Energy Strategy Reviews

Between path dependencies and renewable energy potentials: A case study of the Egyptian power system

--Manuscript Draft--

Manuscript Number:	ESR-D-20-00168R1
Article Type:	Full length article
Keywords:	Renewable energy; MENA; Egyptian power system; OseMOSYS; energy systems modelling
Manuscript Region of Origin:	GERMANY

Abstract:	Egypt's power system is facing major changes. Rising demand, scarcity of fossil resources and the falling capital costs of solar and wind energy technologies pose the potential to fundamentally remake the national power fleet. Against this backdrop, the paper at hand investigates potential pathways of the domestic power system with a particular focus on regional deployment and associated impacts on the transmission network. To this end, the open-source modelling framework OSeMOSYS was adapted and deployed. The analysis evaluates eight different sub-regions and renewable potentials for 320 sites across Egypt. The study concludes that wind and PV installations prove to be cost-competitive and capable of shouldering a large share of projected demand growth, while their regional deployment should take required grid investments into consideration. The results also indicate that a restrained expansion of renewable energy technologies targeted by the government proves to be more costly than a more aggressive deployment pathway.

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Dresden, 15.01.2021

Subject: Re-submission of the manuscript „Between path dependencies and renewable energy potentials: A case study of the Egyptian power system"

Dear Prof. Howells,

Thank you for the consideration of our work for the journal Energy Strategy Reviews and the opportunity to resubmit a revised version of the paper for publication.

We appreciate the valuable comments we received from the reviewers. We were glad to hear that the article is in line with the aim and scope of the ESR journal. Taking into account the reviewer's input, we have revised parts of the paper to improve the quality of our research.

Please find the responses to the reviewers and the respective revisions made attached to the revised version of the manuscript.

We appreciate you taking the time to review our submission and look forward to your response.

Kind regards,

Matthew Schmidt

Response to reviewer 1:

Dear reviewer 1,

Thank you very much for your valuable input. We believe that your review will improve the manuscript and contributes to the high quality of this research. We have revised our manuscript thoroughly with regard to your comments and indicated the changes made in the table below.

Best regards,

the authors

Response to	**#**	**Reviewer's comment**	**Response**	**Revisions made to manuscript**
Reviewer #1	1.1	The authors are using abbreviations such as, GuD, etc. without stating the terms that those abbreviations stand for. I would recommend that the authors include a table of nomenclature that includes all the abbreviations used throughout the manuscript, or make sure that those abbreviations are clearly and properly stated when they are used.	Thank you for making us aware of the confusion regarding the abbreviation. The abbreviation "GuD" in Figure 7 is an error. We have corrected the error and believe that the abbreviations now used are self-explanatory and therefore have decided against adding a nomenclature to the paper.	The abbreviation "GuD" in Fig. 7 has been changed to "*CCGT*"
Reviewer #1	1.2	The authors have used various figures and graphs, some of the figures are not clear; e.g. figure 12 in which the words on the on the figure are overlapped. I would appreciate that authors present understandable and clear figures.	Thank you for making us aware of the lack of readability. In order to make the presentation of the results concerning the transmission capacity expansion in the various scenarios, we have opted to replace the map with a bar graph to make the visualisation of the results more decipherable.	Figure 12 has been replaced by a bar graph to improve readability.

Reviewer #1	1.3	I would appreciate that the authors correct the line-numbering of the manuscript presented for reviewers	Thank you for making us aware of this. Line numbers have been added to the manuscript.	Line numbers have been added to the manuscript
Reviewer #1	1.4	The authors have referred to MENA countries in the title; however, the paper is solely focused on the Egyptian power sector. I would suggest that the author choose an appropriate title that reflects the case study that is presented in the manuscript.	Thank you for alerting us to the inconsistency. We have removed the reference to the MENA region in the title. The title reads now as follows: "Between path dependencies and renewable potentials: A case study of the Egyptian power system"	The title of the paper has been changed to the following: "*Between path dependencies and renewable potentials: A case study of the Egyptian power system*"
Reviewer #1	1.5	In equation # 1 presented in page # 4: the authors have not referred to the version of OSeMOSYS model that they are refers to. In addition, the authors should provide a detailed explanation and clear algebraic presentation of changes made to the original code.	Thank you for your comment. We have added the version of OSeMOSYS to the paper. Based on your comment we have added tables with the notional conventions used for sets and parameters and their respective descriptions . Futhermore, we have added the algebraic formulation of the individual equations that have been modified or added from the original code. In order to provide interested readers with a more detailed overview of the model formulation, we have created a Zenodo respository with the source code for the model. We have added the link in the appendix.	The version of OseMOSYS has been added to the manuscript. The sets and parameters used in the model have been added in Appendix C as well as individual equations that have been modified or added to the original OSeMOSYS code. Furthermore, we have created a Zenodo page to make the source code available for interested readers and added the link in the appendix.
Reviewer #1	1.6	In the same equation, the authors states the following contradictory clauses: "the region function of OSEMOSYS was omitted" and "These parameters are specified for each respective year, technology, and region considered in the model". So, it is totally unclear, when the region subset is used and when it is neglected.	Thank you for making us aware that the wording led to some confusion. To clarify, the model itself examines different regions of Egypt. These regions were only implemented via region specific "Fuels" and "Technologies" and not through the built-in OSeMOSYS "region" parameter. We have changed the respective text and added Figure A.3 to clarify the modelling approach.	The previous passage *"In order to reduce the computational effort of the model, the region function of OSEMOSYS was omitted and an allocation of the stock and flow variables was assigned to the different subregions by means of indices." was revised to "In order to reduce the computational burden of the model, Egypt constitutes a single region for the built-in region set. The sub-regions of Egypt are*

				mapped to specific stock and flow variables as is shown in Figure A.3 in the appendix."
Reviewer #1	1.7	It is unclear where PV utility scale and PV rooftop technologies are considered.	Thank you for your comment. In the analysis we have not considered small-scale (rooftop) PV systems. We kindly refer you to the following passages in the paper. In Section 5.3.2 we state " *As a note, distributed behind-the-meter PV installations are not considered in the analysis conducted*." For futher context in section 6.4 we note, "*It should also be emphasised that urban centres were excluded as candidate sites for PV installations. However, the use of small-scale rooftop PV systems could significantly contribute to the local supply and have a strong impact on the results reported above.*" We hope the references provide clarity.	No change made in the manuscript.

Reviewer #1	1.8	In page # 9: the demand input to the model is unclear. However, the authors provided a multi-nodal energy model for Egypt's power sector, in this manuscript the definition of demand in each node should be stated clearly. In particular, what are the categories of that demand that have been used; e.g. residential, industrial, .etc.	Thank you for your valuable comment. The focus of the paper is concerned with analysing the technology-specific capacity expansion at an aggregated level. Therefore, the electricity demand is not explicitly disaggregated for individual sectors. The assumptions concerning demand scenarios employed in the paper are sourced from a combination of projections made in the literature as well as trends in historical data. More specifically, the demand growth trajectory are based on forward projections of IRENA (2018), where as the hourly demand profiles are based on synthetic profiles derived in Toktarova et al. (2019). The aggregate demand for the low demand scenario is sourced from IRENA (2018) while the projection for the high demand scenario consists of a forward projection of historical trends. For the regional disaggregation of demand, historical data for Egypt was used. As the relative demand across the individual regions (nodes) has historically remained stable and a high level of urbanization has already been achieved, the aggreagated demand was allocated accordingly. We have added a passage in the paper to clarify the fact that the demand is modelled at an aggregate level and individual sectoral demands are not specified.	We added: "*It should be noted that the demand is modelled at an aggregate level, i.e., individual demand sectors are not explicitly considered, since the focus of the paper lies in evaluating impacts at a systems level.*"

