil refining was a primary contributor to the total energy output for 2030, followed by electricity generation. McPherson and Karney (2014) used LEAP to evaluate the present state of Panama's power production and predict how it could evolve in the future and the impact on various factors including the potential for global warming, resource diversity and system marginal costs. Ates (2015) used the LEAP system as a means of evaluating the capacity for enhancing energy efficiency and mitigating carbon emissions in Turkey's steel and iron sector. Emodi *et al.* (2017) utilized the LEAP system to examine the future energy supply and consumption and carbon emissions of Nigeria between 2010 and 2040. Mirjat *et al.* (2018) employed LEAP to simulate the power system of Pakistan over 2015–2050. Hu *et al.* (2019) developed the Shenzhen-LEAP model, capitalizing on the city's post-industrial characteristics in constructing four scenarios to investigate its energy supply and demand from 2015 to 2030. Nieves *et al.* (2019) built a LEAP model to forecast and evaluate the energy outlook in Colombia for the years 2015–2030 and further to 2050, considering two distinct pathways in their analysis. Moreover, Felver (2020) utilized LEAP to forecast Azerbaijan's potential CO_2 emissions through three distinct scenarios. Shahid *et al.* (2021) created an LEAP model for Pakistan's electricity system from 2016 to 2040. Furthermore, an LEAP model was developed by Yang *et al.* (2021a, b) to examine the ecological and socioeconomic impact of the introduction of renewables in the Chinese province of Zhang.

(5) *Energy modelling studies with a focus on Egypt:*

Some studies utilized energy modelling to underline the importance of promoting renewables for generating electricity and fostering a green economy in Egypt. Shaaban and Scheffran (2017) developed a methodical approach in order to assess the different power supply systems in Egypt. The results of their research showed that for a meaningful long-term evaluation of the energy sector, power projects should have social and environmental considerations factored in and not only technical and economic aspects. Rady *et al.* (2018) assessed the economic and environmental implications of Egypt's planned growth in the power sector using OSeMOSYS, exploring two different energy demand scenarios. Findings revealed that wind power technology is the most appropriate choice for boosting renewables in the country's energy mix. Moreover, wind power represented a feasible alternative that could potentially reduce the dependence on natural gas in Egypt's energy sector. Mondal *et al.* (2019) examined Egypt's power sector energy supply strategies using the TIMES model, with a particular emphasis on CO_2 mitigation, renewables integration and restrictions on natural gas usage. Findings of their research indicated that energy mix diversification is necessary to improve supply reliability, reduce reliance on fossil fuels and lower GHG emissions.

In light of the aforementioned, we found that in the existing literature on Egypt, there has been a noticeable gap in the provision of an integrated analysis that combines both energy demand and supply. Previous studies have primarily focused on either energy demand or supply analysis in isolation, overlooking the interconnected nature of these factors and the specific determinants of Egypt's energy demand profile. This study stands out as the first in Egypt to address this gap, utilizing an integrated modelling approach to fill this research gap by introducing an integrated model that considers both energy demand and supply. Through identifying the key factors that determine the country's energy demand profile until 2050, the study offers valuable insights into the future energy landscape and examines the potential environmental impact if the current energy mix is relied upon. The study also presents empirical evidence on various energy generation scenarios that align most effectively with Egypt's future energy demand with climatic factors considered.

3. Overview of Egypt's energy sector

Energy is a main driver of economic development in Egypt, which constitutes more than 13% of the country's overall gross domestic product. Moreover, the energy sector is considered a significant contributor to employment in Egypt and a major source of jobs for many Egyptians (Information and Decision Support Center, 2022). Moreover, energy constitutes a vital component within the comprehensive framework of Egypt's sustainable development strategy, Egypt's Vision 2030, which encompasses ten interconnected pillars emanating from the broader economic dimension. Anchored within this visionary strategy, the energy pillar has a prominent role in driving the country's transition towards a more sustainable and resilient future, incorporating ambitious goals aimed at transforming the country's energy landscape towards a low-carbon future. The energy pillar's primary objectives are boosting the renewables share in the energy mix, improving energy efficiency and enhancing energy security (Ministry of Planning and Economic Development (MPED), 2016, 2021a). Furthermore, Egypt is gifted with a plethora of different sources of energy, including natural gas, oil, hydroelectric and a promising potential for solar and wind energy. Moreover, the country is endowed with a substantial expanse of land, characterized by a mostly sunny climate and consistently strong wind patterns, making it an optimal geographical region for the implementation of renewable energy initiatives and the market for renewable energy has the potential to generate billions of dollars in revenue (Information Trade Administration, 2022). In line with its broad plan for sustainable energy, Egypt's Integrated Sustainable Energy Strategy Egypt aims to grow its local content by sourcing 42% of its electricity from renewables by 2030 (Ministry of Electricity and Renewable Energy (MoERE), 2015b; Supreme Energy Council (SEC), 2016; Arab Republic of Egypt, 2023).

