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Abstract

Fossil fuel are used in power generation in oil and gas producing countries due to the resource availability. However, the growing electricity demand, the potential exports revenues associated to hydrocarbons as well as the environmental policies have to be taken into account for the definition of the electricity generation mix. Thus, the development of the power generation capacities according to the resource availability and the economic factors (demand and costs) is investigated through a modeling approach. Over the past ten years, Egypt has become an important gas producer and a strategic gas supplier for Europe. Moreover, natural gas represents around eighty percent of the Egyptian power sector mix. However, this extensive share of natural gas in power generation mix could not be sustainable in long-term due to the limited hydrocarbons' resources of Egypt. In this study, the current and future power generation situation of the country is analyzed through a dynamic linear programming model. Finally, a power generation strategy based on a gradual integration of nuclear and renewable is suggested.

Keywords: Energy Sector; Egypt; Power Generation mix

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1. Introduction

The increasing trend of the electricity demand is mainly associated to both economic development and demographic evolution in most of the countries. To meet this need, the main sources of electricity production used in the world are still the power plants using fossil fuels (coal, gas and oil to a lesser extent) that provide 67% of electricity production in the early 2010s, followed by hydro plants (16%) and nuclear (13%). Other renewable types of power plant (wind, solar, geothermal, biomass and etc.) provide the rest of that production. In Europe for example, renewables account for nearly 20% of electricity production. As part of the European "20-20-20" initiative, the development of electricity from renewables is supported by incentive policies based on guaranteed purchase prices or bids for the construction of power generation units. For example Germany, under its Energiewende plan adopted in 2011, is accelerating its energy transition to almost total abolition of non-renewable power units in its electricity generation mix in long term. MENA[1] region is not an exception in this global electricity-generation-decarbonisation trend and is following the same path. Expansion of non-fossil energy in MENA countries, is driven by a number of key factors: energy security enhancement, major energy demand growth, urbanisation, water scarcity and of course environmental concerns. With high fossil fuel prices resulting in both huge bills for net oil-importing countries and opportunity costs for net oil-exporting countries, non-fossil resources have become an increasingly attractive alternative to domestic oil and gas consumption. From 2008 to 2011, non-hydro renewable resources for power generation more than doubled to reach almost 3TWh[2] and grew at faster rate than their conventional counterparts (REN21-2013).

[1] Middle East and North Africa
[2] Tera-Watt-Hours

The most appropriated power generation mix is implemented to reach the electricity demand according to the resource and the technologies availability. Thus, in a large number of oil and gas exporting countries, fossil fuel are used for power generation to provide electricity to a growing population with a low cost. However, the growing electricity needs of the population, the environmental concerns and the potential value of oil and gas resources on foreign markets make that the optimal electricity generation mix has to be designed according to these constraints or targets. Egypt is a typical case for such problem with a growing population and gas reserves which could be used for exports and power generation. Over the past decade, Egypt had solid economic growth due to its rising exports and investment and also its strong national consumption. Energy sector has been highly interconnected with economic activity of the country. Most of the energy demand growth came from growing industrial production and robust population expansion. Energy demand growth has also been promoted by the governmental subsidies coming from exports revenue (mainly hydrocarbon resources). Unfortunately this subsidization policy contributed a lot to fiscal deficit of the country. Recently government has announced several times the suppression of these subsidies. No action has been taken place regarding this issue until now and it seems that nothing will be realized (at least in the short-term future) due to social events and uncertainties that the country is currently facing with following the Arab Spring and recent socio-political movements.

Egypt’s highest export revenue comes from natural gas. However, its production is slowing down largely because of the lack of foreign investments (notably from International oil Companies). This production decline will also impact the petrochemical industry fed with natural gas as row material. Natural gas is the key fuel in Egypt, especially in industry and power sector which is the largest energy consumer sector of the country.

In this paper, electricity generation mix of the country is explored through a linear programming model. Sensitivity analyses is performed on several economic factors to point out the crucial role of the discount rate as well as the carbon price on investment decisions. For this purpose, economic context of Egypt is presented in section 2 and section 3 specifically dedicated to the power sector. The methodology is developed in section 4 and the results are analysed section 5.

2. Energy and environmental policy and the power generation mix development

Oil and gas resources availability aims to define the best strategy to use them for the people's welfare over a long period. Furthermore, the decision process for energy policy has to deal with a lot of uncertainties concerning both the potential amount of resources and the economic activity along several decades. The undesirable effects of oil revenues on the long term economic activity are clearly analyzed in the so-called Dutch Disease case (Corden & Neary 1982). In this context, the definition of the electricity mix to reach a growing energy demand has to take into account the revenues from the resource exports, the power generation costs and the environmental policy.

Egyptian Ministry of Planning defined the energy strategy of the country by issuing its 6th Five Year Plan (2007-2012). The plan mostly included the investment plans for electric power, oil and natural gas industry. Energy efficiency improvements, security of supply and willingness to adopt nuclear technology were also considered as chief strategic targets. Oil and gas sector promotion consist mainly efforts targeting the expansion and intensification of the exploration activities and completion of the 20-year 10 billion dollar Petrochemicals Master Plan (lunched in 2002 for constructing 24 petrochemical units across the country by the end of 2022). And the strategy for the power sector aims to improve efficiency, promote renewable energies and security of supply for all sectors, encourage the development of grid in rural regions and facilitate more interconnection with neighbouring nations (Ministry of Planning 2007). This 5-year plan has been revised and discussed in 2011 again but no official strategy has been yet released. However, most probably increasing focus on export maximizing, upstream investment incentives and ensuring demand satisfaction will be the key components.

Egypt was first Arab nation signed the Kyoto protocol in 1999. From then Egypt seeking to diversify its current energy mix by increasing usage of renewable energy sources such as hydro, wind and solar. The Renewable Energy Expansion Plan, adopted in 2008, sets target for renewables sources to reach 20% of total domestic energy supply by the year 2020. 12% will be provided by wind and hydro (NREA 2011). However, at the moment there is no solid support scheme (stable feed-in tariffs for example) in place for the promotion of renewable sources. The total energy related CO_2 emissions of the country since 1990s is shown in figure 1.

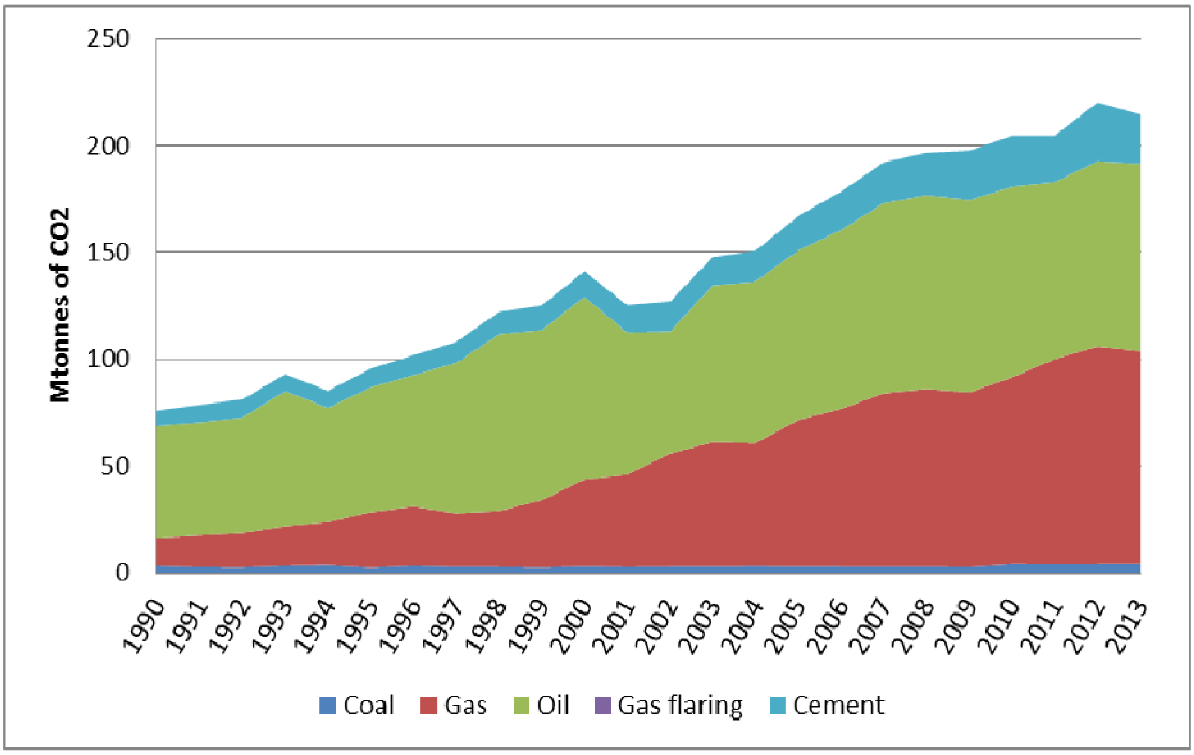


Figure 1: Energy related CO_2 emissions in Egypt from 1990 to 2013

(Source: Global Carbon Atlas 2014)

The Egyptian Environmental Affaires Agency defines the country's environmental policies. The entity established in 1982 and thereafter the Ministry of State for the Environmental Affaires was created. Environmental policy of the country (National Environmental Action Plan) addresses environmental issues and strategies for encouraging effective use of energy in different oil sector activities, expansion of gas network and use of natural gas.