Reviewer #1	1.9	Also, the authors have various demand growth scenarios, one of them is based on IRENA and the other two are based on the authors own assumptions. Since, the objective of this research is not to forecast the electricity demand in Egypt, I would highly recommend that the authors use demand scenario provided by authoritative and/or energy research institutions, such IEA. It is worth to note that providing an accurate forecast requires extensive data and specific forecasting models, which are not provided in this manuscript.	Thank you for the suggestion. Due to the political situation in Egypt, demand forecasts are difficult to make and vary greatly in the literature. For the year 2040, the following range of demand projections for Egypt have been employed: Rady et al. (2018) -> 350 TWh; Mondal et al. (2019) -> 524 TWh; Talotis et al. (2016) ->691TWh; Toktarova et al. (2019) 1525 TWh. Exploiting the assumption made in IRENA (2018), which derives their growth projections based on the relationship between electricity demand and economic growth, we extrapolate a forward projection of the demand growth for the High Demand Scenario. Using this approach, a the demand scenarios reflect a range the encompasses most of the projections while ignoring extreme outliers in the literature. We have added a sentence to the manuscript to provide some context.	We added: "*The demand trajectories used reflect the broad range of demand forecasts for Egypt employed in the extant literature (cf. Talotis et al. (2016), Rady et al. (2018), Mondal et al. (2019))*."
Reviewer #1	1.10	In the results section, specifically figure # 8 and 9, it is misleading to see some locations in the desert of Egypt and marked as high-demand, without giving any further details. Again, it is highly recommended that authors provide to the reviewer and the reader a clear and enough explanation for the definition of the demand used in the model.	We apologise for the confusion. The legends in Figure 8 and 9 refer to the areas used by wind and PV power plants in the Low Demand Scenario and the High Demand Scenario and not the areas of demand itself. For purposes of clarification, we have reworded the legend entries.	Legend in Figure 8 & 9 have been changed from "Wind/PV Sites Low Demand" to "*Wind/PV Low Demand Scenario*" and "Additional Wind/PV Sites due High Demand" to "*Additional Wind/PV Sites in High Demand Scenario*"

Reviewer #1	1.11	In figure # 9: as I can be inferred from the figure; nuclear capacities to be added in various location of Egypt. I would suggest the authors discuss the applicability of such scenario.	Thank you for your suggestion. We have tried to contexualise the results regarding the addition of nuclear capacities in Section 7. " *Only in the scenarios where high gas prices are assumed and a restrained build-out of renewable energies is targeted, is it cost-optimal to invest in nuclear power plants. An optimal location for these would be in Cairo or the Nile Delta region. The location in the Alexandria region currently under consideration would not be optimal under the framework conditions of the model. In addition, nuclear power plants are only viable if used as baseload generation capacities and are not endowed with the flexibility to accommodate fluctuations in renewable energies*." This, of course, only occurs in the most extreme scenario with a high demand and restricted renewable energy expansion. Considering the fact that we do not include ramping constraints and other technology-specific operational constraints, this could potentially impact the results. Futhermore, due to the fact that we allow incremental increases in capacity and do not restrict additions to entire generation blocks, the results have to be interpreted accordingly.	No changes made to the manuscript.

Reviewer #1	1.12	In the section of summary and outlook, the authors stated that "Due to decreasing domestic production volumes, Egypt has become dependent on gas imports", that clause is untrue as Egypt has recently started to export natural gas. I would recommend the authors use update sources	Thank you for pointing out this inaccuracy. As the manuscript was put together over a period of time, we unfortunately neglected to update the passage with more recent developments. We have appended the statement with a more recent source to reflect the discovery of gas deposits.	The previous passage "Due to decreasing domestic production volumes, Egypt has become dependent on gas imports." has been revised to *"Due to decreasing domestic production volumes, Egypt became dependent on gas imports in 2015. Although new gas deposits have been developed and Egypt is once again in a position to export natural gas, Ouki (2018) points out that this could well be short-lived and that in the coming years export levels might experience a precipitous decline."*
Reviewer #1	1.13	Finally, the authors have presented various location of renewable power generation, however, the presented model lacks definition of any constraints to the availability of the sites for construction of such renewable energy systems. For instance, the potential wind location on the western north coast of Egypt in reality a lot of constructions, urban development plans, and agriculture projects are in place. Since the authors considers a multi-nodal energy model, I would suggest the authors add spatial constraints that reflects the reality.	We kindly refer you to Section 5.3 (page 7). As described, the geodata used are based on the MapRE project (IRENA and LBNL, 2015) and therefore take into account exclusion criteria including topographical restrictions, environmentally sensitive or built environments as settlements or infrastructually developed areas. As a result, areas close to the Nile river and within the Nile delta are also excluded.	No changes made to the manuscript.

Response to reviewer 2:

Dear reviewer 2,

Thank you very much for your valuable input. We believe that your review will improve the manuscript and contributes to the high quality of this research. We have revised our manuscript thoroughly with regard to your comments and indicated the changes made in the table below.

Best regards,

The authors

Response to	#	Reviewer's comment	Response	Revisions made to manuscript
Reviewer #2	2.1	However, I would need some more clarification of the important competitiveness and market issues for the readers to better understand the situation and the validity of the scenarios developed: - What is the large scale market price level of electricity in Egypt? i.e. what is the level that the technologies are competing against? How is this foreseen to change in the analysis period? - What is the end-user price level of electricity and distribution fee in Egypt? This would be especially important for understanding the possibilities of domestic-scale PV	Thank you for your questions. As described in sections 1 and 2.1, the electricity sector in Egypt is strongly regulated and, in large part, state-owned and vertically integrated. Thus, a competitive environment with market prices does not exist. For the analysis, we abstract from the current situation and assume a perfectly competitive market environment in order to deploy an optimisation model based on a cost-minimisation approach. Thus, based on the interplay between the temporal demand profile and cost structures and availabilities of generation technologies, the cost-optimal capacity expansion across the model horizon is endogenously determined. We have added a passage to the paper clarifying the motivation behind the modelling approach used. With regards to electricity consumers, end-user prices are subsidised based on the yearly household	We added "In order to deploy an optimisation model based on a cost-minimisation approach and thus facilitate the assessment of the current energy policy outlook of the Egyptian government against a cost-optimal generation portfolio, we abstract from the current realities of the Egyptian electricity sector and assume a perfectly competitive market environment."

			consumption levels. Due to the politically tense environment, the government has been reticent to lift the subsidies and raise prices to reflect the existing cost structures in the system. Prices are based on the monthly consumption and vary (according to the latest price increase (MOEE 2019)) from 30pt (ca. EUR 1,5 *ct/kWh) for < 50 kWh/month (low income households) to 145pt (ca. EUR 7,3 ct/kWh) for consumption levels >1000 kWh. Commercial users pay between 65 pt/kWh (ca. 3.4 ct/kwh ; <100 kWh/month) and 160 pt/kWh (ca. 5.5 ct/kWh; >1000 kWh/month). Considering these low prices, there is little incentive for private house owners to invest in domestic PV utilities. Furthermore, as the market is regulated and mostly state-owned and operated, there is also no market-based competition between the technologies.	
Reviewer #2	2.2	- Table 1: variable costs of either NG technologies or diesel? Do these contain the fuel costs or not? Why is there such a big difference between them? - Table 1: I don't think that coal and nuclear lifetimes are the same. Based on my knowledge of European electricity market, coal PP's move to considerably less op. hours at age of about 30 years, whereas for well-maintained nuclear PP can be in full operation for 60 years. Also the coal capital cost seems quite high?	Thank you for your questions and making us aware of your concerns with respect to the assumptions employed. The variable costs listed for natural gas and diesel technologies do not include fuel costs. The assumptions made are sourced from Hussein et al. (2016), which provides cost data specifically tailored to the Egyptian context. Since we did not compile the data, we do not have access to the specific assumptions made and therefore cannot provide you with an exact explanation as to why there is considerable difference. Depending on the methodology used, the variable cost structure is sometimes composed of different cost elements. By using the same source for both technologies, we believe the foundational assumptions are consistent. Since the variable costs, however, are relatively	No changes made to the manuscript.