The energy sector in Egypt has traditionally been centred around the production and exportation of oil and natural gas. In terms of oil production, Egypt is the third major natural gas producer in Africa and the 25th largest in the world. The country also functions as a critical channel for oil transported from the Persian Gulf to Europe and the United States of America (Energy Information Administration, 2020). Egypt has emerged as a frontrunner in the global petroleum industry, with significant achievements since 1886, when the country marked its entry with the drilling of the first well in the Jamsa area, situated on the western coast of the Red Sea. In 1961, the country discovered its first offshore oil field, Belayim offshore, which was also the first in the entire Middle East region. Currently, the Western Desert dominates oil production in Egypt, accounting for the largest share at 56%, Suez Gulf at 23%, Eastern Desert at 12% and Sinai at 9% (Ministry of Petroleum (MoP), 2023a). The Mediterranean Sea contributes the largest share of natural gas production in Egypt, accounting for 62% of the total output, followed by the Nile Delta region at 19% and the Western Desert at 18%. In recent years, numerous natural gas discoveries have been made in Egypt to cater to the needs of the local market. Examples include the Nooros discovery in the Nile Delta, the North Alexandria and the West Nile Delta discoveries in the Mediterranean Sea, in addition to the Zohr gas field, which is recognized as the largest natural gas find in the Mediterranean Sea and one of the largest worldwide (MoP, 2023b). These assets, coupled with the existing Suez Canal and Sumed pipelines along with the country's potential for renewables, notably solar and wind energy, reflect its promising path towards a sustainable energy future and further establish Egypt as a crucial energy hub in the region given its pivotal geographical location, which positions it strategically for exportation and transit of energy (MoERE, 2022b).

Electricity is a key component of Egypt's overall energy system, playing a crucial role in powering and sustaining the country's socioeconomic development. The sector primarily relies on a mix of conventional and renewable energy sources to meet the growing electricity demand, dominated by oil and gas at approximately 90%. Renewable energy sources (wind and solar) account for 5.1%, while hydropower constituted 4.8% of total electricity generation capacity in 2021 (MoERE, 2022b). Thermal power plants contribute a significant share to Egypt's electrical energy generation capacity. As of 2021, around 89% of Egypt's electricity generation came from thermal power plants that mainly rely on the combustion of fossil fuels, natural gas and oil to generate electricity (Global Data, 2023). However, this heavy dependency on fossil fuels has contributed to high levels of GHG emissions, exacerbating climate change. Egypt's total GHG emissions accounted for approximately 325.515 $MtCO_2e$ in 2015. The energy sector alone accounted for 64.5% of these emissions, and 97% of this amount was attributed to fossil fuel combustion activities to generate electricity (Egyptian Environmental Affairs Agency (EEAA), 2018).

In recent years, Egypt has undertaken significant steps towards addressing climate change and reducing emissions, in line with its commitment to sustainable development and the 2030 Agenda and within the context of the Paris Agreement (MoERE, 2015b; MPED, 2016, 2021a, 2021b; Arab Republic of Egypt, 2022; EEAA, 2022). The Benban Photovoltaic (PV) Park, one of the world's largest solar power projects, exemplifies Egypt's dedication in this area. With a total capacity of 1.5 gigawatts (GW), this project significantly contributes to the diversification of the energy mix while concurrently decreasing reliance on traditional fossil fuels and reducing GHG emissions. The country has also implemented several solar energy initiatives on a smaller scale, such as the Kom Ombo PV plant, Kuraymat concentrated solar power (CSP) plant in Sharm El Shiekh, rooftop solar panel installations and solar water heating systems, contributing to the overall sustainability efforts. Moreover, the country's strategic location along the Gulf of Suez allows for favourable wind conditions, making wind energy a viable clean energy option. Examples of successfully implemented projects include Zaafarana and Gabal El-Zeit wind farms, contributing markedly to national renewable energy goals (MoERE, 2021a; 2022b). Egypt is currently constructing its first nuclear plant on the Mediterranean coast. The primary objectives of this project are enhancing energy security, reducing carbon emissions, diversifying its energy portfolio and decreasing its reliance on fossil fuels (SEC, 2016; Nuclear Power Plants Authority, 2023).

4. Methodology

4.1 Materials and methods

The study used the LEAP created by the Stockholm Environment Institute. LEAP is an energy-economic modelling tool with the ability to perform scenario-based modelling of the energy sector using top-down, bottom-up and integrated approaches. It is widely used for energy policy analysis and assessing measures for climate change mitigation. It can also support capacity expansion planning at the macroeconomic level over the medium to longer terms, with a forecast period of up to 50 years. The system is not specifically designed to model a particular energy system, but it is a flexible tool that can be customized to generate models for a variety of energy systems, each with its own dataset (Stockholm Environment Institute (SEI), 2020). The system supports a variety of modelling approaches for energy demand, including detailed bottom-up calculations for end-use consumption and top-down macroeconomic modelling. On the supply side, it offers various modelling and optimization methods to accurately simulate energy production and capacity development. The system also maintains optimization capabilities, even in cases with constraints on GHG emissions and air pollution.

