Modeling for Power Generation Sector in Developing Countries: Case of Egypt

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Abstract

In this article, the economic and environmental implications due to the projected evolution of the power sector in Egypt until 2040 are assessed and discussed. The Reference Energy System (RES) of the Egyptian power sector has been defined and implemented in the Open Source Energy Modelling System (OSeMOSYS), based on two different energy scenarios. To increase the accuracy of the analysis, the discount rate on capital investments for the energy technologies has been imposed as a time dependent exogenous variable. Moreover, the robustness of the obtained results has been tested through a sensitivity analysis on the main exogenous parameters.

It is found that Combined Cycles, Wind, and Photovoltaic rooftop systems are compatible technologies to be included in the future Egypt's power generation mix. In particular, based on the abundant Egypt's renewables resources endowments, wind power technology comes first in achieving the proposed target on renewables penetration in the country's generation mix, and it might be a feasible alternative to replace a part of the natural gas share. Moreover, the significant impact of discount rate on capitals on the final results is highlighted: low values of discount rate would skew generation mix to include higher investment cost technologies and vice versa.

Keywords: Energy Modelling; Developing Counties; Egypt; OSeMOSYS, Energy Scenarios.

Highlights

- Implications of future energy scenarios in Egypt have analyzed based on OSeMOSYS.
- Sensitivity analysis has performed on relevant techno-economic scenario parameters.
- Combined cycles, wind and PV are key technologies in future Egypt’s power mix.
- Efficiency of combined cycles is relevant in reducing power cost and emissions.
- Wind technology may replace a part of natural gas share in the electricity mix.

1. Introduction

Security and affordability of energy supplies are aspects of paramount relevance in shaping future energy policies and countries’ energy power mixes. These aspects will become increasingly important in the future, since according to IEA the global demand for electricity is expected to increase with respect to the current consumption levels between

50% (Sustainable Development scenario) and 70% (Current Policies scenario) by 2040 [1]. Energy modelling frameworks are widely recognized as useful approaches for planning future investments towards a viable and sustainable national power sector, identifying the future energy power mix that enables to fulfill the demand of electricity at lowest cost, in compliance with technical, environmental and political constraints. Moreover, energy modelling frameworks enable to assess the effects of various uncertainty sources that might arise at both local and global levels, such as fossil fuels prices increase due to political instabilities in some regions [2].

A proper use of energy models may support the sustainable economic growth of national economies: while contributing in facing the current environmental challenges, an efficient power mix enables to reduce the cost of electricity, encouraging foreign investments in sectors different than the energy one, hence resulting in positive spillover effects. The use of energy models to support policy making and energy planning activities in developed countries is a well-established practice: the European Commission has financially supported several research projects to model sustainable scenarios related to the evolution of European energy sector. As an example, the PRIMES model allows analysis of national energy sectors to forecast their future energy demand, prices, and supply, while considering the development of their related technologies [3]. For similar purposes, the DICE [4] and MERGE [5] modelling frameworks have been proposed. While developed economies make extensive use of energy models calibrated with high quality data, the same cannot be always said for Developing Countries (DCs), where the financial availability and the access to high-quality data are two major challenges. Despite this, the number of energy models applications in DCs are increasing: among other modelling frameworks, Howells et al. have developed the Open Source Energy Modelling System (OSeMOSYS), defined as a partial equilibrium long-term energy planning supportive tool with a bottom-up representation of energy conversion technologies [6]. Several recent application of OSeMOSYS can be found in literature: as an example, the assessment of the evolution of Tunisian and Sub-Saharan power sectors has been recently performed based on an open-source energy optimization framework, which emerged in recent years to overcome the aforementioned limitations [7,8]. Due to its open-source nature, which ensures data transparency and results reproducibility, OSeMOSYS is defined as particularly suited to be applied to shape country's energy mix in future energy scenarios [9].

1.1. Egypt's power sector

Among other DCs, the economy of Egypt is expected to grow rapidly in the next decades [10]: between 2014 and 2015, its average population and GDP growth rates were respectively about 2.1% and 4.4%, resulting in an increase in the electricity peak load by 7.2% (28 GW), with a forecasted value of 85 GW in 2035 [11,12]. This strong dependence on fossil energy supplies is mainly due to the strong subsidies on fossil energy utilities imposed so far, and it makes Egypt fragile and vulnerable to socio-economic events (like the 2011 turmoil [13]), resulting in low levels of reliability and security of supply [12]. Egypt is characterized by a regulated energy market, of which the electricity sector is managed by the state-owned Egyptian Electricity Holding Company (EEHC), which manages electricity production, transmission, and distribution sectors. In order to meet the annual increase in electricity demand between 2011 and 2015, the installed capacities have increased approximately by 30%, from 27 up to 35 GW. In 2015, the installed capacity generated 174 TWh as gross energy. The average annual increases of installed capacity and gross energy generation from 2011 to 2015 are 6.8% and 4.5% respectively. According to 2015 statistics provided by EEHC, the natural Gas (NG) fueled thermal power plant is the dominant technology in Egypt's electricity generation mix with 90% share of the total installed capacity. As a result, the natural gas consumption by power plants has increased by approximately 10% from 2014 to 2015 to satisfy the production needs of the new additional capacities [12]. Hydropower (7%) is the second major resource used in electricity generation; however, its utilization is driven by the irrigation and residential demands. Finally, power generated from the other renewable sources is 2%. The electricity produced by the power generators is fed into the country's national transmission grid and delivered to meet various sector demands through distribution networks that cover the majority of the territory [12]. Various alternatives are considered to meet the forecasted demand increase. In particular, additional 15 GW capacity of natural gas combined cycle technology is planned to be in service by 2018. Moreover, to promote the diversification of the power generation mix, Egypt govern considers adding 7.1 GW coal-fired capacity by 2022: however, this alternative is debatable, as Egypt does not have coal reserves. For such reason, the operating cost of such plants might be escalated due to the incurred coal transportation costs. Considering the increase in the share of the renewable technologies in the production mix, the target share of renewables is set to be 22% by 2022, according to Egypt's Intended Nationally Determined Contributions (INDCs) in 2015 United Nations conference on climate in Paris [12,14]. In addition, the penetration Furthermore, investments are planned in the electricity trade infrastructure with neighbor countries. Egypt's transmission grid is connected to Libya, Sudan, Jordan, and Lebanon. A 3 GW trade connection is planned to link Egypt with Saudi Arabia, which has a different peak load demand profile [12].

For such reasons, the development of Egypt's power sector will be a challenging task, and energy modelling could play a key role in assessing optimal future scenarios, hence providing crucial information to policymakers. In this regard, the Egyptian government has already started to consider the use of energy models to plan for a more reliable electric supply [15]. Unfortunately, technical and economic data required to setup energy models can be hardly recovered, with particular references to costs of energy technologies, average efficiencies and availabilities.

1.2. Objectives of the paper

The overall objective of this research is to provide a quantitative assessment of future development scenarios for the power generation sector in Egypt. The evolution of Egyptian power generation sector is here assessed within a time period between 2018 and 2040 based on the OSeMOSYS energy modelling framework, hence developing the *OSeMOSYS-Egypt model*. The least cost power generation mix will be identified according to two different electricity demand scenarios, and compared with the energy plans announced by the Egyptian government [15]. Moreover, the robustness of the obtained results is tested through a sensitivity analysis on the main exogenous parameters, including costs, efficiency and production targets of energy technologies, capital discount rate, water and natural gas resources availability. The novelties introduced by this study are:

- To enrich the current literature with a detailed analysis about Egypt's power generation sector. This analysis has led to a detailed representation of the Egypt's *Reference Energy System* (RES), considering the specific characteristics of the energy demand of disaggregated sectors, technologies, and transmission and distribution infrastructures [6,16].
- To implement the developed RES in the OSeMOSYS-Egypt model, validating its analysis capabilities by considering various scenarios of electricity demand growth until 2040, by performing an in-depth sensitivity analysis, and by providing policymakers with a comprehensive representation of the achieved results.