			small in comparison to the fuel costs, which make up the bulk of the generation-dependent costs, the impact on the results is negligible. With regards to the assumptions made about the economic lifetimes of the technologies, these were sourced from EIA (2016) and World Nuclear Association (2019), respectively. We checked the data to verify that we did not inaccurately report the values. In the list of reactors that have been retired, which can be view at the following link: https://www.world-nuclear.org/information-library/nuclear-fuel-cycle/nuclear-wastes/decommissioning-nuclear-facilities.aspx, the vast majority of the economic lifetimes of the plants do not exceed 40 years. We believe the economic and risk-specific factors that influence the operation of nuclear power plants are important to consider.	
Reviewer #2	2.3	Is there any CO2 price/cost assumed? If not, this would need some sensitivity analysis, as the analysis extends to the year 2042. ETS systems or carbon taxes are becoming more common.	Thank you for your suggestion. The focus of the paper deals with evaluating the current energy policy targets of the Egyptian government against the backdrop of falling capital costs for renewable energy technologies and the country's favourable renewable resource potentials. As carbon pricing ist not currently instituted nor under consideration, we decided against integrating carbon prices in the scenario framework. Considering the fact that the energy sector is largely vertically integrated and regulated by the government, a carbon price would not necessarily be practical as the costs would be borne by the government. It is true that a lot can change within the modelling horizon applied, however, the results derived from the analysis	No changes made to the manuscript.

			already point to the domestic renewable energy resources being cost-competitive without an established carbon pricing mechanism.	
Reviewer #2	2.4	I recommend some further sensitivity analysis taking into account my comment on coal vs. nuclear lifetimes.	Thank you for your suggestion. As mentioned above, the assumptions with respect to the coal and nuclear lifetimes have been sourced from Hussein et al. (2016). While a sensitivity analysis is always important to consider, based on informal ex-post checks of the model results, we do not believe that the inclusion of a sensitivity analysis would fundamentally alter the results or conclusions of the analysis and thus improve the paper.	No changes made to the manuscript.
Reviewer #2	2.5	I recommend in-depth discussion / analysis on to what extent domestic-scale PV could change the results given in this analysis.	Thank you for your suggestion. You raise an interesting point. We have tried to address this limitation of the analysis in the paper in section 6.4 by stating "the use of small-scale rooftop PV systems could significantly contribute to the local supply and have a strong impact on the results reported above. In terms of an in-depth discussion, as described in sections 1 and 2.1, the electricity sector in Egypt is strongly regulated and, in large part, state-owned and vertically integrated. This includes subsidised end-user prices depending on the yearly household consumption levels. Due to the politically tense environment, the government has been reticent to lift the subsidies and raise prices to reflect the existing cost structures in the system. Prices are based on the monthly consumption and vary (according to the latest price increase (MOEE 2019)) from 30pt (ca. EUR 1,5 *ct/kWh) for < 50 kWh/month (low income households) to 145pt (ca. EUR 7,3 ct/kWh) for consumption levels >1000 kWh.	No changes made to the manuscript.

			Commercial users pay between 65 pt/kWh (ca. 3.4 ct/kwh ; <100 kWh/month) and 160 pt/kWh (ca. 5.5 ct/kWh; >1000 kWh/month). Considering these low prices, there is little economic incentive for private house owners to invest in household (rooftop) PV systems. Furthermore, the optimisation model deployed technology-specific competition at the wholesale market level, which by nature does not incorporate investments of prosumers at the household level. While it would be possible to make assumptions about the level of PV penetration at the household level and include this exogenously in the model, without an economic incentive or specific targets to inform such assumptions, we believe it would be difficult to provide a detailed analysis or discussion within the scope of the analysis performed.	

Response to reviewer 3:

Dear reviewer 3,

Thank you very much for your valuable input. We believe that your review will improve the manuscript and contributes to the high quality of this research. We have revised our manuscript thoroughly with regard to your comments and indicated the changes made in the table below.

Best regards,

The authors

Response to	#	Reviewer's comment	Response	Revisions made to manuscript
Reviewer #3	3.1	Page 3, line 20 - "... a particular example of xx disadvantaged countries or..." - xx = financially	Thank you for alerting us to the error. We have made the correction in the manuscript	Changed "guuunancially" to "financially"
Reviewer #3	3.2	P. 7, line 46 - "..exhibit an evenly production output..." - even	Thank you for alerting us to the error. We have made the correction in the manuscript	Changed "an evenly production output" to "steady generation levels"
Reviewer #3	3.3	p. 13, line 36 - transmission losses are mentioned, are they included in the model?	Thank you for your question. Transmission losses were included in the model. The transmission losses were calculated based on historical values. Average losses across the last five years (2014-2019) amounted to 4.35%. We employed this value across the whole time horizon of the model. We have updated Table A.2 in the appendix with the respective values assumed.	Table A.2 in the appendix has been updated with the transmission losses (%)
Reviewer #3	3.4	Given the modeling horizon, why not include a scenario with carbon costs?	Thank you for your question. The focus of the paper deals with evaluating the current energy policy targets of the Egyptian government against the backdrop of falling capital costs for renewable energy technologies and the country's favourable	No changes made to the manuscript.

			renewable resource potentials. As carbon pricing ist not currently instituted nor under consideration, we decided against integrating carbon prices in the scenario framework. Considering the fact that the energy sector is largely vertically integrated and regulated by the government, a carbon price would not necessarily be practical as the costs would be borne by the government. It is true that a lot can change within the modelling horizon applied, however, the results derived from the analysis already point to the domestic renewable energy resources being cost-competitive without an established carbon pricing mechanism.	

Highlights

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Between path dependencies and renewable energy potentials: A case study of the Egyptian power system

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ARTICLE INFO

Keywords:
Renewable energy
MENA countries
Egyptian power system
OseMOSYS
Energy systems modelling
Energy transition pathways

ABSTRACT

Egypt's power system is facing major changes. Rising demand, scarcity of fossil resources and the falling capital costs of solar and wind energy technologies pose the potential to fundamentally remake the national power fleet. Against this backdrop, the paper at hand investigates potential pathways of the domestic power system with a particular focus on regional deployment and associated impacts on the transmission network. To this end, the open-source modelling framework OSeMOSYS was adapted and deployed. The analysis evaluates eight different sub-regions and renewable potentials for 320 sites across Egypt. The study concludes that wind and PV installations prove to be cost-competitive and capable of shouldering a large share of projected demand growth, while their regional deployment should take required grid investments into consideration. The results also indicate that a restrained expansion of renewable energy technologies targeted by the government proves to be more costly than a more aggressive deployment pathway.

