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Evaluating liquefied natural gas export quantities from Egypt using system dynamics approach

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Background: Egypt and nearby countries have been discovering new sources of natural gas (NG) leading to proven increased reserves. Egypt has two liquefaction stations for exporting Liquefied Natural Gas (LNG), while nearby countries do not have such stations.

Aim: Egypt adopted a policy to export LNG to major importing countries in Europe. Hence, this article aims to analyse the dynamics of the factors affecting the LNG export supply chain, and the main elements of adequate policies needed to optimise decisions related to LNG export in Egypt.

Settings: The input data for this study were obtained from official national and international reports.

Method: A system dynamics simulation model is used as a decision support system model to optimise decisions related to LNG exports in Egypt.

Results: The model gives insight into the effect of investment in new discoveries, investment in renewable energy and changes in population, gross domestic product (GDP) and LNG export prices, as well as the quantity of LNG re-export on the dynamics of LNG export Present Value and quantity.

Conclusion: The research provides a novel decision support system that can be used in adopting adequate policies along the LNG industry supply chain targets, optimising decisions related to exports of LNG. For Egypt, investments in new discoveries and making a long-term agreement to buy NG to be re-exported, are recommended strategic decisions to consider when targeting the optimisation of decisions related to the export of LNG. Investment in the generation of renewable energy and decreasing the home usage patterns come next in importance.

Keywords: system dynamics; LNG supply chain; LNG Simulation; LNG in Egypt, LNG exports; Zohr field.

Introduction

The Egyptian economy has been suffering from a large deficit in its energy balance. This increased the structural deficit in the national budget. NG (NG) discoveries in Egypt, such as at the Zohr gas field, significantly increased the proven NG reserves. The country was transforming into a net NG exporter in 2019. Egypt needed to plan its Liquefied Natural Gas (LNG) production along the whole supply chain to participate significantly in optimising its decisions, regarding LNG in the NG export market, especially in the light of the Russian-Ukrainian conflict.

Egypt works according to two parallel trends to make the country a regional hub for exporting energy. The first is to import Mediterranean NG, liquefy it to be re-exported as LNG along with the production surplus. The second direction is to make Egypt a hub for exporting electricity to Africa, Asia, and Europe. Several factors led to the electricity surplus in the market, which is expected to grow significantly soon. These factors include: new NG discoveries, diverse renewable energy sources (solar, nuclear, and wind) and interconnected electrical projects. But the LNG export market and large demand prioritise the first direction. In this regard, a number of Mediterranean countries signed agreements to supply gas to Egypt in 2019, for re-export after liquefaction, followed by the formation of the Eastern Mediterranean Gas Forum (EMGF) to cooperate in establishing a regional gas market in the eastern Mediterranean region (AmCham 2019).

As the generation of electricity accounts for the largest part of NG consumption in Egypt, 63% of the total gas consumption (EGAS 2018/2019), there is a trade-off between the two previous trends.

Consequently, the research problem is concerned with the conflicting policy trends in Egypt. Additionally, despite its adoption of the first direction, that is, focusing on the exports of LNG, studying how to optimise decisions regarding the export quantity and the Present Value of LNG export along the supply chain were ignored. Hence there is an urgent need for a decision support system for NG to help the country understand the dynamics of the industry and different parameters contributing to optimising the decision-making process. System dynamics (SD) simulation is a technique used to evaluate the effect of such dynamics and different parameters on LNG export and returns. To the best of our knowledge, this is the first study that builds a decision support system for LNG exports and, more specifically, in Egypt.

The rest of the paper is organised as follows: in the second section the potential of Egypt to be a regional NG export hub is analysed; in the third section the theoretical background and relevant literature are discussed; in the fourth section our methodology is analysed, and in the fifth section some empirical results are introduced, while the last section includes a discussion of the results.

Egypt as a regional natural gas export hub

Many factors led Egypt to become a hub for NG export. Taking into consideration that electricity generation uses the largest part of NG consumption, the efficiency of available NG resources becomes important. In this section, the Egyptian market of NG is analysed, and the efforts made to turn the country into a regional hub for natural gas export are clarified.

The discovery of NG in Egypt started in the early 1960s (LYNX 2019), and the use of NG for industrial purposes began in 1976 (IGU, TAQA & EGA 2018). Egypt's consumption of NG continued to be equivalent to production, since the first discovery until 2005 (British Petroleum Statistical [BPSR] 2021; Hegazy 2015). In 2003, Egypt started a project to export NG abroad (LYNX 2019). In 2005, this project took two tracks (AmCham 2019). The first concerns the export of NG through a pipeline between Egypt, Jordan, and Israel. The second is through the liquefaction of NG at two stations in Damietta and Idku, opened in 2005 and 2006. Egypt's gas exports in 2005 amounted to 6.98 billion cubic meters (BCM). Since then, the country continues to be a net exporter of NG (Hegazy 2015). The average growth of domestic production between 2000 and 2008 reached 17% annually. The share of NG in generating gross domestic product (GDP), jumped to 8.3% in 2005 and 2006 compared to 5.4% in 2004 and 2005, outperforming the petroleum sector for the first time according to the Egyptian Ministry of Planning and Economic Development data.

From 2009 to 2015, an energy problem in Egypt began to arise due to several factors (AmCham 2019; Farag & Rowihil 2020; Hegazy 2015). The first factor is a drop of 33% in the production due to the dramatic reduction in foreign investment, leading to a reduction in exploration and production. According to Schäfer et al. (2018), the reduction in foreign investment is the result of political instability in Egypt in 2011, when the management of the demand for energy was not optimised, and the production of some oil and gas fields reached maturity and started to decline. The second factor was the population growth which, combined with a very generous energy subsidy policy, strained production, leading the government to direct the available petroleum resources to supplement the domestic electricity shortage. The third factor is the relatively low prices paid by the government to foreign operators. Another contributing factor is that the Damietta station was forced to stop exporting LNG due to the lack of gas. Also, repeated attacks on the gas export pipeline in 2011 and 2012 led to the end of it. Finally, the historically extremely low domestic energy prices discouraged new producers to enter the market.