The rest of the paper is organized as follows: section 2 provides a general literature overview related to the topic of energy modeling; section 3 provides the definition of the Reference Energy System (RES) for Egypt, a description about the energy model adopted for the analysis, including the setup of its main parameters, decision variables, objective function, and constraints. In the same section, the adopted future scenarios are introduced and described. Sections 4 and 5 respectively report and discuss the obtained results and the sensitivity of the model on the most relevant exogenous parameters. Concluding remarks, recommendations, and future research interests are provided in section 6.

2. Literature review

The relevance of energy modelling frameworks in interpreting emerging and future needs of the energy sectors in DCs, and in shaping their future optimal expansion capacities has been addressed by several studies. Pandey et al. have highlighted the relevance of having efficient energy policies to avoid the socio-economic problems caused by shortage of energy supplies to the production sectors [17]. Bazmi et al. described the complexity of developing a valid energy policy, which has to consider various technical features related to power generation technologies and other economic factors. Recently, the use of *Energy Planning Mathematical Optimization Models* (EPMOMs) to shape energy sector policies has emerged as a robust and systematic approach to investigate the future changes in national energy sectors [18]. Urban et al. identified some of the limitations that might hinder applying EPOMs in Developing Countries, highlighting the major factors that should be considered for successful application: for instance, consideration of unofficial economy, poor performance of electricity generation sector, and accurate representations of energy demand by other sectors of the economy [19].

Several research efforts were deployed to match the available EPMOMs to DCs energy sectors by considering the formerly stated aspects. For instance, building on the available open sources data and geographical information systems, the least cost electrification strategy has been defined for Sub-Sahran African countries [7]. TIMES modelling tool was applied to define the optimal energy generation capacity expansions in South Africa up to 2050 by considering five different demand sectors, with the aim of calculating the overall primary fossil fuels requirements and their related environmental impact. In the Asia-Pacific Economic Region, Malaysia and other 15 countries set up various MARKAL models that consider the specific features of their energy sectors [20]. Eshraghi and Ahadi developed a MILP model to define the optimal choices for the energy sector in Iran, comparing the obtained results with the ones obtained by an OSeMOSYS modelling framework: both the models suggested to increase the investments in similar technologies [21]. The OSeMOSYS modelling framework was similarly applied to shape future energy sectors in different regions, briefly described in the following. Considering South America's available primary resources, Moura et al. concluded that installing mega hydropower capacities and connecting the continent's transmission grids would reduce power generation costs and pollutants emissions [22]. Awopone and Zobaa applied the OSeMOSYS modlling tool to define the Ghana's optimum power generation mix from 2010 up to 2040, concluding that implementing pollutant emissions constraints would result in a more diversified electricity generation mix [23]. Groissböck and Pickl applied an OSeMOSYS model generator to address the evolution of Saudi Arabia's power sector assuming various scenarios for fuel prices, concluding that there is an indirect relationship between the fossil fuel prices and the amount of emissions produced [24]. Taliotis et al. support the significance of deploying energy models in countries where shifts in energy policies are expected. In particular, they developed an OSeMOSYS model to plan for replacement of oil-fired power plants by natural gas-fired power plants and renewables technologies in Cyprus assuming various scenarios and environmental constraints [25]. Welsch et al. enhanced OSeMOSYS model generator by adding some short range operational constrains in an attempt to address the operational side of the expected energy policies. However, the results of such a model were different from the OSeMOSYS model generator version of 2011, and the authors of that study noted the uncertainties embedded in forecasting operational numerical data input for a long period ahead [26]. Dhakouni et al. assessed the potential of increasing the penetration of renewable energy resources in the Tunisian power generation mix. Based on OSeMOSYS model framework, the authors of that work concluded that higher energy independence of the country could be achieved with minor increases in the costs of the Tunisian electricity system [8].

Similar to other DCs, the evolution of the Egyptian energy sector was addressed in both academic literature and funded consultation projects to define the optimal future energy strategy. Taliotis et al. have applied OSeMOSYS to assess the evolution of the electricity generation sector in Egypt as well as 45 African countries up to 2040 [27], assessing the effects of connecting the electricity transmission infrastructure and allowing the electricity trades with other countries. Based on the results obtained from such a model, the total installed capacity in Egypt should exceed 200 GW on 2040 [27]. In a similar way, Davidsson and Hagberg applied OSeMOSYS modell framework to 18 African countries, including only industrial, rural and urban electricity demand, assuming a high level of demand aggregation, and without considering the exact electricity Egypt’s demand load profile. In the studies of Davidsson and Hageberg, wind power technologies were not included in Egypt’s electricity production mix, even if Egypt actually has wind technologies installed capacities [12,28]. TIMES model was applied to model Egyptian energy sector up to 2035 [29], and results have been obtained based on various scenarios, such as assuming an increase in the price of the fossil fuels, a decrease in the renewable costs, and an introduction of nuclear and coal fired power plants within the current energy mix.

Based on that study, the installed capacity should be 130 GW on 2035 to meet the electricity demand, and the expected electricity generation mix would include shares of coal, wind, nuclear, and more than 40 GW of solar technologies [15]. In this study, the proposed model will consider a detailed description of the power generation sector in Egypt, in order to overcome the limitations resulting from the previous studies, mainly related to the high level of aggregation of power generation and energy demand sectors.

3. Methods and models

This section provides the definition and implementation of the Egyptian Reference Energy System (RES) in the OSeMOSYS-Egypt model. Moreover, the main exogenous parameters are here introduced based on the analyzed energy scenarios, and they have been derived from scientific publications [28,30,31] and from grey literature, including reports by EEHC [12], World Bank [11] and IEA [32]. For the sake of clarity, transparency and reproducibility, Authors are willing to share the defined RES, the related input parameters and the results of the model.

3.1. Definition of Egypt's Reference Energy System (RES)

A *Reference Energy System* (RES) is the basic structure of all the energy modelling frameworks. It consists in a graphic representation of the structure of the power generation sector and it is generally composed by four tiers, including: *Primary fuel supply*, *Power generation technologies*, *Transmission and distribution infrastructures* and *Final demand sectors*. The RES adopted for the OSeMOSYS-Egypt model is presented in Figure 1, and it is described in the following.

Primary fuel supply. It represents primary resources that contribute to electricity generation, that is, the maximum resources capacities that could be exploited by each technology. Some of them have been disaggregated according to their origin of supply (i.e. domestic vs imported), to enable the application of resources bounding constraints like additional transport costs or availability limits. Similarly, renewable solar resources are categorized to different solar power generation technologies that might be constrained by geographical locations, such as the land resources needed for onshore wind technologies. Six different primary fuel supplies are available in the Egyptian context (see Table 1): non-renewables (*Coal*, *Natural Gas* and *Nuclear* resources) and Renewables (*Wind*, *Water* and *Solar Radiation*).

Power generation technologies. The available power technologies convert primary fuel supplies into electricity carrier. Thirteen types of power technologies are available in the Egyptian RES (see Table 2), classified based on their input fuels. *Hydroelectric plants* includes all the hydropower technologies currently available in Egypt. Other renewable technologies includes *photovoltaic plants* (distinguishing among large scale and rooftop plants), *concentrated solar power plants* and *wind farms*. Natural gas is contemporarily fed to five technologies: *steam cycles*, *simple gas cycles*, *combined cycles*, *combined heat and power cycles* and *hybrid concentrated solar power plants*. Other non-renewables includes *ultra-super critical* (USC) *coal plants* (traditional coal-fired technology are not available due to the lack of domestic coal supply), and *nuclear plants*. Finally, due to the connections of the electricity system with neighbor countries, *high voltage electricity imports* are treated as a fictitious power generation technology as well. Main references for the estimation of fixed and variable costs of power technologies are Davidsson et al. [33], US EIA [34] and IRENA [35].