Egyptian government provides subsidies for various types of fuel such as natural gas, kerosene, butane, diesel, gasoline and fuel oil. Gas prices heavily subsidized for industrial usage and power generation to bring more incentives to both sectors for switching from oil and oil products to gas and thereby letting more oil for export. Global fuel price rising in the international markets resulted in more restricted government budget. Moreover, cheap gas prices compare to global prices boosted domestic gas demand. Following the national demand increase and no reaction concerning these subsidies, Egypt became a net importer of oil in 2010 (BP, 2011). This trend will most probably continue given the intensive depletion observed in the Egyptian oil fields in addition to the national demand increase. Several announcements have been made by the government to decrease energy subsidies. For instance, in 2007, the Egyptian government announced its intention to phase out subsidies for natural gas for both energy intensive and non-intensive industries with different time horizons, respectively in 2009 and by the end of 2013. However, following economic crisis, the government fixed natural gas and electricity prices for all industries. Egypt spent around 20.3 billion dollars for energy subsidies in 2010, equivalent to almost 13% of the country's GDP (World Bank 2011). Nevertheless, subsidy reforms (particularly in residential and commercial sectors) seem to be very unlikely to be occurred, especially in power sector, under current peculiar socio-political situation of the country.

3. Power Sector Overview

3.1 Organisation, Market and Regulation

Egyptian power sector went through some restructuring and unbundling reforms in 2001. The existing vertically integrated monopolistic system was unbundled into six generation, one transmission and nine distribution companies. Under the supervision of the Ministry of Electricity & Energy, the Egyptian Electricity Holding Company still owns 90% of generation and distribution sectors and 100% of the transmission company. The Egyptian Electricity Holding Company (EEHC) is the only entity empowered to approve and construct any generation capacity or to buy power from international private developers of electricity. Even though the 2001 unbundling reforms aimed to eventually privatize the sector, but Electricity Holding Company remained 100% public and it is very unlikely to see any privatization process in the near future.

Egyptian Electricity Holding Company (EEHC) consists of totally sixteen electricity companies separated according to the region in which they operate and also the type fuel they use. Cairo, East Delta, Middle Delta, West Delta and Upper Egypt are the thermal power companies while Hydro Plans Company is in charge of all hydro generation across the country. Several privately own power units have also finance and built under BOOT (Build, Operate and Transfer) financing scheme put in place in late 2002 by the Egyptian government. Port Said East Power Company, the Sidi Krir Generation Company and the Suez Gulf Company are examples of these private operators. There are currently three International Private Producers operating in Egypt. The first international operator was US-based InterGen, a joint venture of Bechtel Enterprises and Shell Generating Limited, along with some local partners to operate Sidi Krir BOOT project.

At the moment power market in Egypt is organized in the "Single Buyer"[3] structure. Egyptian Electricity Transmission Corporation sells power from the generation entities (including private independents) to the 9 regional distribution companies. Approximately 10% of the Egypt's distribution grid is owned by 6 small private companies who manage the sale of mid and low voltage power to final consumers. These companies are as following: Global Energy Company, the Alexandria Carbon Black Company, the Om El Goreifat Company, the National Electricity Technology Company and finally the Mirage Company. For the purpose of controlling and regulating all the issues related to generation, transmission, distribution and consumption, the Egyptian Electric utility Organization & Consumer Protection agency was created in 1997 by the government. Many other specialized regulatory authorities have also been established to regulate the various areas of the power sector, such as Nuclear Power Plants Authority, New & Renewable Energy Authority, Hydro Power Projects Execution Authority and etc.

3.2 Electricity Supply and Power Plants

Egypt has increased its generation capacity from 15.5 GW in 2000 to almost 27 GW in 2010. Power output has also been doubled from 78.1 TWh in 2000 up to 148 TWh by 2010 (IEA 2012). EEHC had to deal with some outages in 2010 during peak hours because of the growing usage of air-conditioners during hot days. Egyptian government announced ambitious goals for increasing capacities to satisfy the growing domestic demand. EEHC is currently applying the 6th Five Year Plan targets capacity additions of 7 GW over the 2007-2012 periods (EEHC 2012). The plan includes 3 GW of Combined Cycle and 4 GW of Steam Turbine capacities. Recently, EEHC has also proposed the 7th Five Year Plan for 2012-2017 periods, including an additional 5.25 MW of Combined Cycle plus 7.15 MW of Steam Turbines (EEHC, 2012).

[3] For more information regarding this market model please refer to appendix A.

Concerning renewables, in 2007, the Renewable Energy Expansion Plan adopted for renewable penetration of 20% in to the network by 2020, where hydro power represents 5.8%, wind 12% and 2.2% from other renewable energy sources, especially solar (EEHC 2012).

Combined cycle and steam units (both using natural gas as fuel) accounted for 62% of the total capacity in 2010. These technologies have been considerably promoted by the Egyptian government since 2000 as gas production increased and subsidies over natural gas encouraged the investment in this technology. In 2011, Al Damietta and Al Shabab power plants with total capacity of 1.7 GW were added to the network.

Egypt started producing hydro power in 1960’s after the construction of the Aswan High Dam station. Since then, no new major project has been realized. In 2010, total capacity of hydro was 2.8 GW accounting for 9.5% of total generation (IEA 2012).

Oil-firing power plants account for 18% of power generation of the country it has not historically been encouraged by the government because of its expensive price leading to very high subsidies for the government. Oil has been mainly used in the peak summer months for meeting air-conditioning demand. Share of fossil fuels (oil and natural gas) in the total power generation of the country accounts for almost 90% of fuel types used for national electricity demand’s satisfaction (figure 2).