1. Introduction

The electricity sector in Egypt is facing major challenges. Due to a growing population and rising per capita income, the country's electricity demand is rapidly increasing [47, 54]. While substantial investments in new power plant capacities have made it possible to reduce the incidence of large-scale power outages, an increasing shortage of access to fossil energy resources and ageing infrastructure continue to pose problems for the domestic electricity supply [9, 20, 41]. Today the country primarily relies on natural gas as a feedstock for power generation. While the country's natural gas reserves are technically large enough to cover domestic demand, in recent years, the production volume in some gas fields has declined as Egypt's demand has continued to rise. Since 2015, the former gas exporting country has been forced to buy more expensive natural gas on the world market or to switch to other sources. Recently developed gas fields in the Mediterranean Sea, some of which are significant in size, are not expected to keep pace with long-term forecasts of domestic energy demand growth [35]. The energy sector in Egypt is strongly regulated. Extensive subsidies to the energy sector have led to distorted market prices, inefficient consumption levels and heavy burdens on the national budget. Since 2014, the subsidies have been gradually reduced, but this has partly led to public opposition and protests in an already politically tense environment [27, 39].

Considering these recent developments and the forecasted growth in power demand, Egypt urgently needs to extensively expand its power plant fleet in the most cost-efficient manner possible. Renewable energy technologies that exploit the domestic endowment of wind and solar resources figure to play a decisive role in this respect, as conditions are very favourable for their deployment by global standards [30, 22]. The government has therefore set forth plans to increase the share of renewable energies in the power mix to 42% by 2042. In order to analyse possible development paths of the Egyptian electricity sector and to assess the cost-efficiency of the government's plans, the paper at hand develops and deploys a comprehensive power market model tailored to the Egyptian power system based on the open-source modelling framework OSeMOSYS [17]. Eight sub-regions with 429 capacity expansion options are examined. In terms of renewable technologies, site-specific hourly feed-in profiles are utilised, offering a high-resolution assessment of potential locations for wind and solar capacity build-out. Disaggregating the country into various sub-regions, potential impacts on the transmission grid and expansion requirements are analysed. In line with government plans, the cost-efficiency of introducing coal-fired or nuclear capacities is also evaluated in a scenario framework. Using the model setup, the analysis addresses questions concerning the cost-efficient composition of the domestic power fleet in the year 2042 with a particular focus on the spatial allocation of renewable energy capacities as well as providing a

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broad estimate of the impact on the transmission network of an increased penetration of renewable energy in the power system.

The remainder of the paper is organised as follows: Section 2 provides a brief overview of the current structure of the Egyptian power fleet and the respective expansion targets set by the government. Section 3 examines the extant literature on model-based analyses of the future of the Egyptian power system and highlights the contribution of the paper at hand. Section 4 details the input data of the model and its structure as well as the associated scenario framework. Section 5 reports selected results of the scenarios considered. Section 6 discusses the limitations of the model and compares the reported results with similar published studies. Section 7 closes the paper with a summary of the analysis performed and provides a brief outlook on potential extensions of the research.

2. Current structure of the Egyptian power fleet and expansion targets

2.1. Structural characteristics of the Eyptian power system

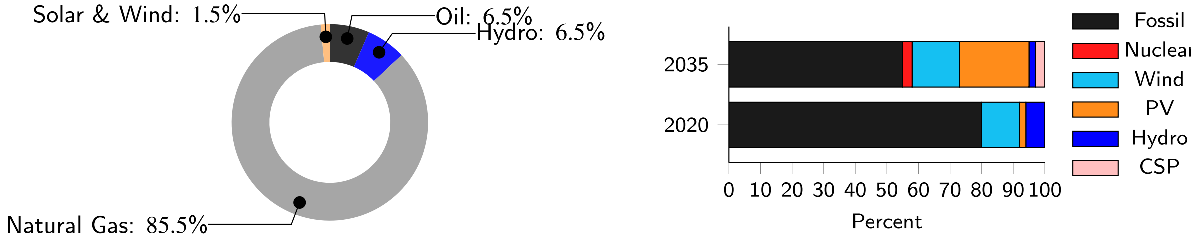
The electricity sector in Egypt is strongly regulated and mostly owned by the government. Although the various sub-sectors of generation, transmission and distribution have been separated in organisational terms over the years, they still continue to operate under the auspices of the Ministry of Electricity and Energy (MOEE). Utilities are run by distribution network operators. Due to their monopoly position, they are subject to regulation. The conventional fleet of the electricity industry is managed by the Egyptian Electricity Holding Company (EEHC). It comprises five regionally separate generation companies and one generation company responsible for the country's hydropower plants. The New and Renewable Energy Authority (NREA) is responsible for the build-out of renewable energy technologies.

With a market share of 94%, the state-owned power companies produce the overwhelming majority of domestic electricity (EEHC, 2019). The remainder is generated by independent power producers (IPPs) or companies operating under the Build, Own, Operate & Transmit principle (BOOT). These are contractually obligated to transfer all production assets to the respective government authority after a period of use of 20 years [7]. With the progressive opening of the market, a significantly higher share of non-governmental entities are anticipated to be actively involved in the future. In its current composition, the electricity sector is dominated by fossil energy carriers. As depicted in Fig. 1a, 85.5% of electricity was generated from natural gas, 6.5% from oil products, 6.5% from hydropower and a mere 1.5% from solar and wind power in 2018. This underscores the current dependency of the domestic power system on natural gas as a fuel source.

The transmission system operator is responsible for the operation and development of the high and extra-high voltage transmission network in the country. Due to the concentration of the population along the Nile, the transmission grid is characterised by a well-developed north-south connection and does not exhibit an extensively branched structure. Although there are connections to the neighbouring countries of Jordan and Libya, as well as a planned power line to Saudi Arabia, cross-border trade is virtually non-existent with a total market share of ca. 0.1%. Large industrial consumers can purchase electricity at the high or extra-high voltage level directly from the grid operator. In total, these purchases comprise a share of ca. 15% of total market volume [11].

The vast majority of power is acquired by the nine distribution system operators and sold at the distribution grid level. Since about half of the total demand is consumed by private households, they have a major influence on the daily load curve. The peak of a typical load curve is therefore in the evening hours when most people return from work. Due to the extensive use of air conditioning systems, electricity demand and temperature are positively correlated. This contributes significantly to the sharp increase in demand during the hot summer months.

In order to deploy a optimisation model based on a cost-minimisation approach and thus facilitate the assessment of the current energy policy outlook of the Egyptian government against a cost-optimal generation portfolio, the analysis abstracts from the current realities of the Egyptian electricity sector and assumes a perfectly competitive market environment.



(a) Share of primary energy sources

(b) Generation capacity expansion targets (in %)

Figure 1: Share of primary energy sources in Egypt's power generation mix in 2018 and the energy-specific generation capacity expansion of the MOEE, source: [11, 34]

2.2. Expansion targets for the Egyptian power fleet

The development of Egypt's power fleet is organised by the Ministry of Electricity and Energy on the basis of five-year plans. The seventh five-year plan ended in 2017. In order to promote self-sufficiency and in so doing prevent potential supply bottlenecks, the government agency has been pursuing a diversification strategy. One component of this strategy involves the increased exploitation of domestic renewable resources. Sites for renewable technologies have been identified and tendering rounds have been organised. In total, projects for wind power plants amounting to 2.3 gigawatts (GW) and photovoltaic (PV) plants amounting to 3.3 GW are currently in the process of being built [32, 34]. According to the government's long-term targets, as illustrated in Fig. 1b, the share of renewable energies is set to increase to 20% by 2022 and 42% by 2035.

Due to the steep increase in demand forecasted, an additional build-out of conventional power capacities is planned. Thus, the ninth five-year plan envisages the construction of new fossil-based generation capacities including coal-fired power plants and in accordance with its long-term diversification strategy even a nuclear power plant [11, 40].