Table 1. Main features of the primary fuel supply available in the Egyptian RES.

Fuel supply	*Acronym*
Water resources	HYD
Natural Gas (domestic production)	NG-Local
Natural Gas (imports)	NG-Imports
Solar power available for Photovoltaic	SOLPV
Solar power available for CSP	SOLCSP
Wind power	WND
Coal power (imports)	Coal
Uranium power	NUC Res

Table 2. Main features of the power technologies available in the Egyptian RES.

Power technology name	*Acronym*	*Energy efficiency [%]*	*Fixed cost [$/kW]*	*Variable cost [$/MWh]*
Hydroelectric plant	Hydro.PP	85	395	0
Photovoltaic large utility plant	PVL	20	2200	72
Photovoltaic rooftop plant	PV.roof	20	2100	86
Concentrated Solar Power	CSP.PP	40	3647	80
Wind plants	Wind.PP	60	2600	52
Steam cycle	NG.SCPP	35	900	59
Simple gas cycle	NG.GCPP	33	730	72
Combined cycle	NG.CCPP	45	1423	10
Combined heat and power	NG.CHP	85	1423	59
Hybrid CSP plant	CSPNG.PP	85	1687	59
Ultra Super Critical cycle	Coal.PP	37	3519	3
Nuclear plant	Nucl.PP	33	10778	4
High Voltage Import	HVI	100	-	-

Transmission and distribution infrastructures. This tier define technical features for connecting power generation with final users. In particular, transmission infrastructures receive high voltage electricity and deliver it to the distribution infrastructure. The latter is disaggregated into three categories to enable a separate allocation of power distribution losses: *distribution to industrial demand* (Dist.Ind), *distribution to general demand* (Dist.Gen) and *distribution to agriculture demand* (Dist.Agri).

Final demand. Electricity demand is classified into seven categories: *residential*, *industrial*, *commercial*, *governmental*, *public lighting*, *agriculture* and *others* (including ancillary activities).

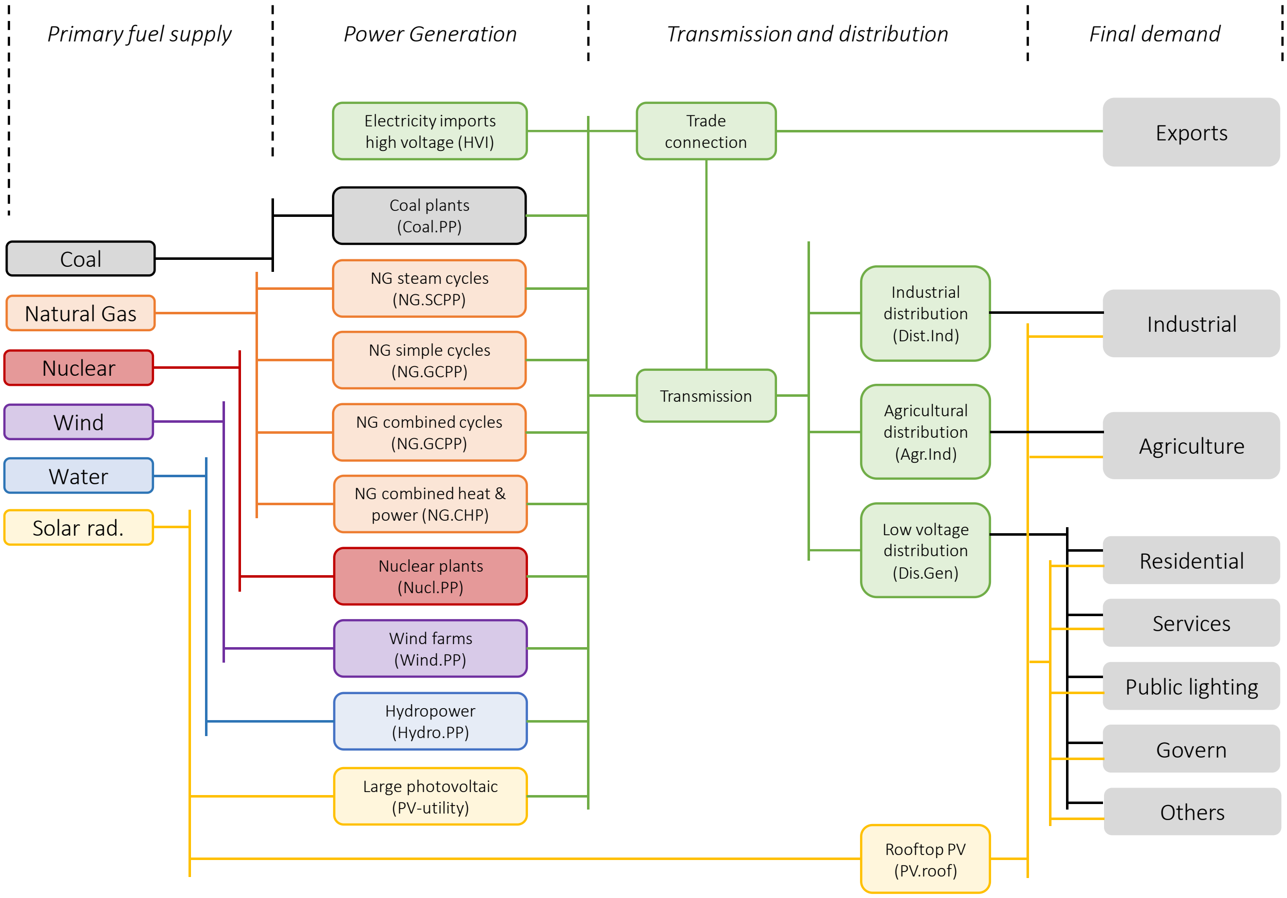

Figure 1. Egypt's Reference Energy System (RES).

3.2. OSeMOSYS-Egypt: setup and application

The Egyptian RES define in the previous section has been introduced in the OSeMOSYS open-source energy modelling framework [6], together with other exogenous parameters here introduced, and hence resulting in the *OSeMOSYS-Egypt model*. The model works by defining the least-cost mix of power technologies that should be deployed and operated to satisfy a temporal and spatial energy demand subjected to a set of technical and economic binding constraints. Accuracy of exogenous parameters provided to the model, such as the cost of technologies and the related efficiencies, is of paramount relevance to obtain reliable results. OSeMOSYS-Egypt considers a spatial scope of a single-region economy, in a time horizon between 2008 and 2040. For the period between 2008 and 2015, the model has been calibrated by considering the data available from EEHC, while for future years until 2040 electricity demand has been derived from scenarios data.

3.2.1. Energy scenarios definition

The OSeMOSYS-Egypt model has here been adopted to analyze two different electricity demand scenarios:

- **IEA New Policies Scenario.** This scenario has been defined by IEA considering the implementation of policies already defined or at least announced by world countries, and the way that such policies could be extended to consider the new intentions made by countries to reduce the global emissions as announced at COP21. Egypt has been considered one of the Middle Eastern countries in this study, where the Compounded Average Annual Growth Rate (CAAGR) of electricity demand is 2.6% for the period between 2014 and 2040 [1].
- **BMI Scenario.** This scenario has been defined by the *Business Monitor International* (BMI) company based on market researches related to the growth in

demand on energy commodities in Egypt [36]. The aggregate increase in electricity demand is defined until 2024, ranging between 3.8% and 5%, while after 2025 up to 2040 it is assumed to be constant and equal to year 2024 (3.8%). Shares in energy consumed by each national sector are kept constant and equal to the baseline year.