Hence, Egypt became an importer of NG again in 2015 (IEA 2019), especially after the NG shortage impacted energy-intensive industries like steel (IGU et al. 2018). The NG share of generated GDP significantly decreased from 8.27% in 2008 and 2009 to 3.25% in 2015 and 2016 according to the Egyptian Ministry of Planning and Economic Development data.

Since 2016, Egypt witnessed an expansion of exploitative activities again for several reasons, including economic and political reforms. Egypt witnessed a boom in production, consumption, and foreign trade (Farag & Rowihil 2020; IGU et al. 2018; MoP 2020). Egypt recently began to switch to the use of NG over other sources in many sectors as a greener energy source.

The development of the infrastructure and the encouragement of investment in the field of NG exploration increased production, especially after the start of production at the Zohr field in the Mediterranean and new discoveries in northern Alexandria and the Nile Delta. This increased the production of NG in Egypt and its world share from 2016 to 2019, with a growth in the production rate by 45.2% for the five years as shown in Figure 1 in the supplementary file (i.e. from 40.3 BCM to 58.5 BCM) (BPSR). Total NG production reached 20% in 2018 and 2019, relative to the previous year (EGAS, different issues) and its share of generating GDP increased till it reached 5.9% in 2018 and 2019.

NG consumption has increased rapidly since 2015, not only in absolute values but also as shares of total energy consumption. This is attributed to the expansion to replace petroleum products with NG as shown in Figure 2 in the supplementary file. This replacement includes the connection of NG to homes, instead of liquefied petroleum gas (LPG) and converting vehicles to be fuelled by NG. As a result, since 2015 gas export has been reduced, switching to domestic consumption instead (Abbas et al. 2020). Consumption of NG in Egypt accounted for 54.9% of total primary energy consumption in 2019 (58.9 BCM). This tendency to replace other sources of primary energy with NG continued, resulting in an increase in the sharing of NG as the primary energy consumed in Egypt to 57.1% in 2020, as shown in Figure 2 in the supplementary file.

NG consumption is distributed among different sectors: electricity generation, the industrial sector, the sector of petroleum, gas derivatives and petrochemicals, and residential consumption (EGAS 2018 and 2019). The latest available data, according to the EGAS database, confirmed that the dependency on NG in the industry was reduced as the government directed the available NG resources to supplement the domestic electricity shortage for residential consumption, as mentioned before. Despite the lack of NG during 2013–2015, already mentioned, NG was directed to residential consumption. This was responsible for seeing the residential consumption of NG as a positive trend. The share to supply cars that consume natural gas in Egypt has stabilised at 1% since 2005 and 2006. In 2020 and 2021, this supply of NG consumption increased by 20% from 1% to 1.2%, as shown in Figure 3 in the supplementary file.

Despite the increase in domestic demand for NG, because other energy sources have been replaced, especially petroleum products and coal, Egypt has succeeded in achieving self-sufficiency regarding NG since September 2018 (LYNX 2019), as shown in Figure 1 in the supplementary file. The reason for this is the increase in production, especially at the Zohr and Atoll fields (AmCham 2019). In 2020, Egypt was considered the second largest producer of NG in Africa, following Algeria, and the fifth largest in the Middle East according to BPSR data. In September 2018, with the recovery of gas prices, Egypt resumed exporting NG in pipelines to Jordan (LYNX 2019; MoP 2020). However, most Egyptian exports of NG take the form of LNG (70% of exports), benefiting from the LNG port factories in Idku and Damietta (Abbas et al. 2020).

The fact that most of Egypt's NG is exported as LNG, is in line with the global trend and expectations that the increase in demand for LNG will exceed the demand for NG in general (Egging et al. 2008). Roar Aune Einar Rosendahl and Lund Sagen (2009), as well as Catalán (2016) ascribed this trend to three main factors. The first is the ability to transport LNG a greater distance, making it cheaper compared to compressed NG. The second is the danger of using pipelines for long distances. The third is that the demand for NG is seasonal, while its production is not. This requires producers to raise their stocks to respond to changes in demand. The best way to store NG is to liquefy it.

Figure 4 in the supplementary file shows the progress of foreign trade in LNG and its share in the world. The figure shows the strong correlation between Egyptian trade in liquefied gas and its share in world trade. The correlation coefficient between them for export reached 97.8%, while import stood at 99.1%. This indicates that the change in Egypt's share in world trade regarding LNG is linked to internal factors related to production and consumption rather than to global trade trends.

Literature review

In this section, three bodies of literature are considered to fill gaps in knowledge related to the objective of the study: identifying the phases through which producing LNG passes along the supply chain, determining the main contributing factors affecting the trade of NG and LNG, and introducing SD as a decision support tool.

Following the accelerating trend to replace oil and coal with NG in the energy systems in many countries in order to cut greenhouse emissions, many publications recognised the importance of analysing the whole value chain of LNG. Some publications determined the phases through which producing LNG passes along the supply chain, while others determined the factors affecting LNG trade in order to model it.