3. Literature overview and research contribution

3.1. Energy system modelling and the global South

Energy system modelling has increasingly been used to identify cost-efficient expansion pathways in individual countries and regions. Most of the models are developed in industrialised countries and are only conditionally suitable for use in countries of the global South due to the differing requirements [48]. To better meet the requirements of these countries, the MARKAL modelling platform was developed on behalf of the International Energy Agency (IEA). MARKAL, like its successor TIMES, has been used worldwide for numerous studies. Mondal et al. [28], for example, investigate potential natural gas shortages and greenhouse gas emissions in Egypt. Although MARKAL or TIMES are free of charge to use, their usage requires access to proprietary software, e.g. programming language and solver.

This can constitute a particular obstacle for financially disadvantaged countries or institutions. For this reason, the Open Source Energy Modelling System (OSeMOSYS) and the Long Range Energy Alternatives Planning System (LEAP) based on it were developed under the direction of the Royal Institute of Technology Stockholm (KTH) [17]. LEAP, on the other hand, is only freely available for institutions of the global South [16]. To this date, the modelling frameworks have been deployed in the development of a large number of energy system models. In preparation for the Conference on Sustainable Development (Rio+20), the United Nations modelled interactions between global climate, land, energy and water systems in the CLEWS model based on OSeMOSYS [50]. With respect to individual countries and regions, applications include, e.g., network expansion and generation capacity planning in South America [31], the development of pathways for greenhouse gas reductions in China [4] and the assessment of renewable energy potentials in Tunisia [6].

3.2. Overview of assessments of future pathways of the Eyptian power system

OSeMOSYS also formed the basis for the TEMBA project, in which the development of the power sector of Egypt and 45 other African countries is investigated. The study's conclusions suggest that the countries could profit from further intertwining their power systems and becoming more interconnected. The study assumes a slowly growing demand and an increase in generation capacities in Egypt to ca. 200 gigawatts (GW) with a demand of approx. 690

terawatt hours (TWh) by 2040 [43]. Using the *RESilion* model, Kost [23] evaluates the development of the power system in North African countries and an enhanced interconnection with Europe. A significant increase in the renewable share in the electricity mix of up to 72% is identified as most cost-efficient. Concentrated Solar Power (CSP) power plants play a significant role in the future power provision, comprising a share of 33% in the region's future power mix. Egypt is divided into three load zones in the study. A total of 14 specific regions are considered for renewable capacity additions. In a study conducted by Mondal et al. [28], power demand is assumed to increase to 524 TWh by 2040. Depending on the share of renewable technologies, between 91 and 120 GW of generation capacity is required to meet load requirements. Wind power, in particular, but also in some cases PV power plants, play a prominent role in achieving the emission reduction targets. CSP power plants hardly figure into the future power fleet. In Rady et al. [38], Egypt is also considered as a single region. Similar to this study, the analysis of the Egyptian electricity sector is conducted with a model based on OSeMOSYS. The availability of renewable energy technologies was determined on the basis of annual averages. With an increase in demand up to 350 TWh in 2040, an expansion of 110 GW of capacity is projected. To ensure a cost-efficient build-out, the expansion of wind power capacities is particularly recommended. Coal-fired, nuclear and CSP power plants are also considered as potential investment options, but are not added in any of the scenarios considered.

3.3. Research contribution

In comparison to previous work on the future development of the Egyptian power system, the paper at hand employs an enhanced spatial and temporal resolution. In addition, the study is carried out with updated cost forecasts. In comparison with somewhat older studies such as Kost [23], capital costs of PV and CSP power plants have developed much differently than previously assumed. By looking at the various sub-regions within the country, sub-regions with differing consumption profiles are examined in detail, unlike in the studies by Taliotis et al. [44], Rady et al. [38], Mondal et al. [28]. This allows for a more detailed assessment of the spatial allocation of future power plants and their potentials as well as associated transmission network expansion requirements. For renewable power technologies, spatial locations and capacity installations are derived. This is performed on the basis of individual hourly feed-in values and thus also in much greater detail than in the above-mentioned studies. This work, therefore, enables not only the identification of general nation-wide trends, but also the delineation of specific developments for individual sub-regions in the country.

4. Model set-up and adaptations

The model deployed for the following analysis is largely based on the model code of OSeMOSYS_2017_11_08. Based on various technology and site-specific techno-economic data parameters, the cost-efficient deployment of generation and transmission capacity and the dispatch of electricity to serve an inelastic demand is computed over the time horizon of the model. Model results offer insights into the cost-optimal composition of the domestic power fleet, the transmission network, the corresponding shares of renewable energy technologies and fossil resource requirements. The model is a bottom-up model that is sector-specific and thus does not represent macroeconomic relationships and feedback loops. In terms of the representation of the power system, it should be noted that for the research at hand, technology-specific emissions are not considered. Furthermore, reserve capacities and ancillary services are not represented in the model. Each individual sub-region is modelled as a single node, meaning transmission costs or congestion within sub-regions are neglected. Transmission capacities between the sub-regions are modelled as net transfer capacities.

In order to reduce computational burden, three representative seasonal weeks were derived in an hourly resolution and then recombined to form work and weekend days. The year 2017 is adopted as the base year for the analysis. Investment periods are modelled in five year time steps. This was done by making corresponding adjustments to the OSeMOSYS code. The five-year investment periods correspond to the Egyptian government's five-year plans for the development of the electricity system. In order to be able to assess medium-term developments, the model horizon runs 25 years to the year 2042. To deal with the end-of-horizon problem of energy system investment models, the model is run for an additional investment period. The output pertaining to the last period is not reported.

The objective function minimises the net present cost of the power system to serve an inelastic demand. This is

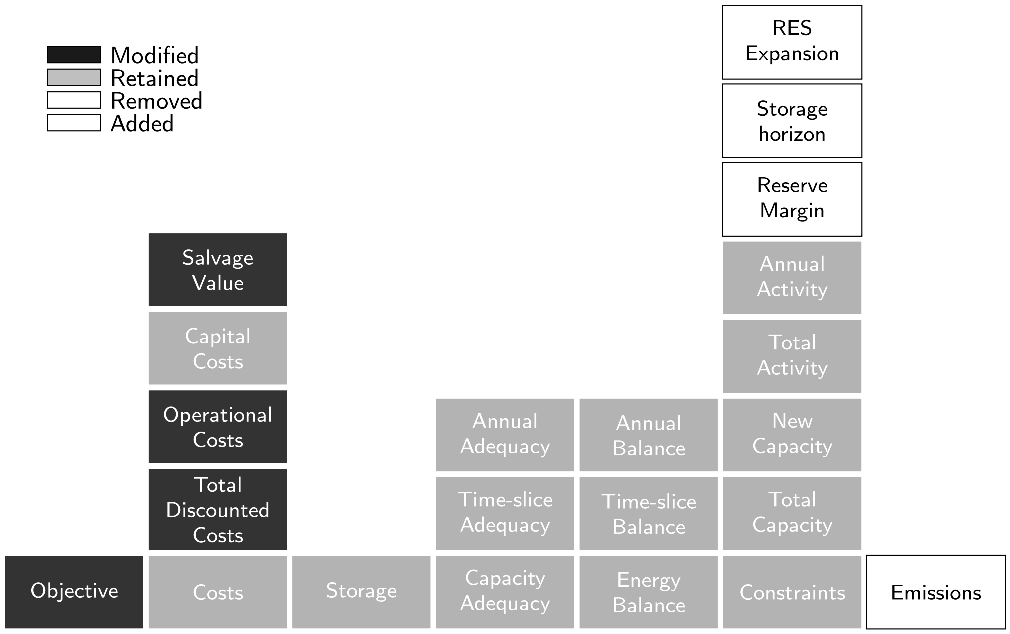


Figure 2: Adaptations made to the base structure of OSeMOSYS, source: based on Howells et al. [17]

done by summing up the total discounted costs of each *technology (t)* in each model *year (y)*:

$$minimize \sum_{r} \sum_{t} \sum_{y} TotalDiscountedCosts_{r,t,y} \tag{1}$$

Technologies (t) comprise all elements that are capable of processing or generating the variable fuel such as a primary energy carrier or electricity. In order to reduce the computational burden of the model, Egypt constitutes a single region for the built-in region set. The sub-regions of Egypt are mapped to specific stock and flow variables as is shown in Fig. A.3 in the appendix.