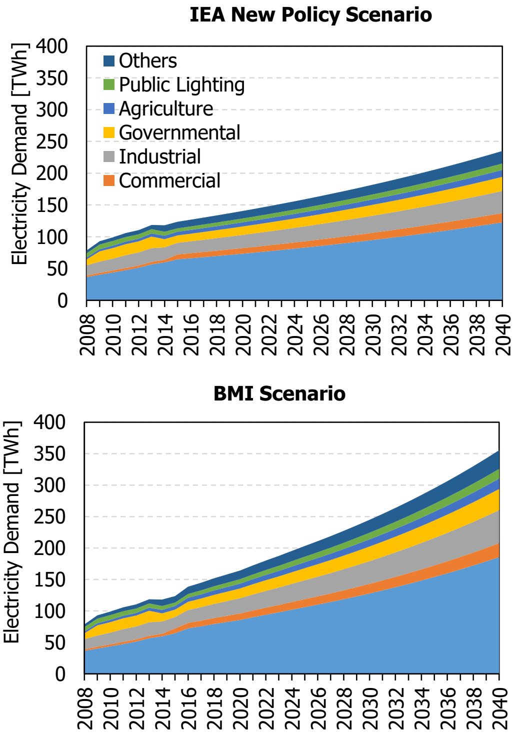

Figure 2. Evolution of the Egyptian electricity demand for IEA and BMI scenarios.

Notice that the above introduced scenarios define several other features related to the evolution of the energy sector at large, including the prospected change in energy consumption modes of other sectors of the economy, like industry and transport. However, only future increase in electricity demand is assumed as exogenous data for the OSeMOSYS-Egypt model.

The evolution of the Egyptian electricity demand based on the two selected scenarios is represented in Figure 2: while under the BMI scenario it approximately reaches 350 TWh in 2040, under the IEA scenario it equals 234 TWh. The discrepancy in the Egypt's electricity demand forecasted by the two aforementioned scenarios could be explained by the fact that in IEA scenarios Egypt’s electricity demand growth rates are given as aggregates of the Middle East countries, so this value might be affected by the level of spatial demand aggregation. For both scenarios, it can be inferred that residential and industrial demands are the major drivers for the increased demand on electricity.

3.2.2. Definition of other exogenous parameters

Definition of the other fundamental exogenous inputs required to setup the OSeMOSYS-Egypt model are here described. Regarding the spatial and temporal attributes of the electricity demand, every year of the considered time horizon has been divided into a set of time slices, and for each slice the type of electricity users have been identified. The set of time slices has been further divided by analyzing the monthly and hourly electricity load profiles provided by EEHC, represented by Figure 3 (respectively in plots A and B).

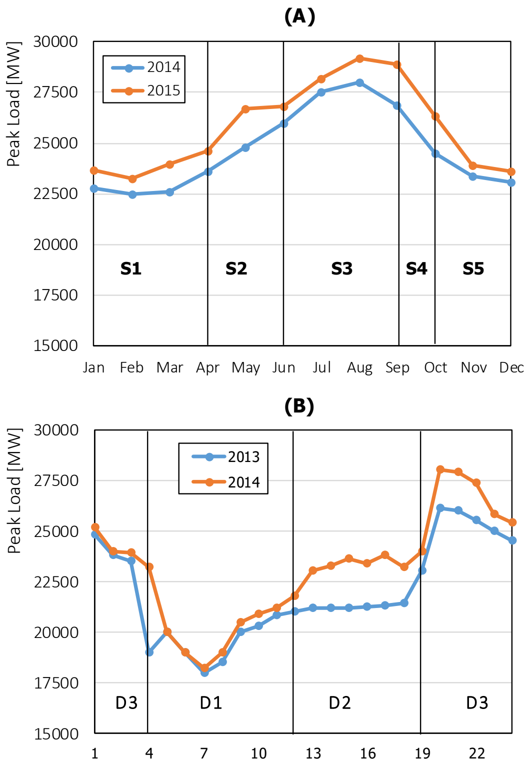

Figure 3. Egypt's monthly demand profile (A) and hourly electricity demand profile (B) in years 2014-2015.

A comprehensive and compact picture of spatial and temporal attributes of the electricity demand is represented in Figure 4 for year 2015: the electricity demand has been divided into a number of monthly intervals, subdivided in turn into different daily intervals. According to such representation, the coupling of the defined monthly and daily intervals results in 15 columns (time slices), covering the whole year. The height of each column is proportional to the electric energy requirements, while its width is proportional to the time for which this energy is required in the considered year. Therefore, the amount of electricity needed by each user type along the typical year is proportional to the area of the squares. For example, the demand of the residential sector occurs during night hours (D3), while the largest portion of the governmental electricity demand takes place during the daytime hour intervals (D1, D2).

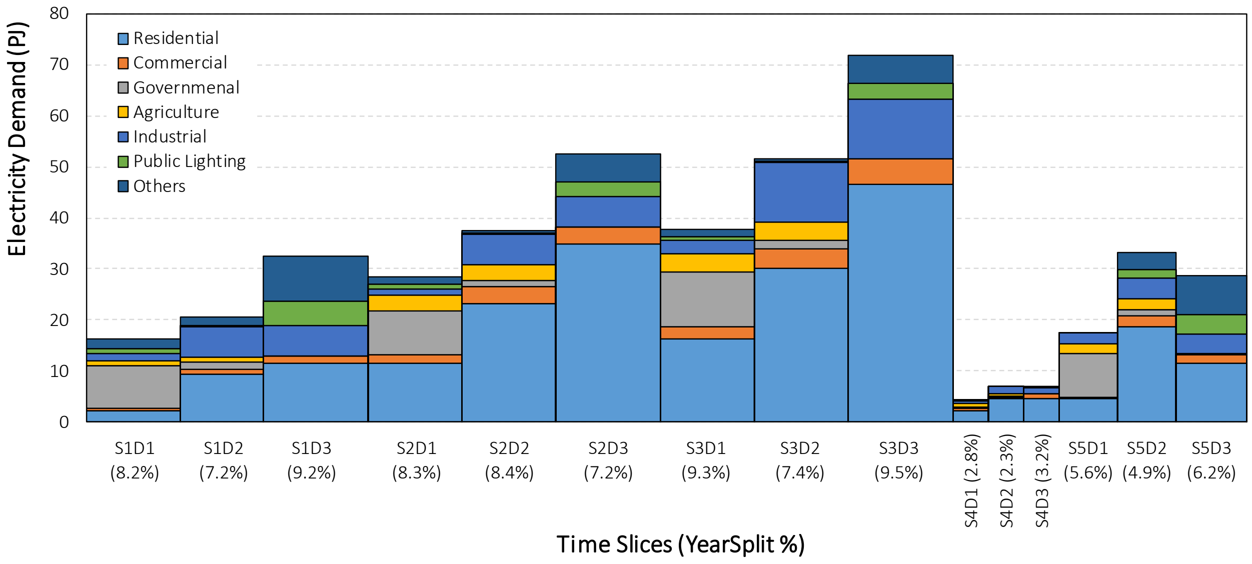

Figure 4. Sectoral Demand profiles over year time slices for years 2014-2015.

The total energy conversion efficiency, the availability factor of each generating technology and the related CO2 emissions have been derived from EEHC reports [12] and from recent literature [37]. Economic cost of each technology is represented in the model by parameters: fixed and variable costs [28]. Discount rate has been set in the model as 22%, as it increased rapidly and significantly in Egypt during recent years, according to the *Egyptian Central Bank* data[1].