4.2 Algorithm of LEAP

In this section, the computational framework for analysing and predicting output data in LEAP is presented, including the calculations of energy consumption, transformation, emissions and energy generation costs.

4.2.1 Consumption. The calculations of the final energy consumption and net consumption for transformation are performed as described below (Feng and Zhang, 2012):

$$\mathrm{EC_n} = \Sigma_i \Sigma_j \ \mathrm{AL_{n,j,i}} \times \mathrm{EI_{n,j,i}} \quad (1)$$

Where *EC* $_n$ stands for the total energy consumption in a given sector, *AL* represents the activity level, *EI* indicates the energy intensity, n denotes the primary energy source, i represents the sector and j is the technology being utilized.

$$\mathrm{ET_s} = \sum_m \sum_t \mathrm{ETP_{t,m,s}} \times \left(\frac{1}{f_{t,m,s}} - 1 \right) \quad (2)$$

Where *ET* s represents the net energy consumption associated with the process of transformation, *ETP* is the resulting energy transformation product. *f* denotes the efficiency of transformation, s is primary energy source, m represents technology used and t is energy produced.

4.2.2 Transformation. Primary energy is converted to secondary energy in the transformation module. As well, this involves the conversion of electricity transmission and distribution (T&D) centres, power plants, oil refineries, coal mining and other processes (Lazarus *et al.,* 1997). Hence, for every process *p* and T&D module, respectively:

$$INPUT_p = \frac{OUTPUT_p}{EFFICIENCY_p} \quad (3)$$

$$EFFICIIENCY_p = 1 - LOSSES_p \quad (4)$$

Where *INPUT* refers to the fuel/feedstock used in a given energy system, *OUTPUT* represents electrical energy generated and *EFFICIIENCY* denotes power plants facilities' efficacy in converting input resources into output.

4.2.3 GHG emissions. Outlined below is the method used to compute GHG emissions derived from final energy consumption and energy transformation, respectively (Feng and Zhang, 2012):

$$\mathrm{GHG_c} = \sum_i \sum_j \sum_n \mathrm{AL_{n,j,i}} \times \mathrm{EI_{n,j,i}} \times \mathrm{EF_{n,j,i}} \quad (5)$$

Where *GHG* $_c$ represents the emissions from final energy consumption, *AL* denotes activity level, *EI* refers to the energy intensity and *EF* represents the emission factor of fuel type *n* and technology j used in sector *i*.

$$\mathrm{GHG_T} = \sum_s \sum_m \sum_t \mathrm{ETP_{t,m}} \times \frac{1}{f_{t,m,s}} \times \mathrm{EF_{t,m,s}} \quad (6)$$

Where *GHG* $_T$ represents emissions from energy transformation, *ETP* is transformation product, *f* represents transformation efficiency and *EF* is the emissions per unit of primary fuel s to generate secondary fuel t using technology m.

4.2.4 Energy generation costs. The following equation is used to calculate the total cost of a given sector (Emodi *et al.*, 2017):

$$C = \sum_i \sum_j \left\{ \left[\sum_n \begin{pmatrix} e & ep \\ n,j,k & n \end{pmatrix} + \sum_k \begin{pmatrix} m & mp \\ k,j,i & k \end{pmatrix} + fc_{j,i} \right] P_{j,i} \right\} \tag{7}$$

Where *C* denotes total cost, *ep* represents the price of one unit of fuel n, *m* introduces raw material demand k per unit of production by technology j in production process i, *mp* refers to unit price for material *k* and *fc* is fixed cost incurred per unit production through technology j in process i.