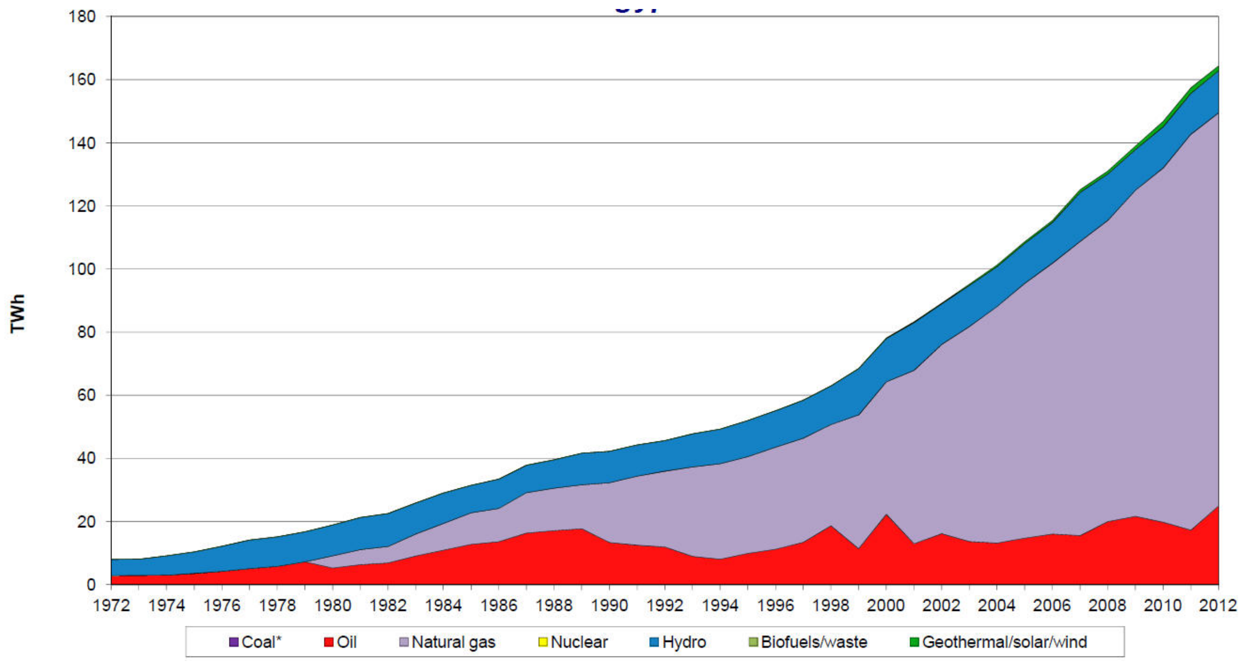


Figure 2: Electricity generation by source in Egypt in 2012 (Source: IEA 2014)

Nuclear power has also been proposed several times by the Egyptian government. Plan to develop this technology were put in place in the 1980's. 1000 MW nuclear capacity were proposed at El Dabaa on the Mediterranean coasts. Project was halted due to the huge costs and safety reasons following the Chernobyl accident. In 2006, following an increase in international oil and gas prices and rising domestic demand of power, the nuclear program revised by the government. Finally, in 2010 Egypt lunched a tender for 1.2 GW El Dabaa Plant with forecasted cost of 1.5 billion dollars and commissioning date of 2019 (Selim 2009). Figure 3 illustrates the entire electricity infrastructure and power plant stations of Egypt.

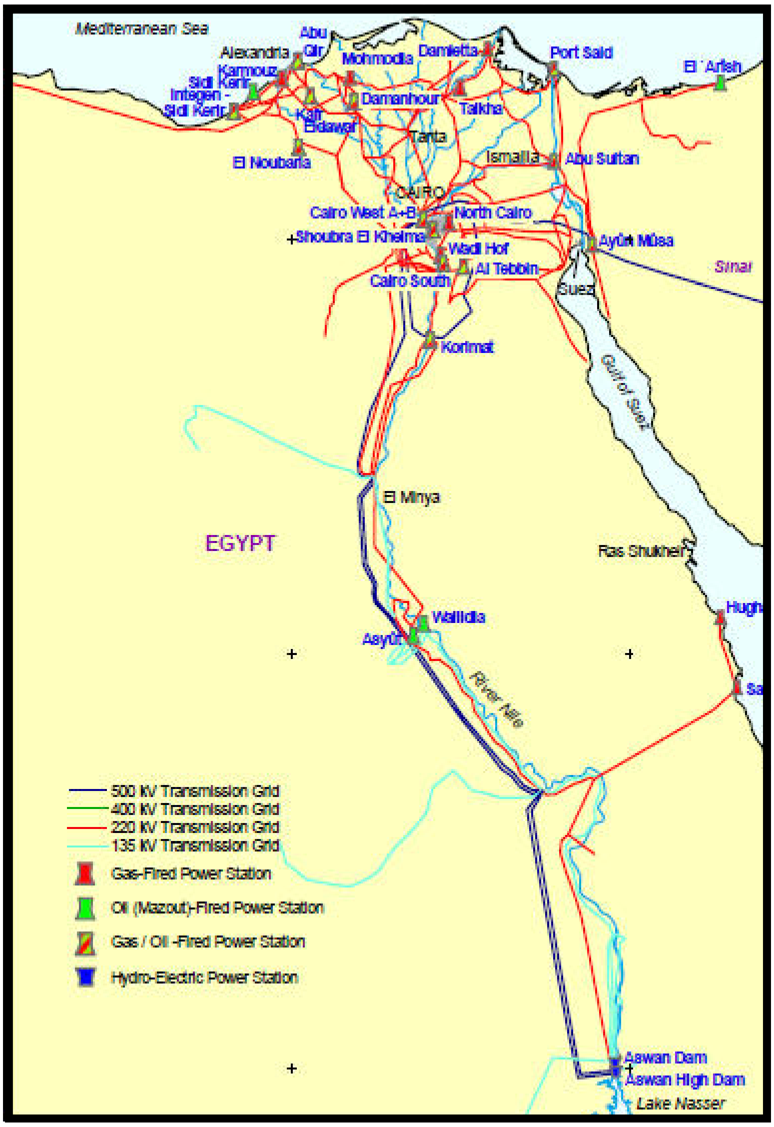


Figure 3: Electricity generation and transmission infrastructure in Egypt

(Source: WoodMackenzie & GENI 2012)

4. Methodology

A linear programming optimization framework was used to assess the costs and savings of expanding the role of non-fossil fuel based power sources in electricity supply. LP (linear program) cost minimizing is an approach that systematically evaluates potential power supply to satisfy the demand at the best societal cost. This method analyses what the incremental cost would be if each source of power generation were to integrate the electricity supply of the country. In pursuit of this objective, a review of relevant non-fossil and fossil based power unit choices on the basis of resource potential, cost and economic benefits is provided. Several choices of technologies that are or are expected to be technically and economically feasible over the next two decades have been identified and incorporated into the modelling effort.

Electricity generation should be provided by a large set of power plants which are characterized by different technologies associated to a very large spectrum of fixed and variable costs. Consequently, this leads to an optimal usage and investments so as to satisfy the current and future demand. Optimizing the overall electricity cost of production by the different types of plants enables us to rank various production means. Indeed, when electricity demand increases and the available power (in the lowest cost category of generation means) is not enough, the system must switch to the generation-mean whose cost category is just one step above the previous one. In other words, the utilisation of power plants are ranked according to their growing running cost (so-called "merit-order" process).

The main contribution of this study is to analyse the optimality of the Egyptian power generation mix via LP models (based on the above-mentioned structure) and to reveal the most optimal decisions for the next 20 years of the national electric system under different proposed investment scenarios through the dynamic model. Afterwards, the sensitivity analysis is realised to measure the competitiveness of non-fossil power sources with fuel-based ones under various discount rate and carbon price scenarios.

During the past decades, a huge body of literature related to the application of sophisticated energy optimization and simulation scenarios have been carried out for optimal planning of the future national energy systems (Abubakat et al. 2013, Haidar et al. 2011, Hainoun et al. 2010, Ostergaard 2009, Sorensen et al. 2008 and Nielsen et al. 2007). Grouping existing literature, there are several studies seem to be related to the optimization of the use of non-fossil sources and the assessment of existing tools and optimal penetration rates of these technologies in the power sytems (Kazagic et al. 2014, Segurado et al. 2011, Kaldellis et al. 2009, Lund et al. 2009 and Karlsson et al. 2008). A study for Algeria, Morocco and Tunisia has been done by Brand & Zingerle so as to analyse the impact of renewables and non-fossil technologies' integration into their electricity systems. For instance, Mazhari et al. used system dynamics and agent based modelling approach in order to find the most optimal and economical mixture of storage capacities and solar plants.

Various types of linear programming models have also been used for future optimal generation mix simulations. Xydis & Koroneos, stated the role of solid wastes in future energy systems, while Chang & Li, pointed out the role of all the renewable energies options for the future generation mix of ASEAN countries.

Although numerous studies have been conducted on the optimization and simulation of future energy systems with various rates of pure renewables penetration, limited papers have appeared on the optimization of power systems with both nuclear penetration and renewables imposition which is the main focus of this study.

Total electricity generation cost minimization, is one of the main modelling approaches in power generation modelling. Examples of such models include POLES[4] (Criqui 2001), MARKAL[5] and TIMES[6] (Loulou et al. 2004). Many other examples have also been developed by consultants and utilities themselves and are not therefore published. The basic idea of these models is to explain electricity prices from the marginal generation cost. In this case, assumption over the future electricity prices does not have to be made. Focusing on

[4] Prospective Outlook on Long term Energy Systems
[5] MARKet ALlocation
[6] The Integrated MARKAL-EFOM System

minimum generation cost implies minimizing the cost to be transferred to the final consumers, irrespective of the electricity price. The main advantage of this method is to analyse the producer behaviour facing with a mix of different types of constraints such as economic, technical and environmental ones. Our approach is similar, in the way that a linear dynamic model is developed where the total costs are to be minimized under certain constraints developed in the next section.