Other constraints imposed in the OSeMOSYS-Egypt model concern the upper and lower bounds for endogenous variables (i.e. installed capacities): for hydropower technologies, the maximum installed capacity is defined as 2.8 GW (corresponding to the current installed capacity), due of the lack in available additional water resources. For CHP technology, the maximum installed capacity is set to zero, since the Egyptian govern is not planning investments in this technology at the current time [12].

4. Results

The developed model has been validated by checking the energy balances of the developed Egypt's RES. As an example, considering year 2008, the amount of electric energy produced by the energy sector (394 PJ) is greater than the electric energy output from the transmission infrastructure (362 PJ), that in turn is greater with respect to the output of the distribution network (282 PJ). The latter is finally equal to the demand of electric energy exogenously defined.

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[1] Egyptian Central Bank: http://www.cbe.org.eg/en/EconomicResearch/Statistics/Pages/MonthlyInterestRatesHistorical.aspx, accessed in 05-10-2017.

This section presents the results obtained from the OSeMOSYS-Egypt model for the considered time window, and considering all the technologies enclosed in the RES: *electricity generation mix*, *installed capacity mix*, *CO2 emissions* and *economic cost*.

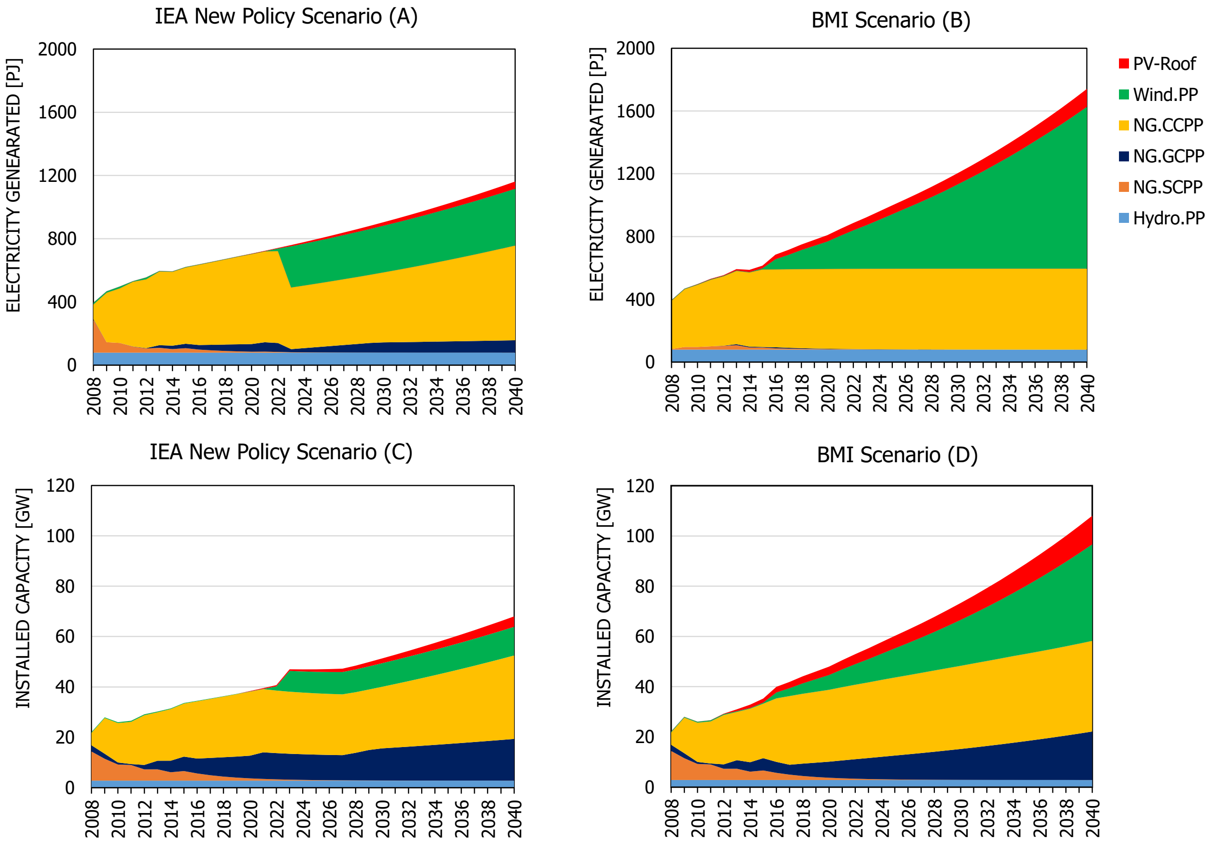

Figure 5. Electricity generation mix (A and B) and the corresponding installed capacities (C and D).

Electricity generation and installed capacity mixes. The prospected energy generation by each technology is depicted in Figure 5 (subplots A and B). For both scenarios, the optimal generation mixes include natural gas simple and combined cycles, wind power, PV rooftop and hydroelectric power. In the IEA New Policy scenario, the energy produced by natural gas power plants will decrease by 2023, due to the Egyptian government objective of achieving the 22% of renewable sources in the electricity generation mix, supporting the penetration of renewables which is expected to reach the 32% of the total production by 2040. On the other hand, in the BMI scenario the increase in energy production by natural gas plants is actually constrained by the availability of natural gas supplies, which are likely to decrease according to the current forecasts [38]. Therefore, wind technology and PV rooftop have to be introduced to meet the increase in demand, leading to an increase in the share of renewable energy production from 14% up to 65% in 2040. For both the scenarios, the contribution of hydropower energy is constant over the whole time window, due to the complete use of water endowment currently available for power generation. Moreover, the contribution of coal technology is negligible: this is motivated by the fact that due to the lack of domestic coal production, coal need to be supplied from foreign countries, and thus the cheap traditional coal power technology is not included in the RES of Egypt, substituted by the more efficient and expansive USC coal power technology.

Figure 5 (subplots C and D) reports the installed capacity of each technology in the considered time window. In 2014, the total installed capacity is reached approximately 37 GW in both scenarios. According to the IEA scenario, in 2022 the share of renewables installed capacity experiences a rapid increase from 2% up to 22%: even if this turns out to be the optimal energy system arrangement to satisfy the electricity demand, its practical implementation would probably meet practical constraints due to the short available time for commissioning and deploying such operating capacity. Likewise the IEA scenario, in the BMI scenario the power capacity requirements are strongly supported by the penetration of renewable sources between 2018 and 2040, mostly due to wind and photovoltaic technologies.

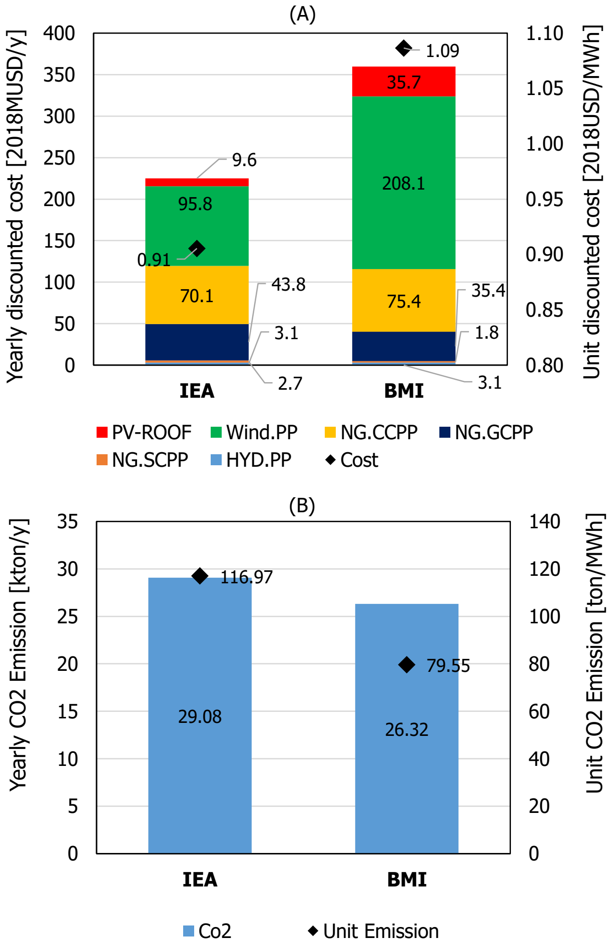

Figure 6. Total technologies' annual installed capacities, the associated total discounted costs (A) and CO2 emissions (B).