4.3 Scenario development

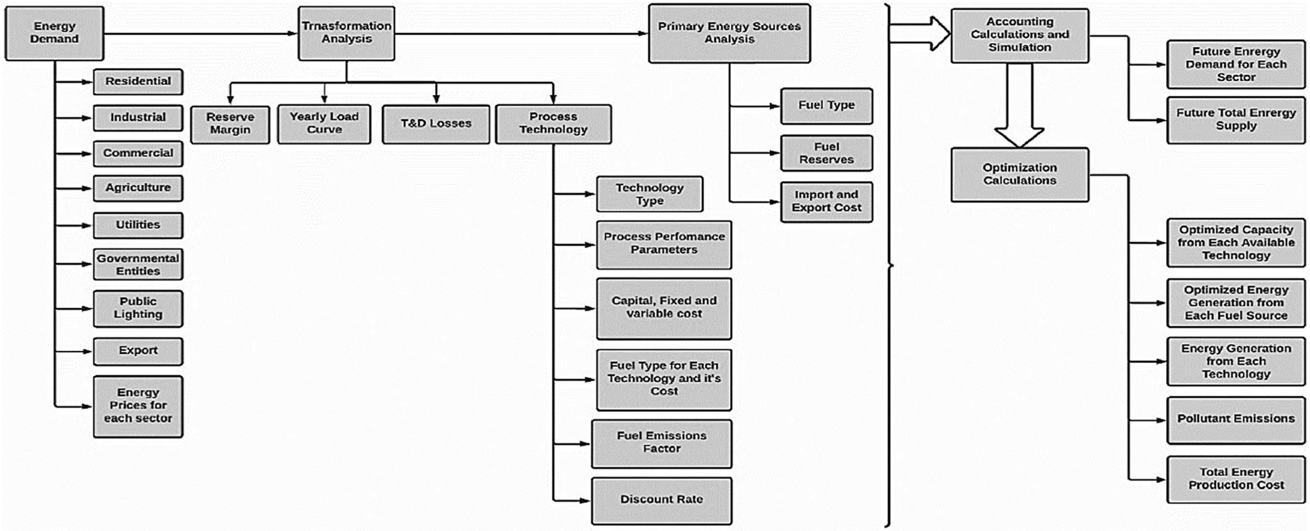
4.3.1 LEAP framework for Egypt. This section presents an overview of the LEAP analysis framework for Egypt. In the base year, the model incorporates historical energy demand data for various sectors including residential, commercial and industrial, along with established energy costs for each. The analysis starts by examining energy demand, which informs resource energy and transformation analyses. Following this, the LEAP model assesses available energy supply resources and technologies for converting energy sources, including fossil fuels and renewables, into electricity, considering existing and projected facilities accessible during the study period and the various performance parameters for all technologies (SEI, 2005). The subsequent resource analysis collects data on primary energy sources, focusing on production costs, import and/or export dynamics and environmental impacts associated with different technologies, particularly fossil fuels. The modelling process includes an accounting phase to calculate projected energy consumption based on demand, followed by optimization that employs cost-benefit analysis. This optimization determines the most economically efficient strategies for expanding capacity and managing supply-side transformation modules, considering all relevant costs and environmental factors. Ultimately, the model outputs include optimized capacity for each technology, energy produced per primary source, overall cost of production and anticipated emissions (SEI, 2021). Figure 1 illustrates the framework of LEAP analysis for Egypt.

4.3.2 Scenario design and analysis. The development of the LEAP model for Egypt took into account the year 2010 as its baseline year and 2050 as the end year of analysis. Four alternative energy production scenarios were examined with the aim of identifying the optimal energy mix scenario for Egypt. The business-as-usual scenario (BAS) serves as the baseline for the model covering the period from 2010 to 2021, developed in the LEAP system to align with current national plans for the fuel mix used in electricity generation. The underlying theory behind the development of the other four scenarios, despite having the same power generation capacity as BAS, involves the phased retirement of traditional energy production plants. These plants would be replaced by technologies introduced in these scenarios such as renewables (wind and solar), hydropower and nuclear, with the objective of maximizing the capacity of each of these technologies by expanding their deployment as much as possible. The proposed scenarios are then compared and evaluated by the LEAP system based on their individual economic costs and benefits, energy requirements and carbon footprint. Table 1 outlines scenarios examined as part of this analysis.

5. Results and discussion

5.1 Supply

5.1.1 Reference scenario – RS1. The model projections indicated that combined-cycle plants will continue to be the leading technology in response to rising energy demand, with capacity expected to increase from 28.36 GW in 2022 to 71.47 GW by 2050. In contrast, steam turbine plants will see limited growth, reaching a maximum of 31.66 GW due to their lower efficiency



Source(s): Authors' own work

Figure 1. LEAP framework for Egypt

Table 1. Summary of considered scenarios

Scenario	Description	Demand	Supply	Nuclear Constraint	Emission Constraint	Renewables Constraint
Business-as-usual (BAS)	The model's baseline scenario reflecting energy developments over the years 2010–2021. It aligns with the current national plans for the fuel mix used in electricity generation, and provides a reference for comparison	A substantial growth in energy demand took place over this period, particularly in the residential, industrial and commercial sectors, with the residential sector as the largest consumer accounting solely for 40% of total demand in 2010. Increases were also observed in the agriculture, utilities, governmental sectors over this period	Egypt experienced significant growth in its energy supply driven by a rise in energy demand. The primary sources of energy were fossil fuels such as natural gas, diesel and heavy oil. Natural gas played a crucial role as the primary fuel for thermal plants accounting for almost 78% of the fossil fuel mix in 2010 reaching up to 95% in 2021. Renewables including hydro, wind and solar also showed an increase in their contribution to energy supply over the same period. The main technologies for energy generation included combined-cycle, steam and gas turbine plants	No nuclear constraint	No emission constraint	No renewables constraint