Egging et al. (2008) investigated the factors affecting a particular country's exports of LNG along the supply chain in 54 countries. The study stated the phases through which LNG passes along the supply chain, starting at discovery and ending at consumption. These phases include discovery, production activities, pipeline and storage operations, liquefaction operations, regasification and storage, tanker transportation activities, related marketing activities and consumption for end use. Related marketing activities include marketing operations related to production, transit and consumption. Consumption in the end-use phase includes the residential, commercial, manufacturing and electrical energy sectors. This study highlighted the significance of all decisions related to the various phases affecting exports of LNG performance.

Egging, Holz and Gabriel (2010) established a model to predict future directions in NG marketing in more than 80 countries covering 98% of the worldwide NG market. This study followed the same methodology as Egging et al. (2008), while dividing the supply chain into more phases, as it divided the LNG market into seven main players along the supply chain: producers, traders, storage operators, LNG liquefiers, re-gasifiers, transmission system operators and consumption markets.

Roman-White et al. (2021) estimated emissions of LNG along the supply chain with an application on Cheniere Energy's Sabine Pass Liquefaction (SPL) that delivers production of LNG from the United States to China. The study identified nine main operations along the LNG supply chain and all of them result in emissions which need to be managed. These operations include production, gathering and boosting, processing, compression, transporting in pipeline, liquefaction, transport domestically and internationally, regasification and consumption.

Mishra (2016) stated that LNG has become the preferred source of clean energy all over the world. Therefore the effects of logistics innovations on LNG global supply chains are analysed. The global supply chains for LNG are divided into several stages, including exploration, followed by gas separation and processing, storage and liquefaction with transporting in pipelines, liquefaction, transporting in LNG tankers, marketing and distribution, regasification and consumption for different purposes. Conclusions confirmed that logistic innovations are critical in all stages along LNG global supply chains.

The review of previous studies regarding the main phases of the LNG supply chain stated clearly that all of these studies agreed on the main phases in the LNG supply chain. The LNG supply chain has two main scopes of activities: an up-stream sector and down-stream sector. The up-stream sector includes activities of exploration and mining. The down-stream sector includes activities of processing, production, liquefaction, transportation, regasification and distribution of LNG. All these activities need to be managed efficiently in order to improve the performance of the entire LNG supply chain.

Barnes and Bosworth (2015) explored the contributing factors of LNG trade around the world, using a gravity model with random effects. They highlighted the significance of GDP per capita for both parties of trade, the percentage of GDP generated from producing NG for both parties of trade, the unemployment rate to control economic conditions, and the distance between the two parties of trade to accelerate the demand for LNG. Catalán (2016) investigated the main determinants of LNG exports using gravity equations. The study illustrated the importance of GDP for both parties of trade, the distance between them, the share in other sources of energy in energy systems for both parties and the share of value added in generating GDP, as the industry is considered the largest consumer of NG. Ackah (2014) analysed the main contributing factors of the NG market in Ghana. Two main contributing factors were added in this study. The first is related to the technological progress which, in turn, is related to the efficiency of using NG whether for production or heating. The second is household spending coupled with changes in consumer preferences.

Roar Aune et al. (2009) assessed the implications of several scenarios regarding future market conditions on the NG global market until 2030. Several contributing factors have been used to measure the demand and supply of NG. On the demand side, the main contributing factors were prices of all energy goods, per-capita GDP growth, population, electricity capacities, electricity price, and generation cost. The NG supply was formulated as a function of field characteristics, production costs, net producer prices after tax, the fields' production capacity, investments in new fields and in reserve extensions, expected prices versus a pre-specified required rate of return, and total transportation costs, whether for LNG, or in pipelines.

Ghorban (2006) inspected the contributing factors of the potential of gas pipeline exports from Iran to the Indian subcontinent. The study highlighted the significance of supply factors including NG reserves, investments directed to the development of the extractive sector, and the availability of the necessary infrastructure to export gas. Nick and Thoenes (2014) assessed the factors affecting NG prices worldwide. The study highlighted the significance of meteorology and long-term variations in the price of alternative sources of energy affecting the NG market.

In a study mentioned earlier, Egging et al. (2008) found the main contributing factors affecting a particular country's exports of LNG along the supply chain to be the total production ceiling, NG selling prices, regulated pipeline transportation costs, capacity of liquefiers, liquefaction costs, maximum LNG liquefaction rate of LNG liquefiers, the set and capacity of the shipping vessels, the set and capacity of LNG re-gasifiers located in the country, as well as the set of storage operators located in the country.

A review of previous studies identified the most important determinants of LNG exports to be included in the model as: Egypt's GDP, population, rate of return on investment, electricity production by alternative sources (wind, solar, nuclear, hydro-electricity and renewable), electric power consumption and its growth, natural power consumption of end users (gas-powered vehicles, the petroleum sector, residential homes and the industrial sector), NG production, quantity of NG available for export, NG sales price, fixed costs required for the production of LNG, and the increase in NG production from each cycle due to new discoveries.

Many factors combined to highlight the importance of understanding the behaviour of commercial, industrial and social systems by exposing the causal relationships between the different contributing factors and parameters. Among these factors are the acceleration of dynamic changes in these systems, the complexity of the systems, and the confluence of several factors influencing their behaviour, considering the need to understand the functioning of these systems in the long term. This helps in making sound decisions, considering the existence of different alternatives to relevant policies (Movahednasab, Rashidinejad & Abdollahi 2019). In response to these requirements, the system dynamics approach (henceforth SD) was designed by Jay W. Forrester in 1961 to help analyse the functioning of economic and social systems over time, taking into account their complex interrelationships (Mudjahidin et al. 2019). In his study, Forrester defined SD as:

> [*T*]he study of the information-feedback characteristics of industrial activity to show how organizational structure, amplification (in policies), and time delays (in decisions and actions) interact to influence the success of the enterprise. (Langroodi & Amiri, p. 206:232)

System dynamics have been widely used to support decision makers in setting business policies in the fields of manufacturing, management, development and environmental studies, taking into account the dynamic environment of relationships (Lee & Chung 2012). System dynamics have their basics from feedback control and nonlinear dynamical system methodologies. The use of SD has become common in these sectors, as it allows the design of a dynamic model that is similar to real systems and provides the possibility of simulating reality. This facilitates the testing of proposed policies by developing many possible scenarios and evaluating their results, while allowing for the testing of possible changes in these scenarios dynamically during the specific period of simulation (Mudjahidin et al. 2019).