Economic cost. Figure 6 (subplot A) reports the yearly total discounted cost of the two scenarios (bars, in MUSD2018/y) and the discounted cost of energy (black diamonds, in USD2018/MWh), evaluated for the period between 2018 and 2040. In general, the total discounted cost of BMI scenario is higher than the IEA one by 60%, while the discounted cost per unit of energy produced is higher by approximately 20%. This is consistent with the increased in the penetration of high cost technologies (i.e. wind energy and PV rooftop) resulting from the BMI scenario. For the two analyzed scenarios, the costs are dominated by wind energy, which contributes for about 43% (IEA) and 58% (BMI).

Investments in natural gas combined cycles contribute with a share of 31% (IEA) and 21% (BMI) in the total economic costs. In addition, the share of PV rooftop technology is higher at the BMI by about fourfolds.

CO2 emissions. Figure 6 (subplot B) presents the overall CO2 emissions for the period between 2018 and 2040 (bars, in kton/y) and the emissions per unit of electricity generated (black diamonds, in ton/MWh). The emissions related to the BMI scenario are less than IEA scenario for about 10%, due to the strong and rapid penetration of renewables. Considering the emission intensity of the electricity produced, the BMI scenario is expected to be always below the IEA one.

5. Sensitivity analysis

A sensitivity analysis has been carried out in order to assess the robustness of the OSeMOSYS-Egypt model and the influence on final results due to changes in some crucial parameters, identified as follows (see Table 3): (1) *investment costs of renewable technologies*, (2) *renewables energy production targets*, (3) *efficiency of natural gas CCPP technology*, (4) *subsidies on natural gas supplies*, (5) *availability of the local natural gas supplies*, (6) *discount rate on capitals*, (7) *prospected water resource availability change* due to the *Renaissance Dam* in Ethiopia. The sensitivity analysis has been conducted by analyzing the separate effects of such parameters on the BMI scenario results only: this is motivated by the fact that, in the opinion of the Authors, this scenario better suits the future trends in energy demand by Egypt.

Table 3. Selected exogenous parameters to perform sensitivity analysis. Where a specific reference is missing, the Authors have proposed reasonable values base on their own experience.

#	*Exogenous parameters*	*Values*	*Reference*
1	Investment costs of renewable technologies	A. [35]; B. 50%; C. 70%	[35], Own assumption
2	Energy production targets by renewables	A. 2022-2035: +22%; 2036-2040: +35%; B. 2022-2035: +35%; 2036-2040: +40%;	[15]
3	Efficiency of NG CCPP	A. + 5%; B. +12%	Own assumption
4	Complete removal of natural gas subsidies	A. 2018; B. 2027;	[39]
5	Availability in local natural gas supplies	Unconstrained	Own assumption
6a	Discount rate on capitals	A. 2%	Own assumption
6b	Time changing Discount rate on capitals	A. 18% to 35% (2% linear increase); B. 11% on 2018 to 1% (1% linear decrease);	Own assumption
7	Hydropower resources availability	A. -16%; B. -80%;	[40]

Sensitivity of the first four parameters on results are reported in Table 4. Reduction in the investment costs of renewable technologies and increase of their penetration targets in the energy mix are likely to happen in future decades, and sensitivity has been here applied by considering alternative possible variability ranges (see Table 3). Neither reduction in renewable investment costs nor increasing their penetration targets significantly affect the total cost of electricity: this could be explained by the fact that the limited resources for natural gas are always the first to be exploited in the BMI scenario, due to the subsidized natural gas market which positions natural gas technologies to be the lowest cost alternative. As shown in Figure 5 (subplots B and D), the constrained natural gas supplies between 2018 and 2040 are not sufficient to deploy additional natural gas capacity. Therefore, wind and PV rooftop technologies contributes to the energy mix with a share of 51%, regardless of their costs and penetration targets. It can be concluded that in the BMI scenario the economic cost of electricity production, the amount of the required natural gas supplies and the share of the renewable technologies are not sensitive to the change in the cost of renewable technologies and to the related penetration targets.

By the end of 2018, three new natural gas combined cycle power plants of 4800 MW each will be deployed [41]. Due to their high efficiency and the related large amount of electricity production, the overall efficiency of the Egypt’s natural gas combined cycles is expected to increase by 5% and 12%, and this would result in a decrease in renewables in the production mix, respectively resulting in 41% and 46%. Despite this, the total costs of electricity production and the required supplies of natural gas have been found to be non-sensitive to such change in efficiency, and this could be justified by the higher portions of the total electricity demand that will be covered by combined cycle technology.

Egyptian economy currently applies subsidies on the exploitation of natural gas reserves for power generation, resulting in a subsidized price of natural gas of 10.24 USD2017/MWh, compared to an unsubsidized natural gas market price of 12.26 USD2017/MWh. However, since the annual natural gas consumption has reached its forecasted production upper limit in 2018, the contribution of other technologies is essential to meet the electricity demand, independently from natural gas price and the level of subsidies imposed. For such reason, results in Table 4 show that the change in cost of electricity production by natural gas technologies does not significantly affect the overall CO2 emissions or the penetration of renewables.

Table 4. Sensitivity of parameters 1 to 4.

#	Parameters	Total discounted cost	Natural gas consumption	Renewable Energy Penetration
0	BMI baseline results	101225 MUSD2008	709 Bm^3	51 %
1	Investment costs of renewable technologies	- 0.01 %	- 0.01 %	0 %
2	Energy production targets by renewables	+ 0.01 %	- 0.01 %	0 %
3	Efficiency of NG CCPP	- 0.02 %	- 0.01 %	-10 %; -5 %
4	Complete removal of natural gas subsidies	+0.01 %	+ 0.01 %	0 %

For a comprehensive assessment of the role of natural gas in the Egyptian power sector, the constraint on exploitation of natural gas local supplies has been gradually relaxed, simulating an increase in the availability of natural gas reserves available for power generation uses that may result from the current discovery of new natural gas reserves (e.g. the Zohr oil field). The future energy mix composition is strongly affected by the assumption of constrained or unconstrained local natural gas supplies, as can be inferred by comparing Figure 5 (subplots B and D) and Figure 6 with Figure 7. This is likely to cause a postposition in the penetration renewable technologies after year 2022, when a minimum level of renewables is exogenously imposed to the model to comply with the current political intentions. However, the unconstrained use of new natural gas reserves may lead to very high and quick increase in renewable penetration in year 2022, and probably it will take more time for renewables to be deployed due to technical constraints. For the planning period 2018-2040, the unconstrained natural gas supplies results in a decrease in the total discounted costs of investment and O&M with respect to the base case (about 18%): this could be explained by the decrease in investments in wind energy from 58% to 39%, and the related increase in investments in natural gas simple and combined cycles by 13% and 9%, as illustrated by Figure 7 (subplot C). As a result, the unit discounted costs of energy turns out to be lower by approximately 95% compared to the baseline result. Moreover, due the increased investments in natural gas technologies, a strong increase in natural gas consumption of about 42% is expected, causing an overall increase in CO2 emissions by approximately 50% (Figure 7, subplot D).