Optimizing the overall production cost of electricity via various types of power plants enables to "prioritize and rank" the different means of production. Indeed, when electricity demand increases and the power available in the category of lowest cost is not enough, then it should implement the generation mean whose cost category is immediately above. This leads to a prioritizing of different equipment based on their operating (variable) costs which allows defining a dispatching of different equipment on the annual load curve. Generation Mix management, made by the cost minimization objective corresponds to an economic optimum: at each time step, the marginal cost (the cost to satisfy a request for additional MWh) is equal to the operating cost of production with the marginal equipment. All equipment with lower production cost will be used and in theory, no more expensive equipment will operate.

In medium and long-term decision-making process, optimization techniques can become very helpful, particularly if we take into account the investment decisions and costs associated with each additional capacity. Model proposed in this study, is solved using dynamic linear programming so as to consider those investment trends to satisfy the growing electricity demand of the country.

Power generation mix structure of the country is modelled under GAMS 24.0.2 (General Algebraic Modelling System) software within CPLEX as a solver. This cost minimization model contains the objective cost function that must be minimized and the demand constrains that have to be satisfied. For the current power generation mix of Egypt (in our model, the year 2010) the production capacities must be respected and in the case of long-term optimization, investments are allowed.

The constraints of the model are the demand equations, the capacity constraints and the investment equations. In the demand equations for each season, the sum of the power generated by the power plants is greater than the demand. On the supply side, the power loaded from each unit is lower than the power capacities times the seasonal availability coefficients. Finally, the installed capacities are equal to the sum of the existing units and investments.

The model is developed based on a long time period. This period is split in several sub-periods associated to the time index t with n(t) years. In each sub-period, we consider a representative year denoted by a(t). Thus there are b(t) years before period t defined as follows:

$$b(t) = \sum_{k}^{t-1} n(k)$$

The model basic structure is as following:

$$\text{Min} \sum_{t} \left[\sum_{i}\sum_{s}\sum_{m} \left(\gamma_t \times E_{ia(t)} \times H_s \times R_m\right) P_{isma(t)} + \sum_{i} \left(\varphi_t \times I_{ia(t)}\right) C_{i(t)} \right]$$

With,

$P_{isma(t)}$: is the Power loaded (called) on the grid by each equipment of type *i*, for the season *s* in the representative year a(t) with demand randomness factor of m (MW)

H_S: Length of the season *s* (hours)

$E_{ia(t)}$: Variable cost of production of each equipment *i* at the representative year a(t) ($/MWh)

t : the time period (step)

a(t) : representative year of the period t

R_m : probability of having randomness factor of m

$I_{ia(t)}$: investment in the unit i at the representative year a(t) ($/kW)

$C_{i(t)}$: capacity to build for unit i at the period t (MW)

γ_t is the discount factor applied to the annual costs of each period. We assume that the costs are the same for all the year of a given planning period, thus it is defined as :

$$\gamma_t = \frac{1}{(1+r)^{b(t)}} \sum_{k=1}^{n(t)} \frac{1}{(1+r)^k}$$

And φ_t is the discount factor applied to investments :

$$\phi_t = \frac{1}{(1+r)^{b(t)}}$$

Where r is the discount rate.

Hence, the total discounted cost of different installed units is minimized according to the electricity demand and available capacity. Different discount factors were applied for the variable and investment costs. As a matter of fact, in this model the variable cost could be different in each year (according to the yearly utilization rate of each power plant) during the life-time of the power plant and the discounting operation has to be adapted accordingly. Instead, the discounting operation corresponding to future investments is less complex since, by convention, the investment occurs in year 0 (initial investment or the so-called "overnight cost") and it can be modeled as repayment of annuities (yearly fixed costs) throughout the life time of each power plant.

For each period, supply (capacity) and demand sides' constraints are as following:

Capacity constraint:

$$\frac{1}{\tau_{is}} P_{isma(t)} \leq \sum_{i} \alpha_{it} C_{ia(t)}$$

With,

α_{it}: availability coefficient of the capacity of equipment *i* activated in year t. It measures the capacity reductions that occur after the construction of a plant.

τ_{is}: coefficient of availability in each season for each equipment *i*

And the evolution of production capacity (new additional investment) during the modelled time horizon is satisfied by the following dynamic power-unit-fleet relation:

$$C_{i,t} = C_{i,t-1} + U_{i,t} \qquad \text{with } U_{i,t} \geq 0$$

In which, $C_{i,t}$ and $C_{i,t-1}$ represent the capacity of equipment i during two consecutive years, and $U_{i,t}$ is equal to the capacity evolution of unit i in year t.

Demand constraint:

All the equipment must provide the seasonal power required for the satisfaction of the consumers' demand and this must be done for each random event m.

$$\sum_{i} P_{isma(t)} \geq D_{sma(t)}$$

D_{st}:	loaded power on the grid for the season *s* (MW)

5. Empirical analysis

5.1 Parameters of the model

Hereby, the demand and costs structures is presented in addition to the techno-economic data used for each power unit in the optimization model. Figure 4 shows a typical daily electricity demand curve (load-curve) of Egypt.

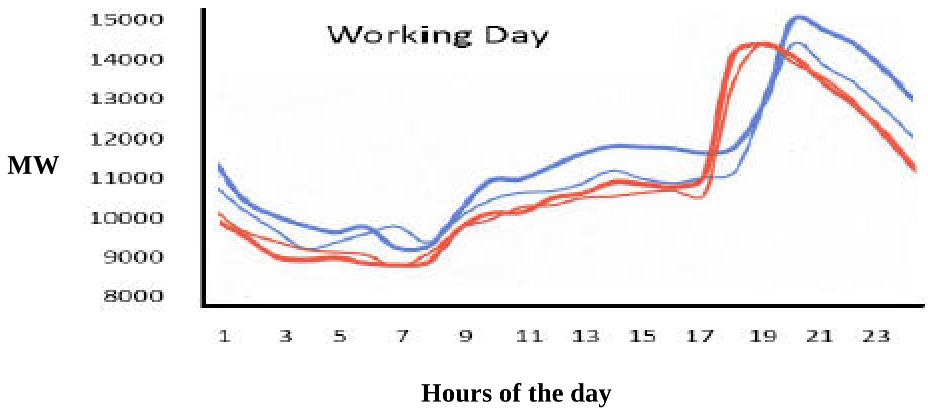


Figure 4: Typical daily load-curve (MW) in Egypt (red goes for winter and blue for summer)

(Source: Beshara 2008)

Therefore, three demand fractions are considered: H_1, H_2 and H_3. H_1 represents the base-load and H_2 and H_3 represent respectively the semi-base and peak daily demands. Thereafter, this 3-fractionned structure of the daily demand is spread to two different seasons: S_1 and S_2. S_1 represents summer season in which we generally observe the peak demand periods (caused by the air-conditioning effect) and S_2 goes for winter season. These demand-compositions for the fractioning hours and seasons hypothesis, are shown In figure 5.