A system dynamics model consists of several interrelated variables. Some of these variables are represented as stock variables while others as flow variables (Langroodi & Amiri 2016). The interrelations and feedbacks between variables in the system are represented as causal loops. A causal-loop diagram represents causally interrelated effects between variables in the system, using arrows connecting variables (Lee & Chung 2012). In each causal-loop diagram, any variable can be included as a constant, or as a function of other variables. The credibility of using SD in expressing the real system requires conducting several tests. Some are prior to the design of the system, such as testing the interrelated effects between variables, and whether the variables are considered stocks or flows. Some tests are done during the simulation process and others test the simulation output. However, most studies are conducting tests only on the final output of the simulation (Mudjahidin et al. 2019).

Langroodi and Amiri (2016) mentioned that since introducing SD models to the supply chain, it has been developed for use in many fields in the past decades. These fields include simulating some products in the supply chain such as food, the automotive industry, electrical and electronic equipment, the maintenance of military weapons, short-life-cycle products and information sharing. Additionally, it is used in simulating value, adding to supply-chain demand planning, measuring the effectiveness of using electronic collaboration tools in the supply chain and simulating the planning of remanufacture.

From the literature, there is little research on using SD in modelling the dynamics in the LNG supply chain. This is especially valid when considering the recent discoveries and the Egyptian liquefication stations with no similar stations nearby. Also, there are huge reserves in the Mediterranean Sea near these stations. This creates a research gap for constructing a decision support model to study the dynamics of the LNG industry in Egypt to optimise the decisions regarding the export quantities and the Present Value of LNG export in Egypt.

Methodology

In this section, the formulation of the model is presented. The general description of the model is shown in Figure 1. The general relationships are described as follows: to compute the Present Value of the exports of LNG, we need to find the annual sales, adjusted by the rate of return and the fixed cost investments. The Present Value of LNG exports is dependent on the price forecast for LNG export and the rate of return. The quantity of annual export is related to quantities in production, imports, and consumption. The surplus quantity from production and import after deducting local consumption, is exported.

Local consumption comes from the generation of electricity, industrial consumption, petroleum-sector consumption in producing other products, home use, and vehicle fuelling. NG is used to generate electricity when the electricity from renewable sources and oil are not enough to satisfy the demand.

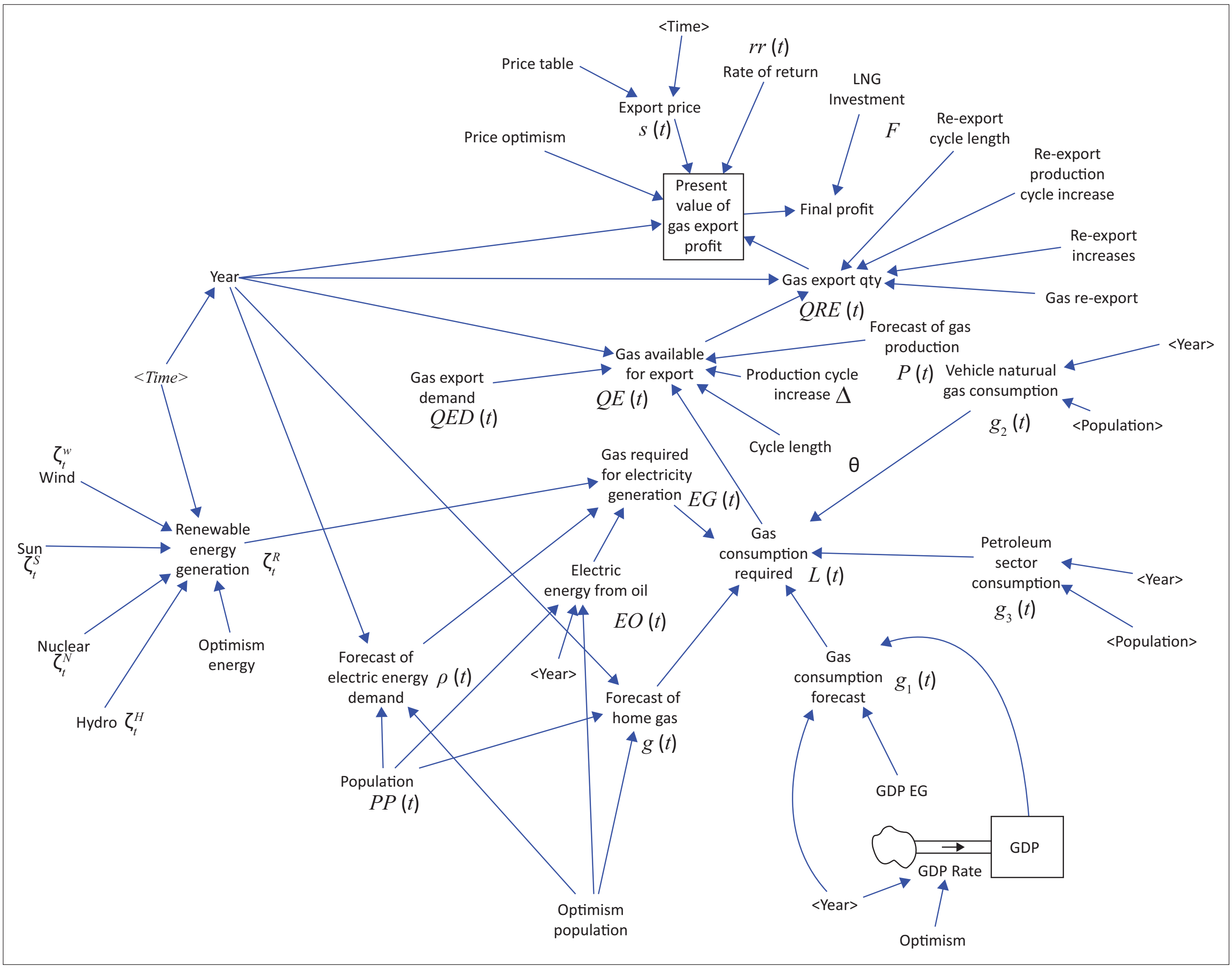
The following nomenclature is used:

ζ_t^w	Wind electricity production at time *t*.
ζ_t^S	Solar electricity production at time *t*.
ζ_t^N	Nuclear electricity production at time *t*.
ζ_t^H	Hydro-electricity production at time *t*.
ζ_t^R	Renewable electricity production at time *t*.
$\rho(t)$	Electric power consumption at time *t*.
$PP(t)$	Egyptian population at time *t*.
$EG(t)$	Electric energy required from gas at time *t*.
$EO(t)$	Electric energy required from oil at time *t*.
$g(t)$	NG consumption at time *t* in residential homes.
$g_1(t)$	NG consumption at time *t* in the gas industrial sector.
$g_2(t)$	NG consumption at time *t* in gas-powered vehicles.
$g_3(t)$	NG consumption at time *t* in the petroleum sector.
L(t)	Local NG consumption at time t.
$P(t)$	NG production at time *t*.
r	consumption rate for each MWh when generated from NG. The result is the volume of NG required to generate 1 MWh.
$QE(t)$	NG quantity available for export at time *t*.
$QED(t)$	NG export demand at time *t*.
$QRE(t)$	NG re-export quantity at time *t*.
s(t)	sale price per BTU
$rr(t)$	rate of return at time *t*
F	fixed cost
$PV(t)$	Present Value of the project resulting from running the project for *t* years
θ	Depletion cycle of NG mines in Egypt
Δ	NG production increase from each cycle due to new discoveries.

Starting at the electric energy generation, the total renewable energy generated at time *t* is defined as the total electricity production from wind, sun, nuclear, and hydraulic sources as these are the sources used in Egypt. This is shown in equation (1):

$$\zeta_t^R(t) = \zeta_t^W(t) + \zeta_t^S(t) + \zeta_t^N(t) + \zeta_t^H(t) \quad \text{[Eqn 1]}$$

For the electric power consumption, a regression analysis is performed using population and time as independent



LNG, liquefied natural gas; GDP, gross domestic product.

FIGURE 1: The system dynamics model of Liquefied Natural Gas Export in Egypt.

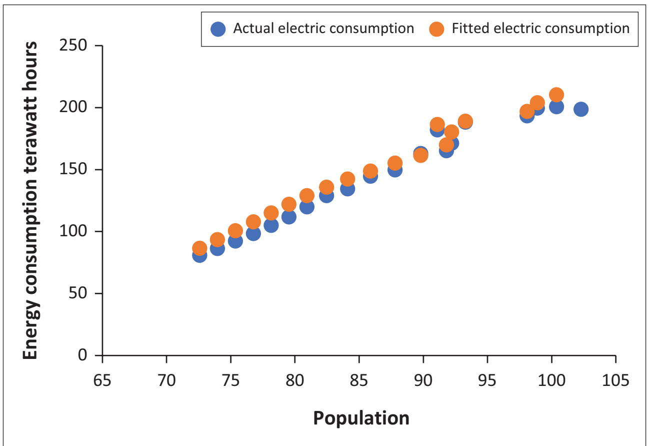


FIGURE 2: Regression of the electric energy consumption.

variables. Hence, the forecast of the electric power consumption is shown in equation (2) and Figure 2:

$$\rho(t) = 8.92784 * PP(t) - 1.29633 * t + 164.346 \quad \text{[Eqn 2]}$$

Hence, the shortage in electric energy that needs to be generated can be formulated as shown in equation (3), assuming that the energy requirement is a priority that must be satisfied through generating electricity using NG or oil:

$$EG(t) = \max(0, \rho(t) - \zeta_t^R - EO(t)) \quad \text{[Eqn 3]}$$

A regression analysis is performed to estimate the electric energy generated from oil, knowing that the Egyptian government adopted the policy of phasing out the use of oil in generating electricity. The independent variable is the population. Hence, the electric energy generated from oil is estimated as shown in equation (4) and Figure 3:

$$EO(t) = -0.0287\, PP(t)^2 + 5.6364\, PP(t) - 247.73 \quad \text{[Eqn 4]}$$

Other sources that consume NG in Egypt include home usage, usage of vehicles powered by NG, industrial usage, and usage of the petroleum sector.