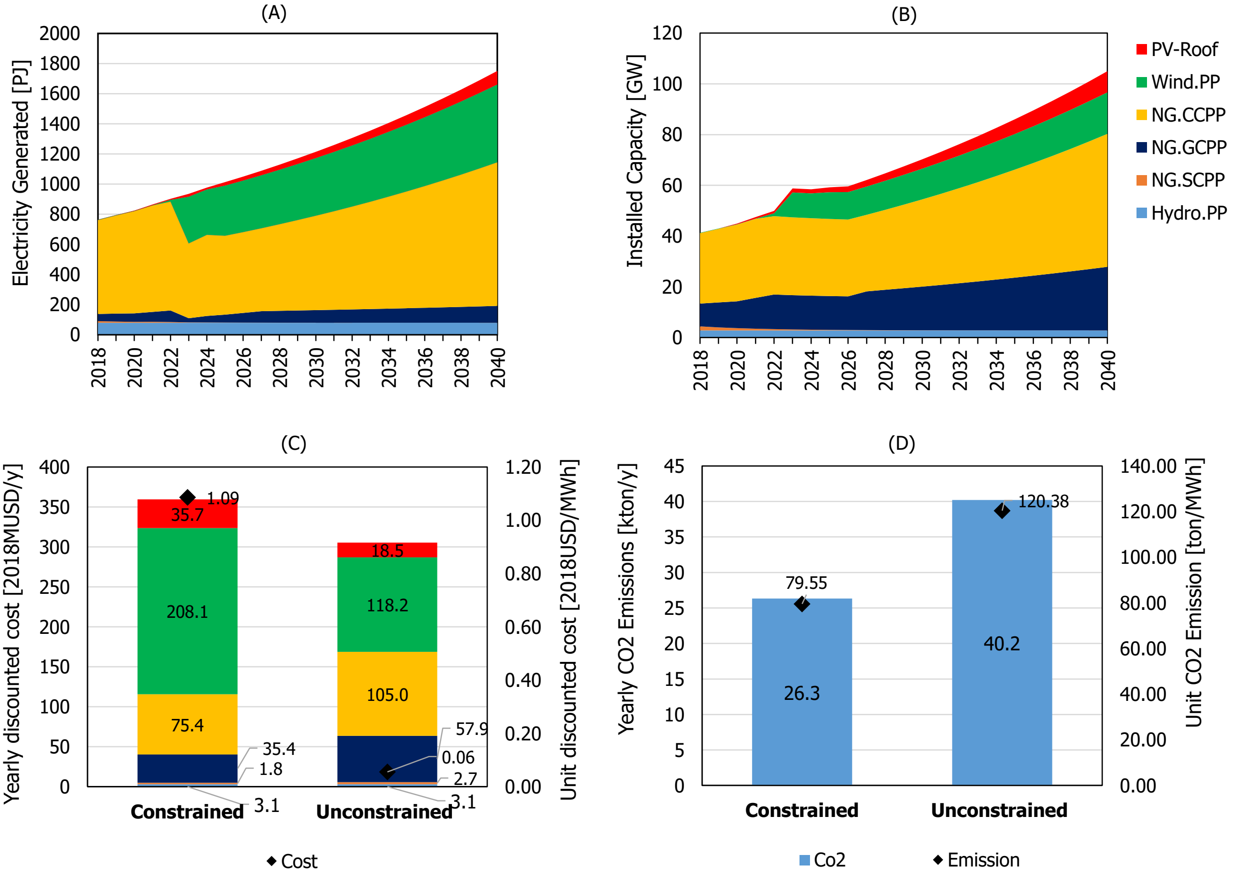

Figure 7. BMI scenario Electricity generation mix assuming unconstrained natural gas supplies.

In Egypt, values of discount rate on capitals has increased by 10% in the last 5 years, reaching the 19% in 2017 [42]. In the OSeMOSYS-Egypt model, the discount rate is assumed to be fixed and equal to 22% over the whole planning period. Since discount rates are usually time dependent, and since investments turn out to be more profitable if discount rate values are low, results obtained with a discount rate of 2%, representing more favorable market conditions, are reported in Figure 8. In particular, the weight of renewable in the total discounted cost increases from about 58% up to 70%. Moreover, technologies characterized by relatively low investment cost, such as natural gas steam cycles and simple cycles, are displaced from the optimal energy mix, leaving only natural gas combined cycles. Despite these changes, running the model with a low discount rate seems not to affect the natural gas consumption and the associated CO2 emissions.

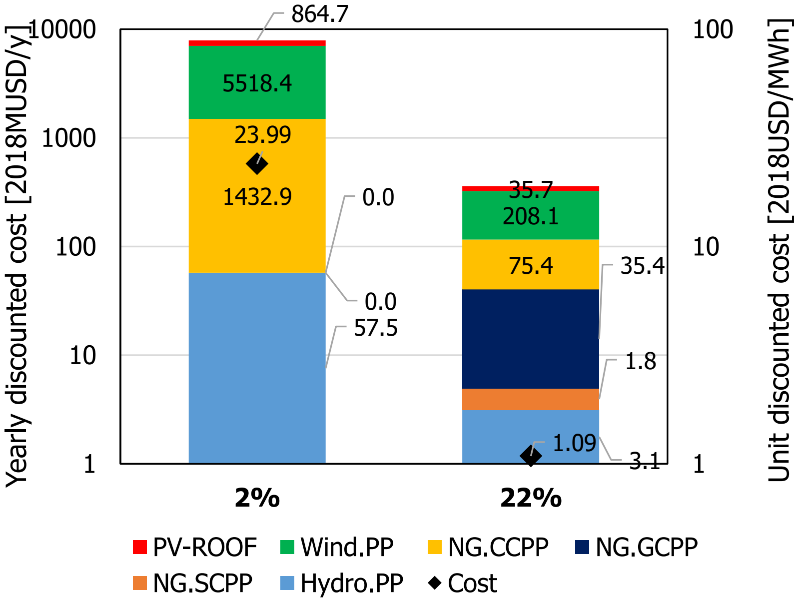

Figure 8. Electricity generation mix assuming changes in discount rate on capitals.

Based on this discussion, it is crucial for the decision makers to understand the effect of the discount rate on investments in the power sector. Egypt’s Central Bank historical data shows that the common discount rate is approximately 8% [42]. To better understand the effects due to time-dependent discount rates, different values of annual discount rates have been introduced in the model, starting from the value of 19% on 2017. As illustrated by Figure 9 (subplots A and B), the shares in the total installed capacity vary according to the assumed discount rate values: PV rooftop installed capacity (high investment cost technology) increases as the value of the discount rate decreases, and the yearly discounted costs change accordingly Figure 9 (subplots C). The share of Wind energy and

PV rooftop technologies in yearly total costs has increased from 56% and 7% (assumption a, Table 3) to 68% and 13% (assumption b, Table 3), respectively, displacing natural gas steam cycle and simple cycle. On the other hand, the share of natural gas combined cycles in the total discounted costs has increased by 5%, causing small differences in CO2 emissions (about 6%, Figure 9 - subplot D).

Finally, reduction of the water resource potential available for hydropower generation is likely to happen in the close future due to the construction of the Renaissance Ethiopian dam, estimated to be within 16% and 80% [40], and this may strongly affect the shape of Egyptian future energy mix. Assuming moderate reductions of hydropower potential, the expected consequences in energy production shares by technology is minimal due to the limited initial penetration of hydropower in Egypt’s total installed capacity (2.8 GW). However, considering the worst-case scenario, a significant reduction of the hydropower-produced electricity by 77%, which will be mainly compensated by an increase in the electricity produced by wind technology (11%) and PV rooftop technology (11%). Hence, the total discounted costs of electricity production for the period 2018-2040 will increase by 11%, and the amount of natural gas consumption and its associated CO2 emission will remain almost unchanged.