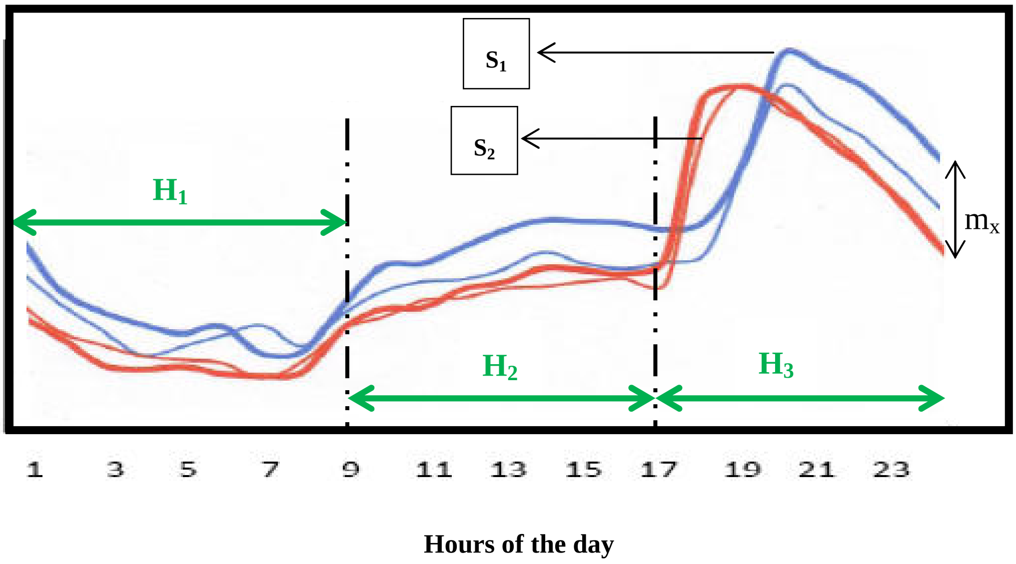


Figure 5: Demand structure in the model

Demand randomness factors (m_x) and their associated probabilities (R_m) introduced in the model assume 10% variability of the registered demand in both negative and positive directions.

Demand increase forecasts for 2020 and 2030 are expected to be respectively equal to 35 and 17 per cents (WoodMackenzie, 2012). The forecasted electricity demand used in this model is summarized in Table 1.

Total electricity demand in Egypt (TWh/y)				
2000	*2005*	*2010*	*2020*	*2030*
78	109	**148**	**200**	**236**

Table 1: Egyptian power demand

(Source: WoodMackenzie 2012 & EEHC 2012)

As the amount of hydroelectricity remains constant, identical to that of 2010 which is equal to 14 TWh (IEA 2012), during modelled time horizon (owing to the already saturated potential of hydroelectricity in Egypt), we subtracted the hydro share directly from the demanded electricity. This process has been also applied for the case of other renewable resources, solar and wind. In other words, the amount of renewable production (based on the Egyptian government target for 20% of renewable share as described in section 2) has been imposed on the loaded power as must-run production units, of course in consistent with their associated availability factors. Hence, whatever the cost of production, these renewables would be always placed at the top of the merit order (generation mix ranking curve) in the model. That's why the generation costs of these units do not impact the decision making process of the model and the competition (in terms of generation cost) would be between nuclear, gas and fuel power plants.

So as to cover the risk related to the intermittent production of solar and wind power plants, we have introduced in the model a necessary investment in the fossil-fuel power plants that play the back-up role in case of insufficient load factor which generally happens during peak consumption, especially in summer. In most of the regions around the world, lowest values of capacity factor for the intermittent technologies are observed during peak demand periods. This is also the case of Egypt with hot and not necessarily very windy summers.

In this model the absence of production from intermittent means is compensated by the least expensive (in terms of total cost) thermal power units which have around 100% of availability (load factor equals to 1) except for the ex-ante planned maintenance.

Wind speed can widely fluctuate in a rather short-time period. These fluctuations cause the need to rapidly compensate for large amounts of increased or decreased production with other power plants in the system. The most reliable way to answer these variations is to use pumped storage and hydro storage facilities which have very quick ramp (start-up) possibilities with relatively large power volume capacities. Unfortunately there is not enough potential for these technologies in Egypt due to its climatic situation. However, gas and fuel power plants can also quickly start and make up for the losses in production. Even though the existing and already operational flexible power plants could be used to provide the needed flexible back up for renewables, but this works only in very short-term. In longer-terms, with the aging of existing power plants and integration of more renewables in the system (up to 20%), construction of conventional back-up power plants would be vital for the stability of the Egyptian power system.

It is also worth to mention that nuclear power can also play a flexible back-up role in power systems. Contrary to what is commonly believed, nuclear power plants have (on average) very responsive load gradients (about 5% of load per minute) even though their start-up time is very long from both warm and cold conditions. For the time being this flexibility potential exist only in very experienced countries in realm of nuclear industry such as France and Germany for example. Therefore, flexibility analysis of nuclear plants is out of the scope of this study due to the fact that Egypt will be a newcomer in the nuclear sector (if the country adopt for the installation of before-mentioned power plants in the time horizon of this study). Under the assumption of 20% renewable integration (for both years 2020 and 2030), at least 4GW and 6GW of flexible back-up facilities would be needed respectively for the years 2020 and 2030. These added capacities do not include the replacement of retired old-age existing power units during the studied period. The necessary replacement capacity is calculated by the model without any flexibility concern for the future power plants. Therefore less flexible plants (such as nuclear in our case) have also been considered. This is not the case of our additional cost calculation for back-up units in the model.

Fuel costs are calculated per MWh on the basis of price information available for gas, oil and uranium (IEA 2012 and World Bank 2012). In the case of gas price, the minimum average price of large gas producing countries like Canada, US, Australia and Russia (6 $/MMBtu) is considered, where domestic prices of natural gas can decouple from international market prices. This averaged price could be a good representative of international gas price for Egyptian power sector, although the real (strongly subsidized) domestic gas price is much lower for the Egyptian power producers. And for oil, Dubai dated average price over the last 4 years has been considered (80 $/bbl), even if sometimes oil products are used in power generation which are more or less expensive than the crude itself. Despite the fact that this study is done under the assumption of stable fuel prices for the matter of simplicity; this should not be considered or interpreted as any sort of prediction of stable energy markets.

In the case of uranium the task is entirely different because the price of U_3O_8 (so-called “yellow cake”) only counts for about 5% of the total cost of power production and therefore any volatility in the price has very small impact on the total cost of electricity generation. Spot-market plays a very limited role for the nuclear fuel (at different stages) and most of the activities are carried out under long term contracts. In the model it is assumed that the nuclear fuel price is equal to 7 $/MWh until fuel fabrication process, plus 2.5 $/MWh more for transport, storage and eventually reprocessing and final disposal (IEA & NEA, 2010).

Apart from fuel costs, which have already been described, the other variable and fixed costs of each type of power plant are also essential for the decision making process of the model. Plants’ life-time and efficiency should also be incorporated in the model so as to be able to evaluate the potential amount of electricity (from technical point of view) that each power plant could produce. Table 2 provides the techno-economic properties of various thermal power plants used in the model. As a matter of fact, year 2010 has been used as the base case for our modeling purpose due the accurate access to complete and detailed techno-economic data (load-duration, costs, efficiencies and…) for that year and moreover as a result of the political issues that happened recently in the country, not many changes have been taken place in terms of investment and costs in renewable energy sources. The almost constant trend of investments in Renewables installed capacities in Egypt between 2010 and 2013 is shown in figure 6.

Techno-economic data for each type of power plant			
Plant type	*Nuclear Plant*	*CCGT Plant*	*Fuel Plant*
Efficiency (%)	33	57	38
Investment cost ($/Kwe)	2050	534	364
Life cycle (years)	60	30	30
Fix O&M cost ($/Kwe)	46	8	8
Variable O&M cost ($/MWh)	0.8	1	0.3

Table 2

(Source: IEA 2010 Median Case)

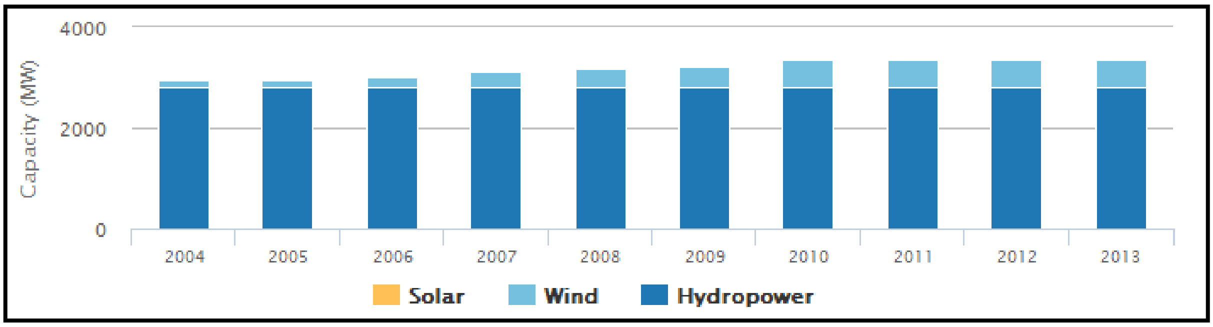


Figure 6:Installed renewable energy capacity in Egypt

(Source: International Renewable Energy Agency 2014)

5.2 Simulation Results and Economic Analysis

Model has been run for over the period 2010-2040. Investments are allowed in the model during all of the periods and time steps so as to reach the final electricity demand increase. Seasonal and daily demands have been coupled with the randomness factors already described in the modelling frame-work section of this paper. However, sensitivity analyses on the model's parameters (electricity demand, power generation cost) point out that both primal and dual results have significant changes when the parameters are modified. Thus, it is decided to take into account the uncertainties on the model's parameters through various discount factor assumptions are run sensitivity analyses on the discount rate.