For Home usage, NG consumption at time t can be approximated, based on the historical data, by a multiple regression line. It is formulated with population and time as independent variables, as shown in equation (5) and Figure 5 in the supplementary file:

$$g(t) = 1.060067 * PP(t) + 3.479217 * t - 78.1299 \quad \text{[Eqn 5]}$$

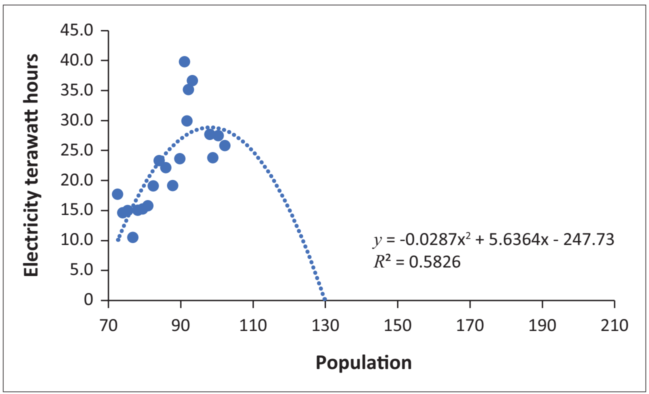
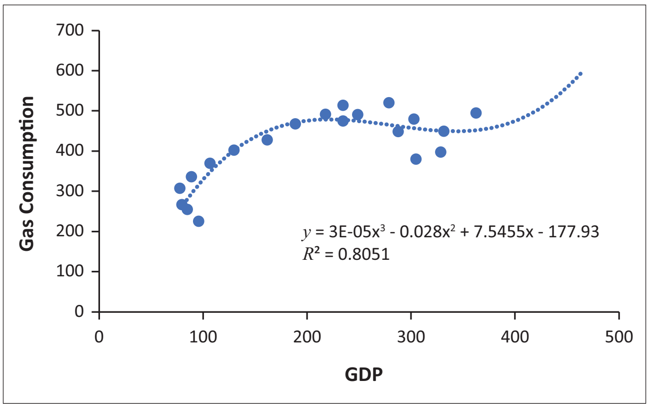


FIGURE 3: The fitted line of the electricity generated from oil.



GDP, gross domestic product.

FIGURE 4: Fit line of the gas consumption of the industrial sector (a-b).

For Industrial usage, NG consumption at time t can be approximated, based on the historical data, by a regression function. It is formulated with GDP as independent variables as shown in equation (6) and Figure 4:

$$g_1(t) = -0.00003GDP^3 - 0.028GDP^2 + 7.5455GDP^3 + 177.93 \quad \text{[Eqn 6]}$$

The usage of NG in vehicles and those in the petroleum sector can both be estimated by regression analysis with time as an independent variable as shown in equation (7) and Figure 6 in the supplementary file; and equation (8) and Figure 7 in the supplementary file, respectively:

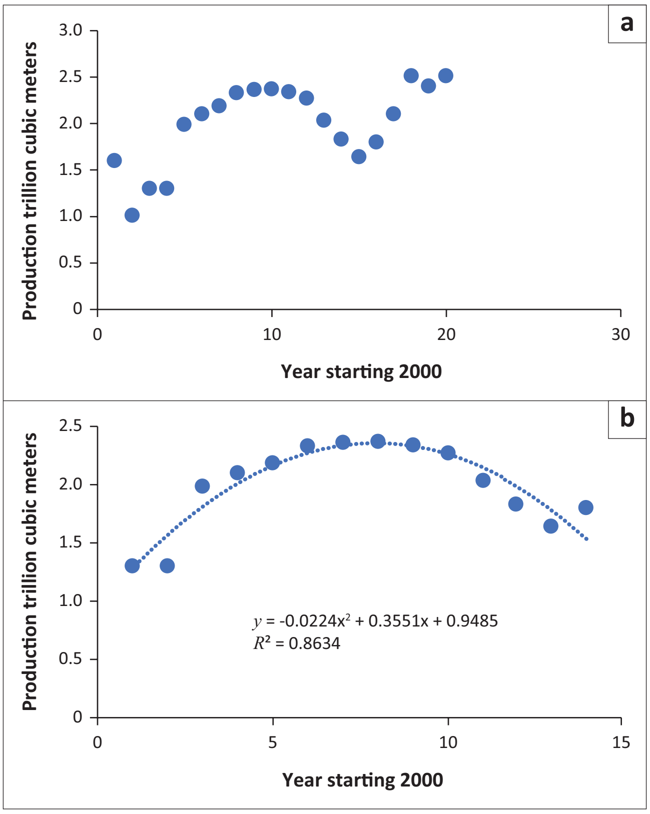
$$g_2(t) = 1.093796 * PP(t) - 1.11047 * t - 68.3392 \quad \text{[Eqn 7]}$$

$$g_3(t) = 5.005655 * PP(t) - 0.69143 * t - 253.662 \quad \text{[Eqn 8]}$$

Then the consumption of NG in given year t it is formulated as follows:

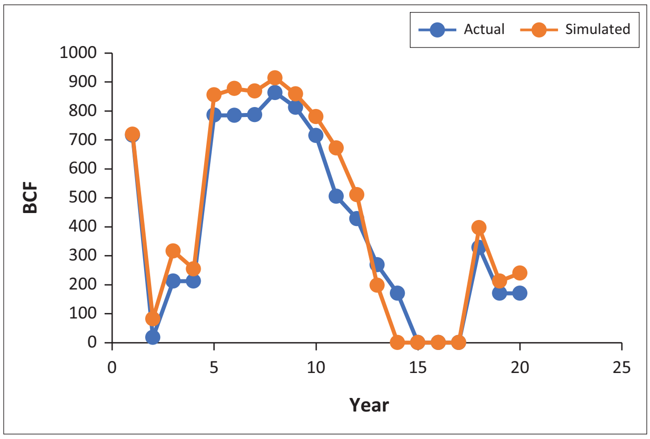
$$L(t) = G(t) + g(t) + g_1(t) + g_2(t) + EG(t) * r \quad \text{[Eqn 9]}$$

The production forecast as shown in Figure 5 is based on the assumption that NG production fluctuates in cycles of repeated increase, followed by decrease; hence one cycle is analysed as shown in Figure 5b. This function is repeated in a cycle of 15 years with the value of production increased at a rate shown in eq (10). The number of cycles is expressed as the quotient resulting from dividing t by θ as in $integer(t/\theta)$, while the remainder represents the value to be used in the cycle represented as $t\backslash\theta$:



NG, natural gas.