(*continued*)

Table 1. Continued

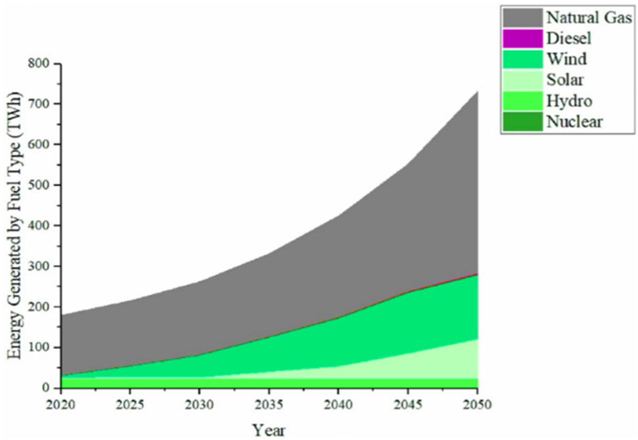
Scenario	Description	Demand	Supply	Nuclear Constraint	Emission Constraint	Renewables Constraint
Reference scenario (RS1)	This scenario replicates the change patterns of energy demand and supply in BAS until 2050	Same as BAS	Same as BAS	No nuclear constraint	No emission constraint	No renewables constraint
Reference scenario (RS2)	Simulates energy demand and supply considering a 5% rise in demand (the peak annual increase in energy demand between 2005 and 2015 (MoERE, 2022a), integration of a new technology into the fuel mix over the period of simulation from 2022 to 2050	An annual growth rate of 5% is applied to the average increase in energy demand	Replicates BAS conditions while incorporating nuclear energy sources into the energy mix	3% of energy generated shall be sourced from nuclear energy sources by 2035	No emission constraint	No renewables constraint
Renewables-promotion (RE1)	Characterized by an increase in the share of renewables in the energy mix and imposing an emission constraint on total energy generated	Same as RS2	Replicates RS2 conditions while increasing the share of renewables in the energy mix	Same as RS2	37% of GHG emissions shall be reduced from electricity sector by 2030	42% of total energy production shall be sourced from renewables by 2030
Renewables-promotion (RE2)	Characterized by a further increase in the share of renewables in the energy mix from 2022 to 2050	Same as RS2	Replicates RS2 conditions while incrementally increasing the share of renewables and nuclear capacities in the energy mix	Same as RS2	No emissions constraint	75% of total energy production shall be sourced from renewables by 2050

Source(s): Authors' own work

and higher costs. Significant increases in capacity are predicted for wind and solar PV plants, projected to reach approximately 40 GW and 26.05 GW, respectively, by 2050. However, CSP plants will only reach around 4.17 GW due to their higher costs, and no further hydropower capacity is anticipated and attributed to the historically limited capacity of hydroelectricity observed during the period of the baseline scenario. Figure 2 illustrates the projected installed capacity in the RS1 scenario categorized by generation type. The model also predicts a continued reliance on fossil fuels, particularly natural gas, with consumption rising from 147.88 TWh in 2022 to 455.73 TWh by 2050. Diesel use is expected to increase modestly, while wind and solar energy generation is projected to grow significantly, with wind rising to 156.97 TWh and solar to 99.18 TWh. Hydroelectricity generation is expected to remain steady at 22.47 TWh through 2050. Figure 3 represents energy generation by fuel type for RS1.

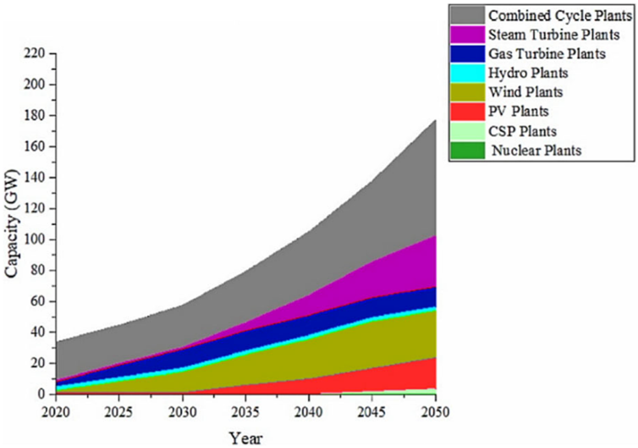
5.1.2 Reference scenario – RS2. According to the model's predictions, the capacity of combined-cycle plants will grow from 28.50 GW in 2022 to 61.44 GW by 2050, with little increase expected between 2022 and 2035 due to nuclear constraints. Steam turbine capacity is projected to reach 33.56 GW by 2050, but the model anticipates no further increase in nuclear capacity until then, aside from the planned 4.8 GW, largely due to high investment costs associated with nuclear power. Renewable energy technologies are expected to follow a similar trend, with wind capacity predicted to reach 39.24 GW and solar PV capacity 28.67 GW by 2050. Hydropower capacity is not expected to increase, while CSP capacity is expected to rise slightly to 4.24 GW. Figure 4 illustrates installed capacity by generation type in the RS2. Natural gas energy generation is forecasted to increase from 147.89 TWh in 2022 to 330.25 TWh by 2050, comprising 53.75% of primary energy sources, and diesel generation is set to grow from 0.86 TWh to 3.76 TWh. Due to a nuclear constraint imposed on energy production in this scenario, nuclear energy is projected to contribute 24.09 TWh to electricity generation, while wind and solar energy generation are expected to rise significantly, with wind increasing from 3.95 TWh to 155.36 TWh and PV energy from 2.97 TWh in 2022 to 98.63 TWh by 2050. Figure 5 represents energy generation by fuel type for RS2.