The major impact of discount rates is on the value of total cost generation cost per MWh which itself includes investment, O&M and fuel costs. In this scenario carbon cost is equal to zero and therefore direct emissions resulting from fossil fuel power plants usage have been neglected.

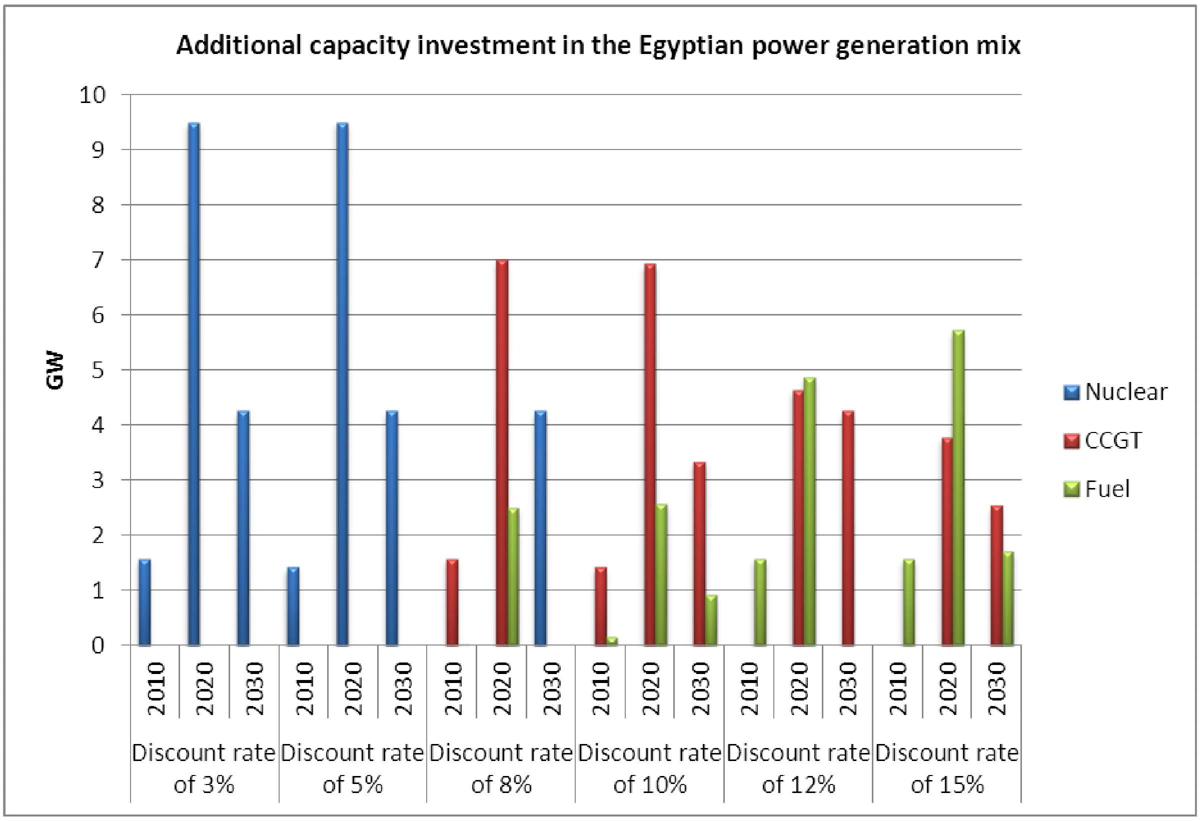


Figure 7

For discount rates below 5%, total demand increase is satisfied with nuclear energy which is considered as the most viable and economic way of generating electricity. Almost 10% of the total investment takes place in the base year 2010. This is almost tripled in the final year

2030. Nonetheless most of the investment occurs in the middle periods between 2010 and 2030. For example in 2020 around 60% of the total investment decision has been realized and the model recommends 9.5 GW of investment in total installed capacity of the country.

For discount rates above 5% other fossil resources, particularly CCGT (combined cycle gas turbines) power plants, become more economic. For instance at 8% discount rate, the model suggests about 1.8 GW of investment in total capacity with CCGT power plants (consuming only natural gas as a fuel) from the beginning of our base (reference) year of 2010. In 2020 (middle period) model suggests not only CCGT technologies but also fuel power plants. Total amount of suggested investment in fuel power plants reaches almost 35% of total additional capacity in 2020. The remaining capacity investment is still in CCGT technologies. The model considered 100% fossil-based generation mix (as the most optimal one) up to at least 2025. From then on, nuclear technology becomes again the most optimal solution to answer the further increase of electricity demand. The fact that technologies within huge initial investment costs (so-called overnight costs) and long construction times become more economic only at the end of the period, could be explained by their notable sensitivity to large discount rates. Moreover, as we have assumed in our model that the last periods' demand will remain constant for a very long period of time (an assumption used for increasing the reliability, stationary and rationality of the dynamic model for investment decision making), nuclear power becomes less risky and optimal solution for long-term demand satisfaction. Economic viability of this long-term decision-making strategy turns out to be less rational for discount factors higher than 8% and even fully disappears for discount factors rates above 10%.

By looking at the results in figure 7 it is also noticeable that for the discount rate values above 10%, investments in fuel power plants turns out to be optimal from the beginning and becomes even the only optimal choice after 12%. Short construction time (compare to the other technologies) and rapid return on investment are the main reasons behind this expensive 100% fuel-based plants investment. Prompt satisfaction of accelerating electricity demand with least costs, is also another reason. However, by moving further in time and giving more time to the investor(s), more capital intensive technologies such as CCGT come into action once more.

It should not be forgotten that the above conclusions obtained under the zero carbon emission price assumption and they can be totally altered by setting a certain amount of CO_2 price in the model. Henceforth, CO_2 costs are introduced in the model. Carbon emissions' amounts were integrated as physical property of each fossil fuel type by taking into account the thermal efficiency of each fossil power plant. Initially, the CO_2 price of 10€ per tonne was designated and then the model was run again. Investment results under this assumption for the same discount rate intervals are shown in figure 8.