FIGURE 5: Forecast of NG production in Egypt (a-b).



BCF, billion cubic feet.

FIGURE 6: Comparing the simulation results versus the actual results for the quantity of gas available for export.

$$P(t) = -0.0224(t\backslash\theta)^2 + 0.3551(t\backslash\theta) + 0.9485 + \Delta * integer(t\backslash\theta) \quad \text{[Eqn 10]}$$

The quantity available for export is defined as the minimum of the NG export demand and the quantity of NG available for export, where the quantity of NG available for export is the difference between production and consumption at time t as shown in equation (11):

$$QE(t) = \min(QED(t), \max(0, P(t)-L(t))) \quad \text{[Eqn 11]}$$

Hence, the Present Value of the net profit is equal to the accumulation of the sale price, multiplied by the quantity of

NG export, adjusted by the rate of return minus the fixed costs as shown in equation (12):

$$PV(t) = \int_o^t (QE(t) + QRE(t)) * S(t) * (1 + rr(t))^{-t}\, dt - F \qquad \text{[Eqn 12]}$$

The Markov Chain Monte Carlo (MCMC) simulation is used for a normal distribution to estimate the selling price. However, the forecast is not quite similar to the actual historical data. Hence, we use the fit function as shown in Figure 8 in the supplementary file for the natural liquid gas as a million dollar per billion cubic feet of NG. We select a logarithmic function assuming that the NG is so precious that the world may curb its rate of price increase. The complete model is shown in Figure 1.

As a validation for the model, the model is run, and the result of the simulation compared to the actual results for the quantity of gas available for export up to 2020 as shown in Figure 6. It is observed that the simulation results are close to the actual data. Hence, the model can be used to infer the effect of making decisions.

Numerical results

In this section, the model is run several times to give insight into the effect of the different parameters on the dynamics of the LNG exports in Egypt. The factors studied in this section are the effect of investment in new discoveries, the effect of investment in renewable energy, the effect of population increase, the effect of GDP increase, export prices, and the re-export quantity. The Present Value and quantity of export are measured as output from the model. The parameters used in the numerical analysis are shown in Table 1.

Figure 7a and Figure 7b show the performance of the model of the most optimistic versus the most pessimistic scenarios for the Present Value and the export quantity, respectively. It is observed that the LNG industry outcome may vary from large quantities in export and large Present Value to a small quantity export and small Present Value. This emphasises the importance of making good decisions to optimise the performance of the model.

Figure 9a and Figure 9b in the supplementary file show the effect of investing in new discoveries for the Present Value and the quantity of export, respectively, in case of no new discoveries, smaller than usual discoveries, and large discoveries. For the smaller than usual discoveries, 300 BCM are added instead of the 500 BCM per 15- year cycle increase, while for the larger than usual increase, we use 800 BCM increase per 15-year cycle.

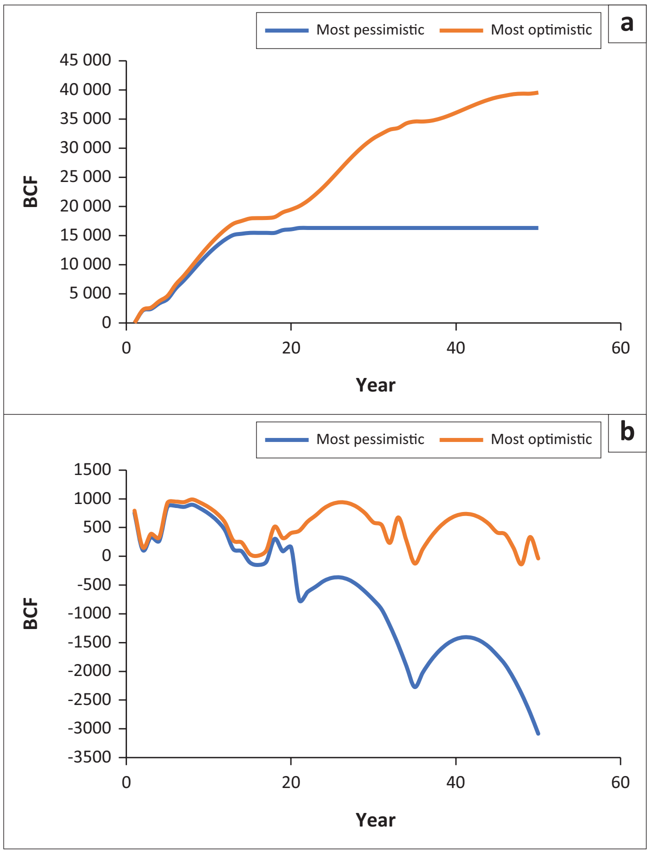
It could be observed that under the current operating conditions for the other factors, if Egypt had not invested in new discoveries (including Zohr), zero quantity would have been available for export from 2020 onwards and the Present Value would have been flat, as no exports would have taken place. If Zohr and current discoveries increase the cycle of production by 300 BCF, which is smaller than expected, there may be a couple of years to import, followed by 8 years of export when this increase will not be sufficient for the nation's consumption. While, if Zohr and future discoveries turn out a higher production than expected (cycle-increase by 800 BCF), there may be enough to export in the coming 12 years. Should similar new discoveries be made, the export of LNG could be sustained. This is supported by the economic theory, according to which investment in new discoveries leads to an increase in the supply of NG, with an increase in potential exports of LNG, assuming that the rest of the factors, affecting LNG exports, remain unchanged.