5.1.3 Renewables-promotion scenario – RE1. In this scenario, the model forecasted limited growth in combined-cycle plant capacity from 2022 to 2030, with a significant increase in CSP capacity expected to reach 65.33 GW by 2050. Steam turbine capacity is projected to rise to 33.67 GW by 2050. To meet renewable energy targets, a substantial increase in renewable technologies is anticipated, particularly in wind and solar power, with wind capacity expected



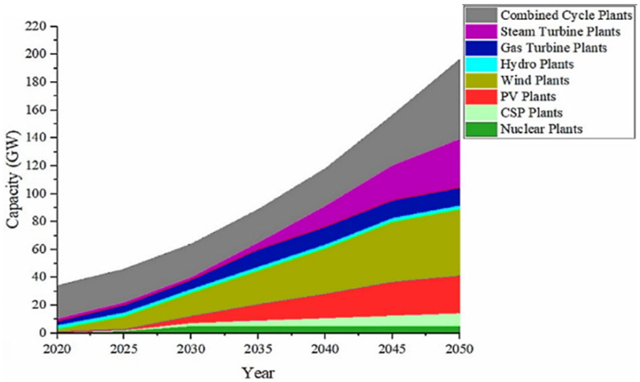
Source(s): Authors' own work

Figure 2. Installed generation capacity by generation type in RS1 scenario



Source(s): Authors' own work

Figure 3. Expected energy generation by fuel type in RS1 scenario

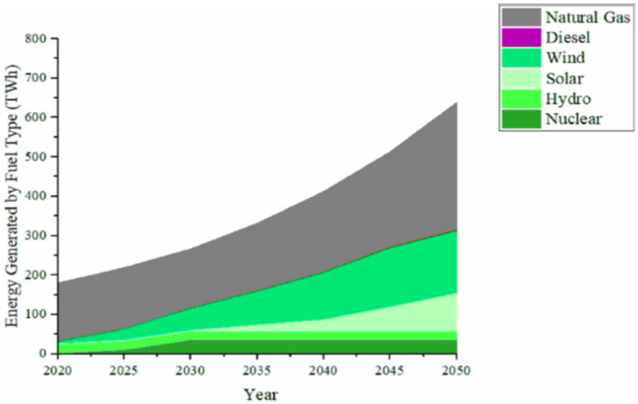


Source(s): Authors' own work

Figure 4. Expected installed generation capacity by generation type in RS2 scenario

to grow from 1.3 GW in 2022 to 11.73 GW by 2030 and 45.24 GW by 2050 and solar PV capacity rising from 14.47 GW by 2030 to 33.76 GW by 2050. CSP dependency is expected to be low, as the model forecasted no dependance on CSP, primarily due to high deployment costs compared with wind and solar PV technologies. Natural gas production is predicted to initially decrease from 147.89 TWh in 2022 to 129.36 TWh in 2030 due to the introduction of renewable and nuclear capacities between 2022 and 2035, followed by a resurgence to 368.83 TWh by 2050, after hitting a low in 2045. Diesel contribution is expected to decline to 0.29 TWh by 2050. In contrast, wind generation is projected to increase significantly, from 3.89 TWh in 2022 to 190.33 TWh by 2050, while solar PV generation is expected to rise from 2.86 TWh in 2022 to 127.91 TWh by 2050. The significance of the roles played by nuclear and hydro technologies is anticipated to reflect those in the RS2 scenario.