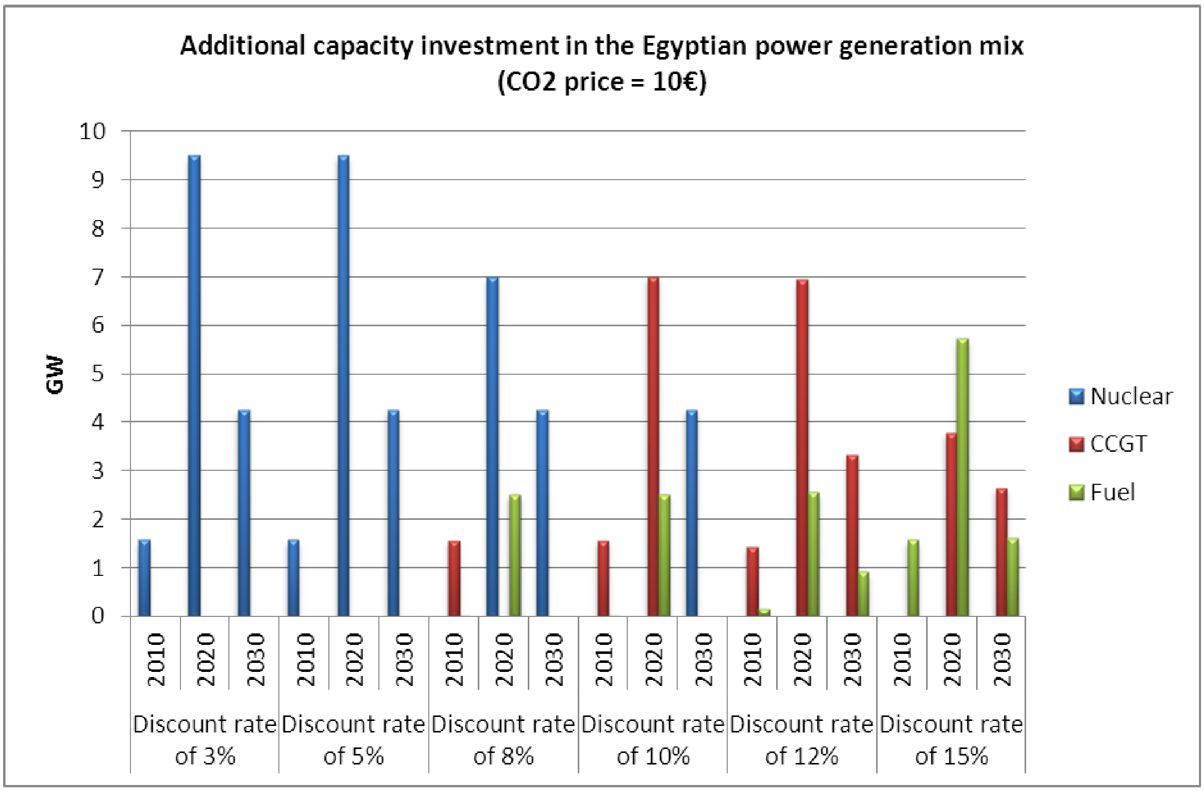
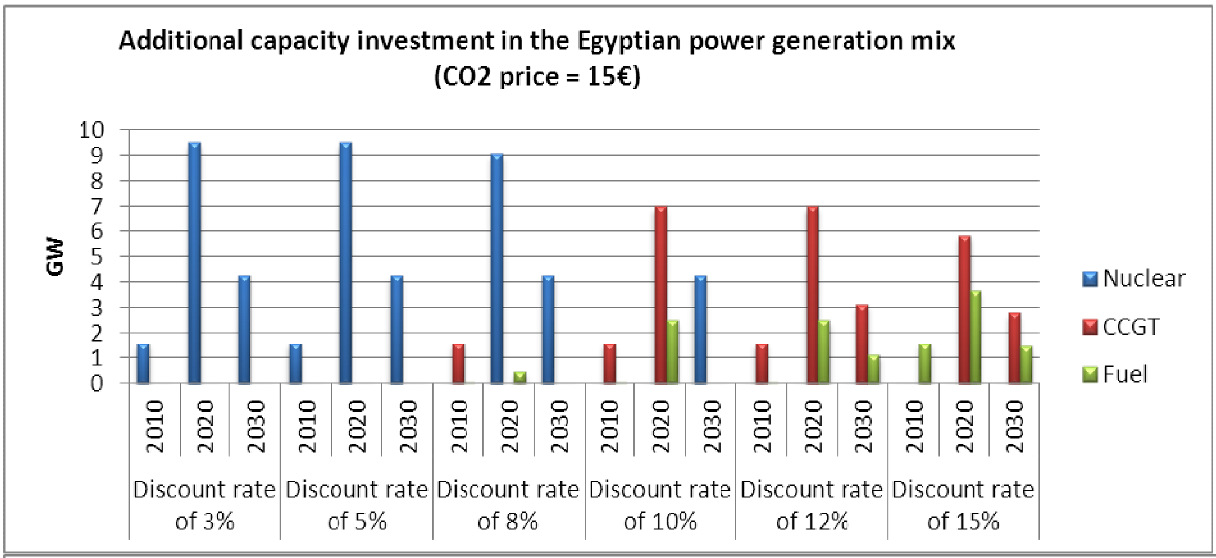


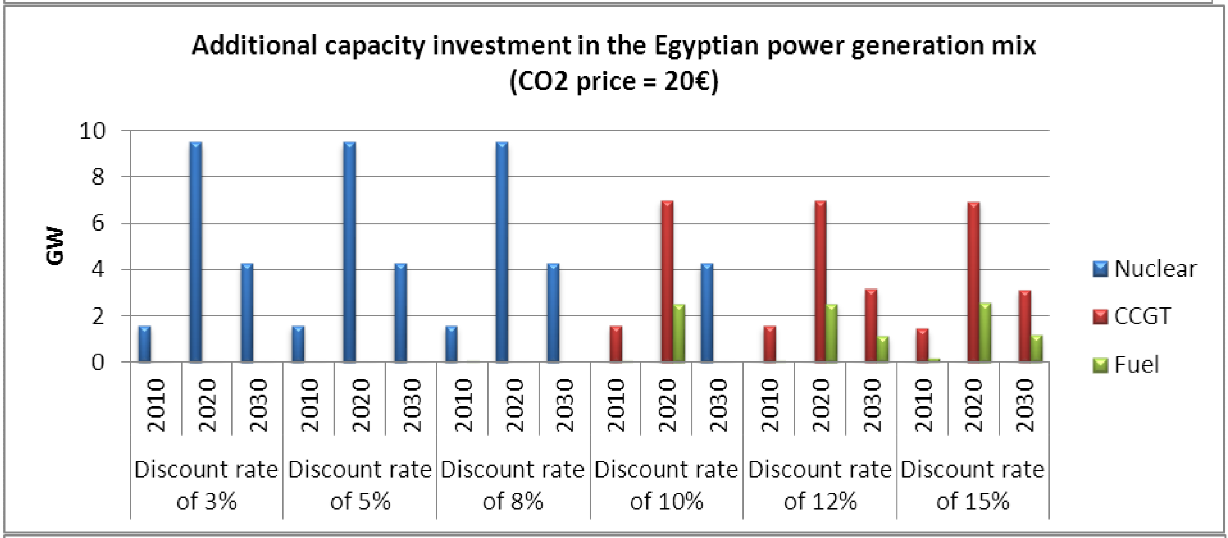
Figure 8

For the discount rates up to 5%, nuclear power remains again the most optimal choice and other technologies are not competitive at all (except as a back-up plant to compensate renewable intermittencies). Significant modification compare to the pervious case (without emissions) can be noted in the discount range of 8% to 10%. In this range, nuclear energy is still present as an economical source of power; for instance around 8% of discount rate, nuclear energy could provide up to 70% of total electricity sector investment of Egypt as a most optimal power unit. However fossil plants start to occupy a bigger share in the power generation mix of the country in 10% discount rate case.

Uncertainty about climate policy is one of the greatest risk factors that investors in power sectors are dealt with at the moment. Climate policy may have a weighty impact on power generation costs with different options. If ambitious carbon reductions are to be achieved globally, the power sector may need to be rapidly decarbonized in many regions. However, the decarbonisation trend observed in non-OECDs in much slower than that of OECDs. Uncertainty about future climate policy (hereby integrated via various CO_2 prices) thereby creates significant insecurity about generation costs of different technologies.

Hence, a sensitivity analysis designed for different CO_2 prices so as to better demonstrate the impact of carbon price increase on the power generation structure of Egypt and obviously the promotion of non and less CO_2-emitting technologies, respectively nuclear and CCGT, compare to fossil fuel based ones. Egyptian optimal generation capacity additions proposed by the model under different CO_2 price scenarios are shown in figure 9.