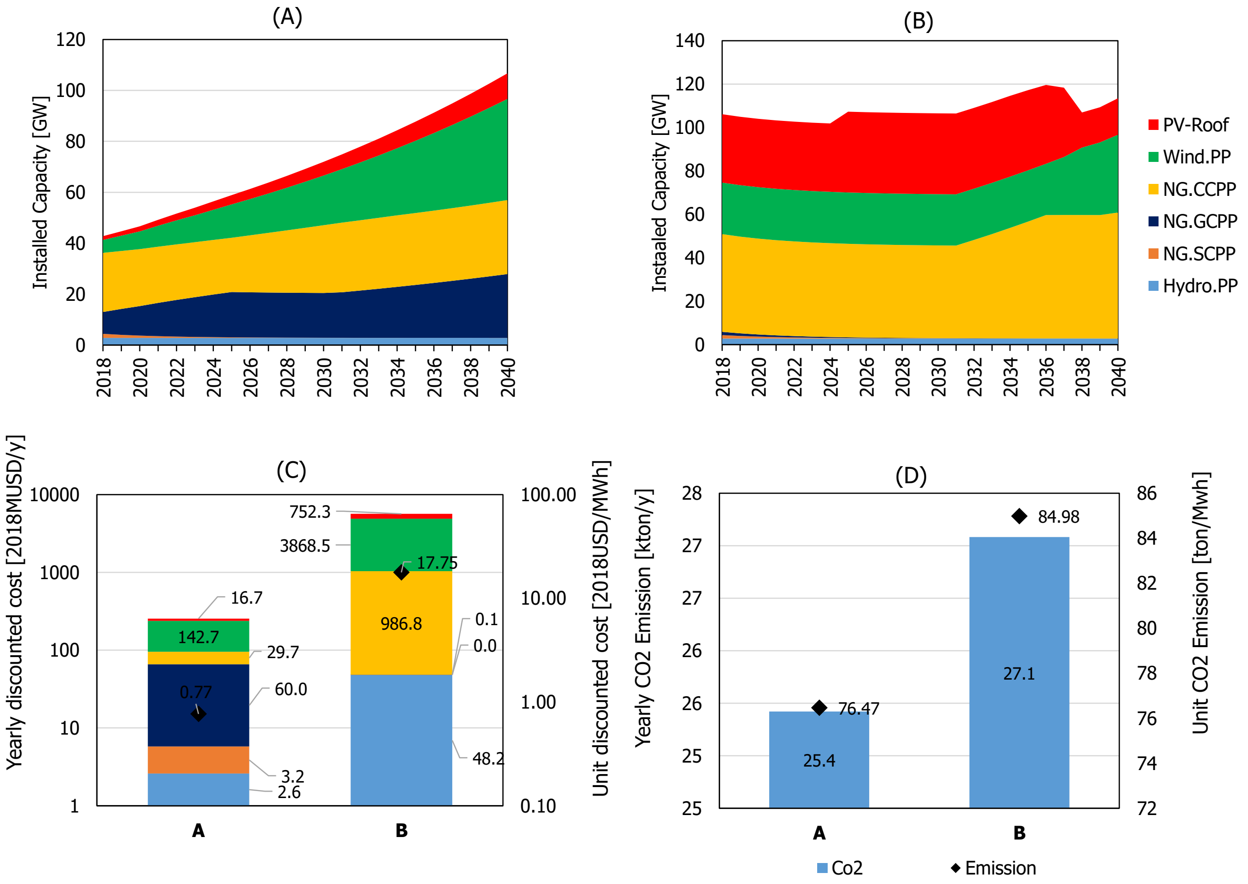

Figure 9. Share of power generating technologies in total capacities according to yearly changing discount rates.

6. Conclusions

The final purpose of this paper was to provide policymakers with comprehensive set of information to better plan for future investments in the Egyptian power sector. To achieve such goal, the OSeMOSYS-Egypt model has been developed to determine the least cost future Egyptian electricity production mix required to satisfy two different future electricity demand scenarios exogenously defined. Moreover, sensitivity analysis has been conducted in order to assess the relevance of some crucial parameters in modifying the results of the model. This research adds to and extends the current literature about energy planning in DCs by defining an Egyptian Reference Energy System based on the data published by Egyptian Electricity Holding Company, including the current and prospected primary energy supplies, power generation technologies, and the various demand categories. Furthermore, the developed REF is generic in nature, so it could be easily extended and implemented to various energy planning models.

For both the assumed scenarios, it is found that the lowest cost electricity generation mix always includes hydropower, natural gas-fired steam cycles, simple and combined cycles, wind power and PV rooftop technologies. This result mainly depends on the low economic cost of such technologies compared to the others: indeed, since Egypt's electricity peak load demand occurs at night hours, investing in large solar power generation utilities results not an economic feasible alternative.

Based on the sensitivity analysis applied to the BMI scenario, it is found that investment costs of renewables, presence of subsidies on natural gas production and change in prospected renewable penetration targets seem to have negligible effects on the shape of the future generation mix. Conversely, increasing the efficiency of natural gas combined cycles technology from 5% up to 12% with respect to the assumed efficiency in 2015 would impact the shape of the electricity generation mix, reducing the penetration of renewables by about 5% up to 10% over the whole planning period. Moreover, assuming unconstrained natural gas supplies results in reduction of the specific discounted costs per unit of energy produced by 95%, which was accompanied by 42% increase in natural gas consumption and 50% increase in the yearly total and unit CO2 emissions. Results of the model are then sensitive to changes in the values of discount rate on capitals: indeed, high values of discount rate cause lower economic costs technologies to be displaced from the electricity generation mix, resulting in more investments in higher economic cost technologies (i.e. natural-gas fired combined cycle, wind and PV rooftop technologies).

However, despite this change in the electricity generation mix, the impact on the values of the yearly total CO2 emissions is moderate (about 6%). Finally, sensitivity analysis has also been applied to quantify the effects caused by the construction of the Ethiopian Grand Renaissance Dam: despite the minimum penetration of the hydropower source in the generation mix (about 2.8 GW), the absolute effect caused by the dam may not be negligible. Indeed, assuming the worst-case scenario, a 77% in reduction of hydropower produced electricity would be compensated by 22% increase in the electricity production of wind and PV rooftop technologies. As a result, the total CO2 emissions level would remain almost unchanged, while the total discounted cost of electricity would be increasing by 11% between 2018 and 2040.

The current version of the OSeMOSYS-Egypt model is able to provide a comprehensive description of the Egyptian power sector. However, the model is characterized by the following main drawbacks that could be considered as possible directions for future improvements. First of all, electricity demand has been exogenously assumed based on the literature: a collaboration with local institutions is advocated by the Authors in order to increase the quality and reliability of the results. In addition to this, the developed model assumes the electricity demand as perfectly rigid, hence it is not able to capture the behavior of the final users in response to a change in electricity price. Secondly, sensitivity analysis has been performed by changing each one of the considered parameters at a time: however, more interesting insights may be obtained by changing them together since some cross-effects may arise. Regarding sensitivity analysis, the same values of discount rate on capital have been applied to all the considered energy technologies: this also might be unrealistic and it may affect the quality of results and the shares of different technologies. Finally, the scope of the model is limited to the power sector only, while great attention is currently devoted to extend the scope of energy models by including multiple energy carriers (heating, cooling, others) and multiple national sectors, hence analyzing the full energy metabolism of the considered economy [43,44].

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