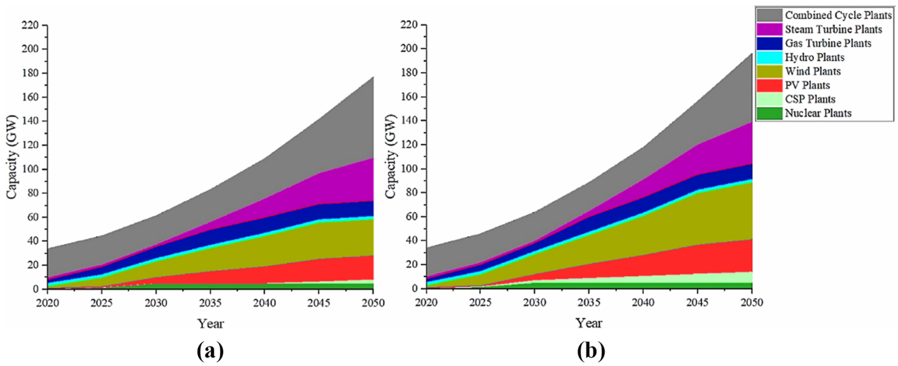
5.1.4 Renewables-promotion scenario – RE2. In the RE2 scenario, designed to promote renewables, combined-cycle plant capacity is expected to increase from 28.34 GW in 2022 to 62.29 GW by 2050, while steam turbine capacity is projected to grow from 2.09 GW



Source(s): Authors' own work

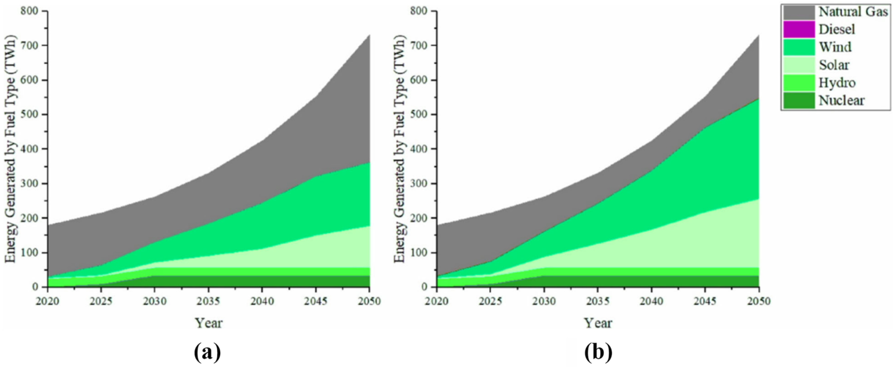
Figure 5. Expected energy generation by fuel type in RS2 scenario

to 31.74 GW. To meet a stricter renewables constraint, wind and solar PV capacities are set to rise, with wind expected to increase from 1.3 GW in 2022 to 22.59 GW by 2030 and 50.26 GW by 2050. Solar PV capacity is projected to grow to 17.84 GW by 2030 and further to 37.65 GW by 2050. CSP capacity is also anticipated to grow from 0.28 GW in 2022 to 5.01 GW by 2030, reaching 9.91 GW by 2050. Natural gas generation is expected to gradually decrease until it hits a minimum of 88.47 TWh in 2045, before rising again to 186.33 TWh by 2050, accounting for a quarter of total energy generation; despite this increase, it is projected to remain considerably lower compared to other scenarios. Diesel generation will decline to 0.81 TWh by 2050. By 2050, wind energy is predicted to dominate the energy mix at 298.73 TWh, starting from 3.89 TWh in 2022, with solar energy also contributing significantly, increasing from 2.86 TWh to 205.30 TWh. No changes in nuclear and hydroelectricity contributions are anticipated. Figure 6 illustrates expected installed capacity by generation type in the RE1 (a) and in the RE2 (b) scenarios. Figure 7 shows the distribution of energy generation by fuel type for RE1 (a) and for RE2 (b) scenarios.



Source(s): Authors' own work

Figure 6. Expected installed generation capacity by generation type in RE1 scenario (a) and RE2 scenario (b)



Source(s): Authors' own work

Figure 7. Expected energy supply by fuel type in RE1 scenario (a) and RE2 (b) scenario

5.2 Emissions

In the RS1, the model's projections indicated that GHG emissions are expected to peak and potentially reach maxima of 389.25 $MtCO_2e$ in 2030 and 493.56 $MtCO_2e$ in 2050. This is predominantly attributed to the extensive dependence on fossil fuels for the generation of energy in this particular scenario, coupled with the absence of constraints on renewables, nuclear and emissions. In contrast, in RS2, GHG emissions will peak at 339.26 $MtCO_2e$ in 2030 and 441.36 $MtCO_2e$ in 2050. This decrease in emissions, opposed to RS1, is a result of the integration of a nuclear capacity (3%) into the energy mix starting in 2035, which helps mitigate emissions to some extent but is counterbalanced by the surge in energy demand, leading to a greater reliance on fossil fuels. In the renewables-promotion scenario RE1, the model projected a modest reduction in GHG emissions compared to the RS2 scenario until 2030, where GHG emissions are estimated to reach 313.91 $MtCO_2e$. This prudent decrease is largely attributed to the increase in energy demand throughout the simulation period from 2022 to 2050, despite constraints on renewables as well as GHG emissions in the electricity sector already implemented. Yet, these factors would have a more noticeable impact in the long term in reducing GHG emissions, which is expected to reach 148.21 $MtCO_2e$ by 2050. The model predicted the lowest levels of GHG emissions in the renewables-promotion scenario RE2. Specifically, the model anticipated a significant decline in emissions from 120.45 MtCO2e in 2030 to 53.40 $MtCO_2e$ in 2050. This significant decrease in emissions is attributed to implementing a higher renewables target by 2050 and the implementation of nuclear capacity.