Costs comprise those associated with the construction ($DiscountedCapitalInvestment_{r,t,y}$) of new technology capacities and their corresponding dispatch ($DiscountedOperatingCost_{r,t,y}$):

$$\begin{aligned} TotalDiscountedCosts_{r,t,y} &= DiscountedOperatingCost_{r,t,y} \\ &+ DiscountedCapitalInvestment_{r,t,y} \\ &- DiscountedSalvageValue_{r,t,y} \qquad \forall\, t, y \end{aligned} \tag{2}$$

These parameters are specified for each respective year (y) and technology (t) considered in the model. The investment in and dispatch of a non-storage technology is associated with capital costs, which are annuitised according to the capacity installed, as well as operational costs for each technology, which are composed of variable and fixed cost shares. Annual operating costs are discounted with respect to the base year to make costs comparable. Furthermore, the salvage value ($DiscountedSalvageValue_{r,t,y}$) of the respective technologies that have exceeded their operational life or have been replaced is incorporated in the objective function. The salvage value is based on the commissioning year, operational lifetime and imputed discount rate. A linear depreciation method is applied.

As displayed in Fig. 2, the base structure of OSeMOSYS has been slightly modified for the analysis conducted in the paper.

- **CSP storage**: Unlike pumped storage power plants, heat generated in CSP power plants cannot be stored for an unlimited period of time. Due to the simplified assumption that the storages must be emptied at the end of each representative day type, i.e., at the transition from work day to weekend day or vice versa, balancing of the storage level over the entire modelling period is no longer necessary, which considerably reduces the computational burden of the model. This is applicable irrespective of the specific season.

- **RES expansion cap**: A further adaptation made to the model involves the exogenously determined minimum shares of RES capacity. An additional constraint which applies both to the flows, whose share is to be determined, and the corresponding technologies is introduced into the model.

5. Data input and scenario framework

5.1. Configuration of sub-regions and seasonal representative days

The model distinguishes between eight sub-regions, which are based on the network areas of the distribution system operators. Their service areas define the respective model sub-regions as depicted in Fig. 3. Northern and southern network areas around Cairo are combined into one sub-region. Historical data indicate that the distribution of total national demand amongst the network areas has remained relatively constant in recent years [8, 9, 10, 11]. The entire country has access to electricity and the level of urbanization has held steady at around 45% for the past decade [33]. For the analysis, therefore, the distribution of total demand between the sub-regions is assumed to remain constant over the modelling horizon.

The availability of renewable energy sources is subject to temporal variability. It is therefore prudent to consider temporal fluctuations in their generation output as well as the temporal characteristics of domestic load profiles. In order to reduce computational burden while accounting for seasonal and hourly fluctuations, representative days are constructed based on the load profile forecasts for Egypt developed in Toktarova et al. [45] by applying a hierarchical clustering procedure from Kotzur et al. [24] (see Appendix A for a more elaborate explanation).

5.2. Specification of renewable energy sites and potentials

In order to provide for a more disaggregated assessment of renewable energy expansion pathways in Egypt, the research conducted makes use of site and technology-specific potentials reported in the Multi-criteria Analysis for Planning Renewable Energy (MapRE) project. This study identifies and evaluates concrete sites for wind, PV and solar thermal technologies in a large number of African countries based on certain sustainability criteria related to cost-efficiency as well as social and environmental impacts. Using geodata provided by governmental and non-governmental organisations potential areas were determined by using thresholds or exclusion criteria like settlements or infrastructurally developed areas. The potential areas were divided into zones vary in size between 30 km^2 and 1,000 km^2 by the extent of spatial homogeneity in resource quality [21].

Using the tool published by MapRE, the attributes of the individual zones are recalculated. While the geodata from MapRE were used, investment and operating cost assumptions are updated in accordance with recent technical and economic developments. In addition to technical capacity and production potential based on weather data, other factors relevant to the choice of location are identified and evaluated. With a weighting of 50%, the levelized cost of electricity (LCOE) is given the greatest consideration. The distance to load centers is included in the evaluation with 15% and the transmission connection, population density and competing site usage with 10%, respectively. The last criterion considered is road access, which is attributed a weight of 5%.

The potential sites are assigned to the Egyptian sub-regions and integrated into the model. The exact number of potential sites considered is determined by repeated model runs until either the potential of a sub-region is exhausted or additional locations do not alter the results within the period under consideration. In total, a number of 165 wind sites, 150 PV sites and five CSP sites are assessed in the analysis (see Fig. A.2 in the appendix).

5.3. Power plant technologies

The expansion of the various power plant technologies depends largely on availabilities and the development of economic parameters. Due to the wide variety of data assumptions used in the literature, fuel prices and cost data vary depending on the source used. A large share of the data used is sourced from Hussein et al. [18]. In the case of coal-fired and nuclear power plants, assumptions are taken from other sources [13, 26]. Due to repeated attacks on pipeline infrastructure in the past as well as legal irregularities in tenders for large-scale PV plants, investors demand considerable risk premiums [5, 37]. Based on the work of Hussein et al. [18], an average weighted cost of capital (WACC) of 10% is assumed. All calculations were made in US-Dollar and an inflation rate of 1% is used.

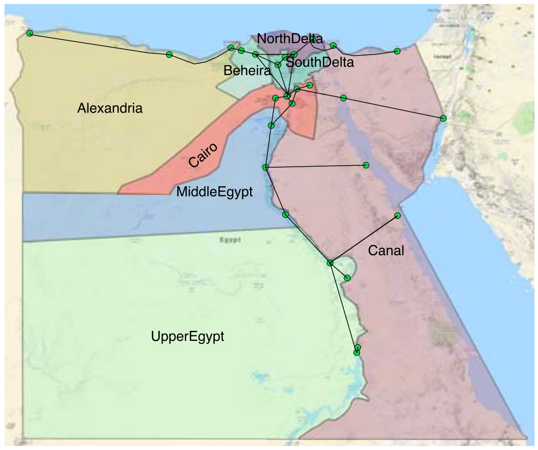


Figure 3: Regional representation of Egypt based on network areas of distribution system with simplified representation of transmission grid

5.3.1. Conventional power fleet

As displayed in Fig. 1a, the current conventional power fleet is primarily comprised of natural gas-fired power plants, including gas turbines, steam turbines and combined cycle power plants. A total of ca. 51 GW of natural gas-based power plants were in operation in 2017. While recent builds achieve overall efficiencies of up to 55 %, a share of older power plants dating back to the 1980s are still in operation, some of which operate with significantly poorer efficiency factors [11].

Diesel generators are characterised by high operational flexibility and low investment costs. However, fuel costs are significantly higher than other technologies. In Egypt, they are therefore used either as reserve capacity in case of power outages, to cover peak loads or in island operation. However, as grid expansion progresses, an increasing number of remote locations have been connected to the grid and existing diesel generators are no longer needed to cover base loads. Currently, a total of 600 MW in grid operation and 185 MW in island operation are installed in Egypt (EEHC, 2019).

As previously stated, the Egyptian government is currently pursuing plans to diversify its power plant fleet. This includes both plans to build a coal-fired power plant as well as well as explore the utilisation of nuclear power. To assess the cost efficiency of these plans, both technologies are integrated into the model as investment options. All relevant techno-economic parameters for the conventional power technologies are listed in Table 1.