Figure 10a and Figure 10b in the supplementary file show the effect of investing in sources of renewable energy for

TABLE 1: The different values used in the numerical analysis for all the parameters.

Parameter	Values used
New discoveries	Normal discoveries (500 BCM increase per 15-year cycle) Smaller than usual discoveries (300 BCM increase per 15-year cycle) Larger discoveries (800 BCM increase per 15- year cycle)
New renewable energy	Normal investment (current governmental plans) Large investment (10% increase in renewable energy)
Population	Normal increase (current annual population increase rate forecast) Large increase (10% increase in the forecast growth rate)
GDP	Pessimistic, neutral, and optimistic all come from different regression functions showing declining, stable and increasing GDP growth rates.
Export Price	Normal increase (current forecast of export price) Large increase (10% increase in the forecasted export price)
Buying gases for the sake of re-export	No increase Moderate increase (increase of 100 BCM per 15-year cycle) Large increase (increase of 300 BCM per 15-years cycle)

BCM, billion cubic meters; GDP, gross domestic product.



BCF, billion cubic feet.

FIGURE 7: Most optimistic case versus most pessimistic case. (a) Effect on Present Value; (b) Effect on Export Quantity.

the Present Value and the quantity of exports, respectively, in the case of normal investment and for a large increase, defined as 10% more energy than planned. It can be observed that the increase in investment in renewable energy is important in long-term planning, but not in the next 10 years, as the results of the investments will not mature until then. The feasibility of such investment is to be compared against the increase in the Present Value and the expected life of new investments. The significant effect of investing in renewable energy generation on LNG export in the long run is supported by economic theory, especially considering that Egypt adopted a tendency to export the excess supply after deducting domestic consumption. Accordingly, substituting LNG with renewable energy sources, especially for electricity generation and industrial sector purposes, will increase the excess supply available for export. However, this effect may be reversed in the short term, as directing investments to the generation of renewable energy may inhibit investment in discovering gas fields, and may reduce the supply of gas, negatively affecting the export of liquefied gas.

Figure 11a and Figure 11b in the supplementary file show the effect of population increase on the Present Value and the quantity of exports, respectively, in the case of a normal increase and large increase defined as 10% more growth rate than planned. It can be observed that the increase in population, despite being one of the main sources of income in foreign currency, reduces the quantity and the number of years of exports, and reduces the Present Value. This can be explained theoretically by the existence of a direct relationship between population increase and energy consumption, knowing that electricity generation is the first consumer of NG in Egypt.

Figure 12 in the supplementary file shows the effect of GDP change on the Present Value. It can be observed that the change in GDP is insignificant in affecting neither the gas consumption nor the quantity significantly. It does not affect the period of export and import. In our opinion, there are two possible explanations for that. The first is that the industrial sector responded to the lack of NG and the price increase by using more efficient equipment. The second reason is that the increase in gas consumption in the industrial sector is much smaller than that in the case of population increase (i.e. the GDP is not expected to increase rapidly and at the same time the efficiency of using NG in industry increases, unlike for the population and electric generation). Also, in Figure 13 in the supplementary file, LNG export price affects the Present Value of LNG export, but does not affect the quantity of LNG export as the policy adopted in Egypt was to export LNG only when there is a surplus in domestic supply.

Figure 14a and Figure 14b in the supplementary file show the effect of buying gas for the sake of re-export on the LNG export Present Value and quantity, respectively, in the case of small, normal, and large increases. It can be observed that in the short term, the buying of NG for re-export increases both the Present Value and export quantitytrs, but all options result in a surplus in both. But for long-term planning, re-export is necessary to satisfy demand and generate revenue. This can be explained theoretically by the increase in NG supplied in the market to be liquefied for the purpose of being re-exported as LNG which confirms the efforts made to establish long-term agreements for buying gas from neighbours to be re-exported after liquefaction.

Conclusion

In this article, we present a SD model for the LNG export quantities in Egypt. New discoveries have been made locally along with nearby countries. It also has liquefaction stations that may be used to export its production of LNG, as well as that of nearby countries. It is hence very important to analyse the dynamics of the elements affecting the quantities of LNG exported.

The model is based on historical data and is validated by comparing its results against the real-life results in historical data which turned out to be close. The model is run for the most optimistic and pessimistic scenarios and the results show that the export quantities and revenue vary drastically from large quantities for export with large profit to no exports with a need for imports. Hence, the effect of different parameters is investigated to have a decision support system to make adequate decisions in future. It can be concluded that investment in new discoveries and in making a long-term agreement to buy gas for the sake of re-export are the recommended strategic decisions to consider. The feasibility of such decisions should be compared against the increase in revenues. However, not taking consistent action in these directions will lead to large shortage in a decade.

Investments in renewable energy generation and in decreasing the home usage patterns come next in importance. The impact of renewable energy takes effect slowly and is still not as reliable as NG. Also affecting the population size or teaching the population to consume the NG more efficiently is not a guaranteed policy to adopt. Despite being less important, these shouldn’t be neglected.

Finally, the export price and the GDP change are not affecting the export quantity in our model. This is explained stating that the change in Egypt’s share of LNG world trade is linked to internal factors related to production and consumption more than it is to global trade trends. The reason is the tendency in Egypt to export the domestic surplus, knowing that electricity generation and the industrial sector dominate NG consumption in the country as mentioned before.

Possible future research includes the analysis of the other trend in exporting electricity rather than just exporting LNG.

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Authors' contributions

All authors contributed equally in all aspects of the research.

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Data availability

The authors confirm that the data supporting the findings of this study are available within the article.

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