5.3 Costs

The model's projections indicated a general rise in production costs across various scenarios. In the RS1 scenario, costs are expected to increase from 5.27 cent/kWh in 2022 to 5.88 cent/kWh by 2050, primarily due to rising fossil fuel prices. In the RS2 scenario, costs are projected to jump from 5.26 cent/kWh in 2022 to 6.05 cent/kWh by 2035, influenced by the integration of more expensive nuclear technology, and are expected to reach 6.20 cent/kWh by 2050, driven by higher energy demand and related fossil fuel expenses. In the RE1 scenario, production costs are forecasted to rise from 5.22 cent/kWh in 2022 to 5.83 cent/kWh in 2030, attributed to the addition of renewable and nuclear capacities and emission constraints, before decreasing to 5.62 cent/kWh in 2040 due to increased reliance on low-cost renewable technologies, followed by another rise to 5.89 cent/kWh by 2050 due to higher energy demand. The RE2 scenario anticipates the highest production costs between 2022 and 2030, reaching 6.44 cent/kWh in 2030 due to additional renewable capacities. However, costs are projected to decline to the lowest level among all scenarios at 5.11 cent/kWh by 2050, attributed to the higher utilization of renewables with lower long-term operational costs.

6. Conclusion and policy implications

Research findings showed that in the RS1, natural gas is projected to dominate energy contribution at 60.42% by 2050, but it also results in the highest GHG emissions. Despite initially lower production costs, these are expected to exceed those of renewable-promoting scenarios (RE1 and RE2) in the long term, making RS1 an unviable option for policymakers due to its poor emissions reduction potential and lack of energy mix diversification. RS1 RS2, which includes a nuclear constraint, aims to enhance energy security by reducing natural gas's share to 53.8% and increasing nuclear production to 24.09 TWh by 2050, but it incurs the highest production costs due to the use of more expensive nuclear technology. On the other hand, scenarios RE1 and RE2 are expected to have the lowest GHG emissions by 2050, with RE2 offering the lowest production costs at 5.11 cent/kWh. While renewable energy may initially raise production costs, they are likely to decrease over time, supporting economic growth and environmental benefits. However, the economic viability of renewables is challenged by their limited availability, highlighting the need for policies that promote renewable deployment, improve infrastructure and gradually phase out gas subsidies. Policymakers are advised to prioritize diversifying the energy mix to reduce dependence on any single source and improve resilience against price fluctuations and supply disruptions. They should also promote the deployment of renewable energy through supportive policies and incentives, such as tax credits and investments in infrastructure that facilitate integration into the power grid. Improving the economic viability of renewables is crucial, which can be achieved through research, innovation and investment in energy storage to address generation intermittency. Additionally, gradually phasing out subsidies on gas supply can open up opportunities for increased renewable investments. Policymakers should keep interest rates low and maintain a discount rate below 15% to attract investments in renewable projects. A careful balance between emissions reduction and energy security is also necessary, with the integrated use of nuclear energy contributing to decreased natural gas reliance, in addition to supporting innovation and research in clean energy technologies through funding and collaboration will further advance the transition to a sustainable energy system.

Abbreviations and acronyms

BAS	Business-as-Usual
CO_2	Carbon Dioxide
CSP	Concentrated Solar Power
EEAA	Egyptian Environmental Affairs Agency
ESOMs	Energy System Optimization Models
GHG	Greenhouse Gas
kWh	Kilowatt-hours
LEAP	Long-range Energy Alternatives Planning
MARKAL/TIMES	Market Allocation and The Integrated MARKAL-EFOM System
MEDEAS	Modelling Energy System Development under Environmental and Socioeconomic Constraints
MoERE	Ministry of Electricity and Renewable Energy
MPED	Ministry of Planning and Economic Development
$MtCO_2e$	Million Tons Carbon Dioxide Equivalent
OSeMOSYS	Open-Source Energy Modelling Systems
RE1	Renewables-promotion scenario 1
RE2	Renewables-promotion scenario 2
RS1	Reference scenario 1

RS2	Reference scenario 2
T&D	Electricity Transmission and Distribution
TWh	Terawatt-hours

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