Table 1
Techno-economic parameters of new-build conventional power plant technologies, source: [13, 18, 26, 55]

Technology	Overnight capital costs (USD/kW)	Fixed costs (USD/kW)	Variable costs (USD/MWh)	Efficiency factor (%)	Lifetime (years)
Existing (NG-based)	-	22	20	specific	30
CCGT (high)	1,050	22	20	55	30
CCGT (low)	750	22	20	45	30
Diesel	160	30	4.6	35	30
Hard coal	3,636	42	46	39	40
Nuclear	4,850	-	15.1	43	40

5.3.2. Renewable energy technologies

The production of renewable energy technologies is highly weather-dependent. Therefore, site and technology-specific capacity factors are derived.

Wind energy capacity: The evaluation of site conditions indicates that for most sites in Egypt class III turbines are most suitable. A Vestas V150 wind turbine with a capacity of 4.5 MW and a hub height of 145 metres was employed as the reference turbine. Respective cost parameters were sourced from Hussein et al. [18]. In order to render site-specific feed-in profiles, capacity factors were constructed using simulations of the hourly power output as in Staffell and Pfenninger [42]. The simulated hourly capacity factors of the reference plant at the respective sites were averaged over a period of ten years (2007-2016). The hourly feed-in values were then converted to conform to the representative days by applying a hierarchical clustering algorithm. The production profiles of the representative days is largely dependent on the distance from the coast. While coastal locations exhibit steady generation levels, sites in the interior of the country are characterised by day-night variations.

PV capacity: Desert makes up a large part of the territory of Egypt. These areas are characterised by high solar irradiation and are also neither populated nor otherwise used, making them ideal locations for utility-scale PV plants. As a note, distributed behind-the-meter PV installations are not considered in the analysis conducted. One example of such a power plant is the Benban solar park. The solar power plant, which is currently under construction, will be the largest contiguous PV plant in the world with 1.8 GW of installed peak capacity at the time of completion [32]. In the model, it constitutes the reference power plant for future projects. To improve the capacity factor at the location, plans foresee the deployment of a single-axis tracking system [51].Based on investment costs of USD 1.35 million/MWp in 2016, Hussein et al. [18] projects a cost reduction to USD 1.08 million/MWp by 2020, falling further to USD 0.79 million/MWp by 2035. The hourly capacity factors for the individual sites were derived using simulated production profiles over the period from 2007-2016. The hourly capacity factors were subsequently transformed into representative seasonal days as per the process for the capacity factors of wind generation. Due to the higher levels of irradiation in the south of the country, larger yields are generated than on the Mediterranean coast, especially in the winter months.

CSP capacity: The prospect of exploiting the solar resources in the desert areas of MENA regions to deploy significant capacities of CSP power plants has long been the topic of energy policy discussions [46, 23]. In particular, the ability to integrate high temperature heat storage to temporally shift production, affording it baseload properties, constitutes a significant advantage over other renewable technologies. The resource potential, however, has failed to materialise in Egypt as currently no significant CSP power plants have been installed to date. Due to limited installed capacity worldwide, its technical development has yet to progress the likes of other RES technologies and capital costs remain relatively high [20]. The most widespread type of construction is one that consists of a solar collector made up of parabolic mirrors and a steam turbine to generate electricity. As this technology continues to develop, Hussein et al. [18] assume a cost reduction of ca. USD 1 million/MW to USD 4.2 million/MW between 2016 and 2035. This forms the basis for the cost assumptions applied in the model analysis.

Unlike the capacity factors derived for wind and PV sites, the output of CSP sites is based on the site-specific capacity and annual power output determined in the MapRE project (see Sec. 5.2). The output is distributed across the year according to the respective DNI values over a ten year period from 2007-2016 [14]. The specific cost assumptions made for the respective RES technologies are provided in Table 2.

Table 2
Economic parameters of new-build renewable energy technologies, source: [18]

Technology	Overnight capital costs (USD/kW)	Fixed costs (USD/kW)	Variable costs (USD/MWh)	Lifetime (years)
Wind turbines	1,350	0	18	20
Utility-scale PV (base year)	1,350	24	18	25
CSP plant (base year)	5,225	22	20	30

5.3.3. Transmission network

As explained above, OSeMOSYS is in its basic structure a market model, in which the transmission network is not explicitly represented. It does, however, provide for a simplified representation of transmission capacities between separate sub-regions. As the cost of infrastructure expansion measures could be an inhibiting factor for integrating high penetration levels of RES, as recent examples in countries, e.g. Jordan, where the tendering of RES projects was halted due concerns over the state of the electrical grid, investigating broad impacts on the transmission network is important [2].

Based on geodata of the current transmission grid, the line distances between existing substations were derived and used as a basis for determining net transfer capacities [53]. In the simplified network representation, transit transmission lines across certain sub-regions are included. Candidate capacities are added between the El Beheira and North Delta sub-regions as well as between Canal and Upper Egypt. Transmission capacities of existing lines as well as the capital costs for candidate connections were determined using Pletka et al. [36]. As a reference, the costs of constructing a 500 kV single line with a maximum transmission capacity of 1,500 MW were used. In line with the linear optimisation approach, incremental extensions of candidate connections are permissible. The respective techno-economic parameters employed for the transmission network can be found in Table A.2.

5.4. Scenario framework

In order to investigate and compare various pathways the power system in Egypt could potentially take as well as represent inherent uncertainties, a scenario framework is adopted. The framework includes three sets of drivers including future demand growth, the subsidisation of fuel prices and the restrictive nature of RES expansion. A graphical representation of the scenario framework is displayed in Fig. 4.

- **Demand growth**: Power demand in Egypt has been growing steadily. This can be attributed on the one hand to a rapidly growing population and on the other to rising per capita income [47, 54]. Future projections of demand growth are, however, subject to uncertainty. Demand forecasts in the literature adopt different assumptions. For example, IRENA [20] assumes a complete correlation of economic growth and energy demand. A stable growth rate of 4% per year is assumed. This would correspond to an increase in demand of up to ca. 434 TWh by 2040. This trajectory was taken as the basis for the scenario *Low Dem*. However, if the average increase in consumption in recent years is taken as a basis for the projection, an annual increase of ca. 7.4% is expected, which corresponds to a total demand increase to 940 TWh by 2040. This trajectory is assumed in the scenario *High Dem*. The demand trajectories used reflect the broad range of demand forecasts for Egypt employed in the extant literature (cf. [44, 38, 29]. It should be noted that the demand is modelled at an aggregate level, i.e., individual demand sectors are not explicitly considered, since the focus of the paper lies in evaluating impacts at a systems level. The demand scenarios are depicted in Fig. A.1b in the appendix.

- **Fuel prices and subsidy reforms**
  In order to analyse the influence of changes in fuel costs, especially considering the established policy of heavy subsidisation and current reforms being undertaken, two scenarios are considered for the respective energy sources [49]. The scenario sets consist of a low and high price development. As the primary energy source in the current electricity mix, natural gas can currently only be substituted to a limited extent. Supply costs therefore have a direct influence on system costs. In addition, the government has been engaged in cutting subsidies for natural gas [35]. With this in mind, the low price scenario is based on the assumption that fuel costs will initially rise due to a rollback of subsidies. The assumption is made that in the long-term Egypt will be able to secure natural gas at the price of recently contracted gas from Israel. For the high price scenario, a figure for the opportunity costs of export losses due to government subsidies is assumed [52]. Price assumptions for the other relevant fossil fuels are provided in Table A.1 in the appendix.