Additional capacity investment in the Egyptian power generation mix
(CO2 price = 15€)
GW
Nuclear
CCGT
Fuel
Discount rate of 3%
Discount rate of 5%
Discount rate of 8%
Discount rate of 10%
Discount rate of 12%
Discount rate of 15%


Additional capacity investment in the Egyptian power generation mix
(CO2 price = 20€)
GW
Nuclear
CCGT
Fuel
Discount rate of 3%
Discount rate of 5%
Discount rate of 8%
Discount rate of 10%
Discount rate of 12%
Discount rate of 15%

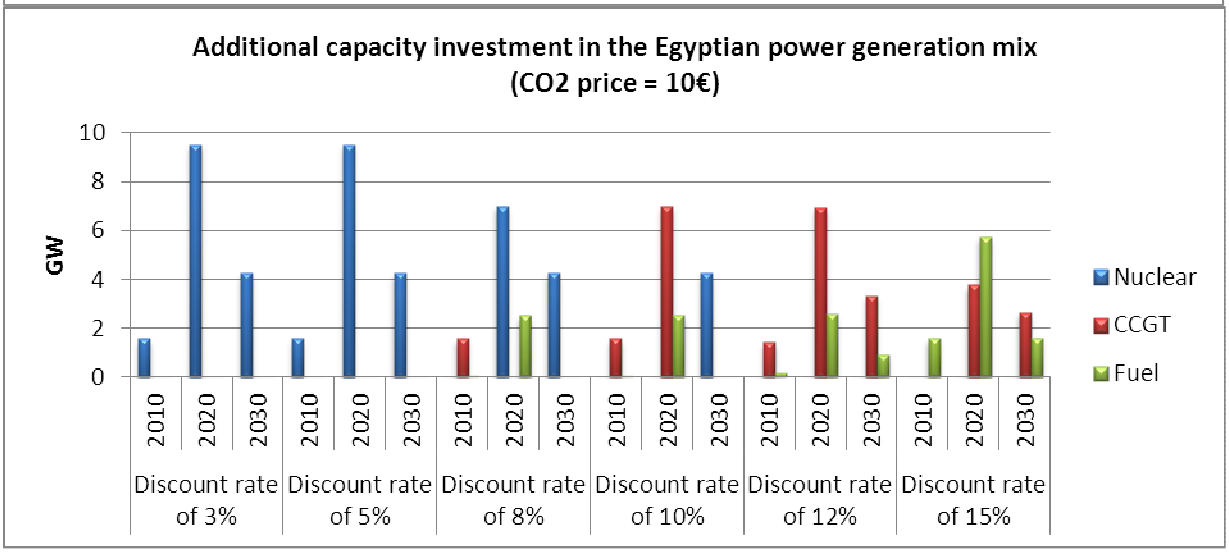

Additional capacity investment in the Egyptian power generation mix
(CO2 price = 10€)
GW
Nuclear
CCGT
Fuel
Discount rate of 3%
Discount rate of 5%
Discount rate of 8%
Discount rate of 10%
Discount rate of 12%
Discount rate of 15%

Figure 9

Finally, it is important to mention that Egypt became a net importer of oil in 2010 (our reference year). In our model we assume that fossil fuel prices (oil and gas) are equal to that of international markets. Hence, if Egypt continues to provide natural gas to power producers under subsidies (with final price lower than that of international markets), all the suggested investments in fuel power plants should be replaced by gas units. This could become also applicable for nuclear units after certain level of subsidies. And on the contrary, under total subsidy-suppression scenario in addition to less uncertain investment and political environment (leading to smaller discount rates) nuclear power choice could be the most economic and optimal solution. Not only it will provide cheaper power but also help to free certain share of domestic gas production for export into international markets. Nevertheless, we should not forget that certain amount of power (almost 20% according to our model) must be still afforded by fossil fuel plants, with rapid start-up time, to assure the back-up role for the 20% integration of intermittent renewables in the Egyptian electricity mix. Finally, an attempt to analyse the pass through effect of intensive subsidies in the wholesale and retail power tariffs of Egypt was performed. For this purpose, a static cost-minimization model (without investment) of Egyptian power supply has been constructed for the reference year 2010. In this model demand's variation is based only on the peak/base periods and seasons. Hence neither medium nor long term demand increase scenarios were applied. The shadow values (marginal values) associated with the loaded power (model's output) for each season and each hour corresponds to the marginal values produced by the last power unit (MWh). Observation of those values for our static model (in reference year 2010) indicates that the long-term marginal cost of electricity production is around 72$ per MWh. Actually this value is the average of all the marginal values generated by the model for each season and hour of the day. Due to the fact that the technology does not change during peak hours, it can be used as a proper indicator of total marginal cost.

The weighted average of Egyptian electricity tariffs (multiplying the share of each consumer by its related tariffs) is equal to approximately 45$ per MWh. Table 3 shows the Egyptian electricity tariffs for each category of demand and consumption. This value is less than 60% of the marginal value given by the model. Hence, if for example the marginal pricing criteria as an optimal way of electricity pricing is considered (in which short-run and long-run marginal costs are equal and future investments are guaranteed), the existing tariffs are far below the optimal level (Boiteux 1949). In other words, the allocated utility of fossil fuels (including subsidies) associated to the power generation is higher than the potential value of these fuels (oil and gas) for a probable export or unsubsidized usages in the power and other energy intensive sectors. This observation confirms the distorted optimality of the current heavily-subsidized power sector of Egypt, in terms of both fuel prices and final tariffs.

Current Electricity Tariff Structure (1 Pt ≈ 0,14 $)	
Sector	*Average Price (Pt/KWh)*
Residential	30
Commercial	40
Agriculture	11
Industry	20

Table 3: Egyptian Electricity Tariffs (Source: EEHC 2012)

6. Conclusion

The economic analysis of the power generation mix with an optimization model point out that, according to resource availability and the future expected electricity needs, being mainly dependent on national fossil fuel reserves for power generation is not an economic optimum. The gas resources could be exported and more power units could be based on renewable resources or nuclear power plants. Moreover, investment in nuclear power units for the demand satisfaction of the next 20 years (between 2020 and 2030) in addition to 20% integration of renewables in the generation mix, can reduce the CO_2 emission of the Egyptian power sector by almost 25 million tonnes per year.

However, these choices are affected by the evolution of costs and demand over twenty years period. Thus, the choice of a low or a high discount rate strongly impact the power generation mix and consequently the CO_2 emission rates.

Efficient utilization of the energy resources concerning the electricity sector requires a considerable promotion of the alternative non-fossil techniques. Even though the renewable sources of power generation can be used efficiently at very decentralized and local scales, yet intermittent nature of these technologies does not permit to provide a large scale continues base-load power. Besides, the need for more fossil-fuel-based back-up power plants would become inevitable to guarantee the national power system equilibrium.

Therefore, a power generation strategy based on a gradual integration of nuclear and renewable is suggested. A power generation mix, based on an optimal choice of fossil, nuclear, hydraulic and other renewables, is considered to be the most appropriate way of electricity production in Egypt.

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Appendix A: Single Buyer Model

In this restructured electricity market, networks (whether transmission or distribution) remain regulated while generation is exposed to competition. For the networks the incentives for capital investments are function of the regulation imposed by the regulatory authorities. Contrarily in the case of generation no explicit price control applies, nevertheless the regulators may monitor generation adequacy and establish additional market and tariff-based incentives to encourage new investments in the sector.

Under a single buyer model only new capacity development is exposed to competition, while the continued operation of plants with respect to output would be exempt from competition and would rather run under (usually long-term) power purchase agreements. The single buyer is responsible to determine capacity requirements and could also direct the technology decision through suitable conditions included in the call for tender for new capacity.

In this model the revenue that a generator is allowed to receive under its contract with the single buyer is normally contains two main components, availability payments and energy payments. The energy payments are intended, among other things, to recompense the generator for the costs associated with operating the plant, that is fuel and variable O&M costs. The availability payments are anticipated to provide the generator with revenue to cover the cost of capital, including a normal rate of return, and the fixed O&M costs.

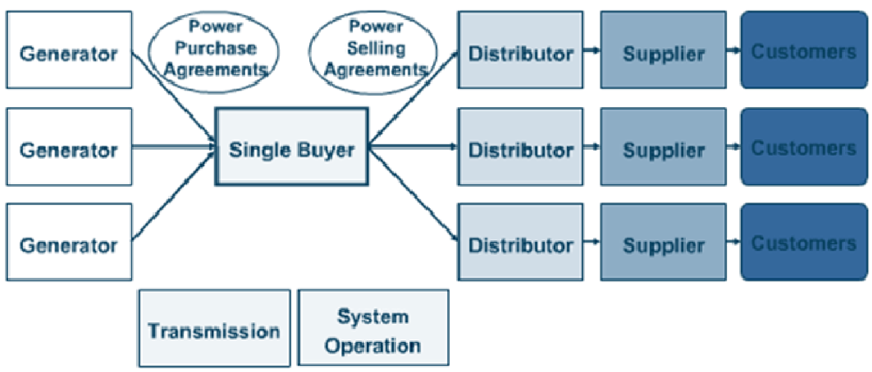

Figure 1-A: Single Buyer Electricity Market (Source: KEMA 2010)

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