- **RES expansion**: Due to the penny-switching nature of linear optimisation models, i.e., a complete switch to other technologies through marginal variations in the corresponding investment costs, the increasingly favourable conditions for the deployment of RES technologies in Egypt can lead to an expansion of these technologies that in light of production capacity and technical restrictions is unrealistic [25]. Furthermore, considering potential challenges with respect to the grid infrastructure as well as issues related to supply security, it is safe to assume that these concerns are likely to curb the pace at which RES expansion is feasible. Thus, two scenarios are contrasted to compare the economic implications of a restrained build-out of renewable energy capacities. In the first, *Free RES*, the cost-optimal expansion of capacity without an exogenous limitation is considered. The alternative expansion scenario, *RES Cap* introduces a constraint on the renewable share of the total electricity mix according to the government's current policy targets. The envisaged targets for the years 2022 and 2035 are adopted as the reference expansion pathway [34]. This corresponds to an increase of 7% in each modelling period. The expansion pathway assumed in the case *RES Cap* is depicted in Fig. A.1a in the appendix.

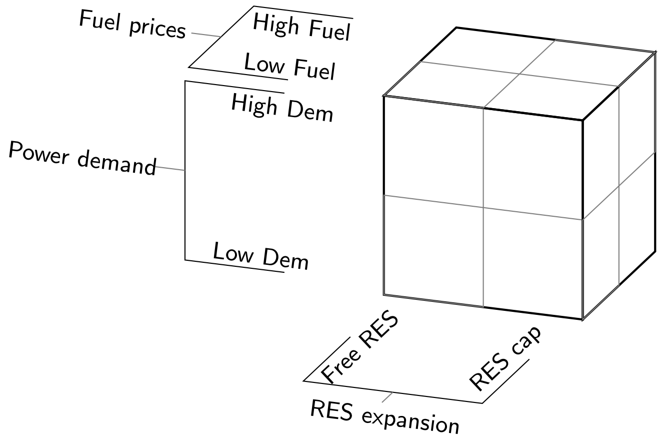


Figure 4: Analysis framework consisting of eight scenario combinations

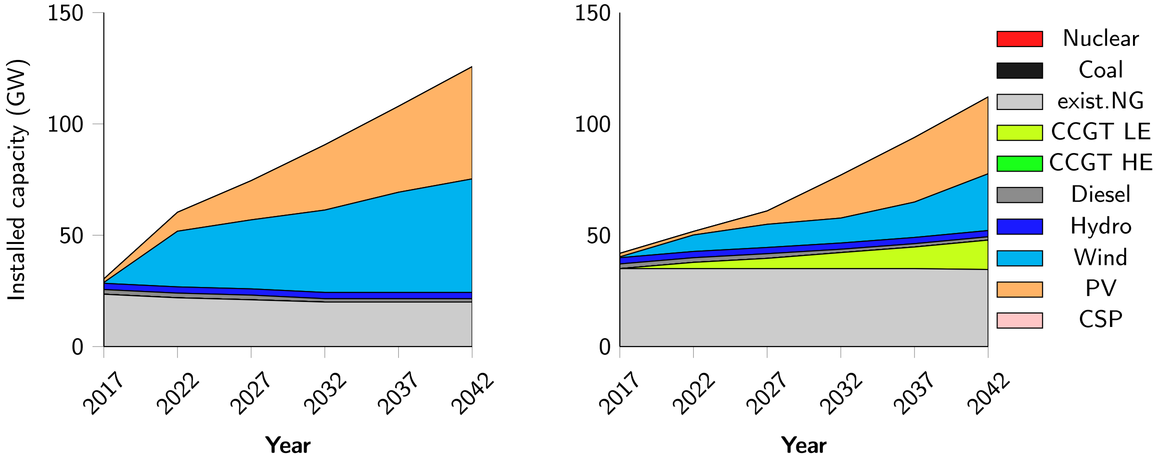
6. Results and discussion

This section provides an overview of the model results of the scenarios evaluated. First, more general developments and nation-wide results are reported. Subsequently, selected results pertaining to developments in specific sub-regions and technologies are presented and discussed.

6.1. Domestic power fleet development

The model analysis clearly indicates that both wind and PV technologies have a significant role to play in the development of the domestic power fleet. Hence, both renewable energy technologies compose a high share of the cost-optimal power plant fleet in all scenarios. Absent an exogenous limitation (*Free RES*), the exploitation of renewable sources is almost sufficient to completely cover increases in power demand. If the share of renewable energies is limited *RES Cap*, conventional power plants will continue to rely on natural gas as a source of energy at low cost (*Low Fuel*), while only in the case of high energy costs (*High Fuel*), nuclear power capacity is added. Diesel generators are also used to cover peak loads. Neither coal-fired power or CSP plants are deployed in any of the scenarios examined.

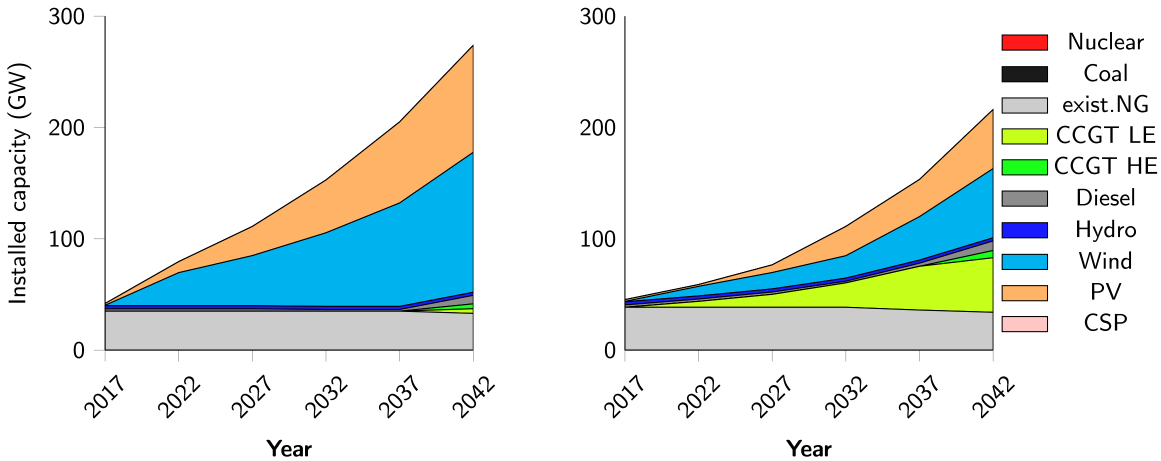
The extent of the capacity expansion up to 2042 largely depends on the assumed demand trajectory and limits put on the share of renewable capacities in the power plant fleet. Under the *Low Dem* trajectory, a capacity build-out of ca. 130 GW in the *Free RES* case and 110 GW in the *RES Cap* case is realised. These results hold for both high (*High Fuel*) and low price (*Low Fuel*) scenarios. The individual composition in the *Low Fuel* case is displayed in Fig. 5a and 5b. Assuming a strong increase in demand levels (*High Dem*), the power plant fleet is expanded to 275 GW in the *RES Free* and *Low Fuel* and to 284 GW in the *High Fuel* scenario. Limiting the share of renewable power capacity (*RES Cap*) reduces the installed fleet capacity to 216 GW in the case *Low Fuel* and to 221 GW under the scenario *High Fuel*. The individual capacity shares of the respective power generation technologies in the *Low Fuel* scenario are depicted in Fig. 6a and 6b.



(a) Free RES

(b) RES Cap

Figure 5: Domestic power plant fleet development with and without a RES cap (*Free RES* & *RES Cap*) in the scenarios *Low Dem* and *Low Fuel*



(a) RES Free

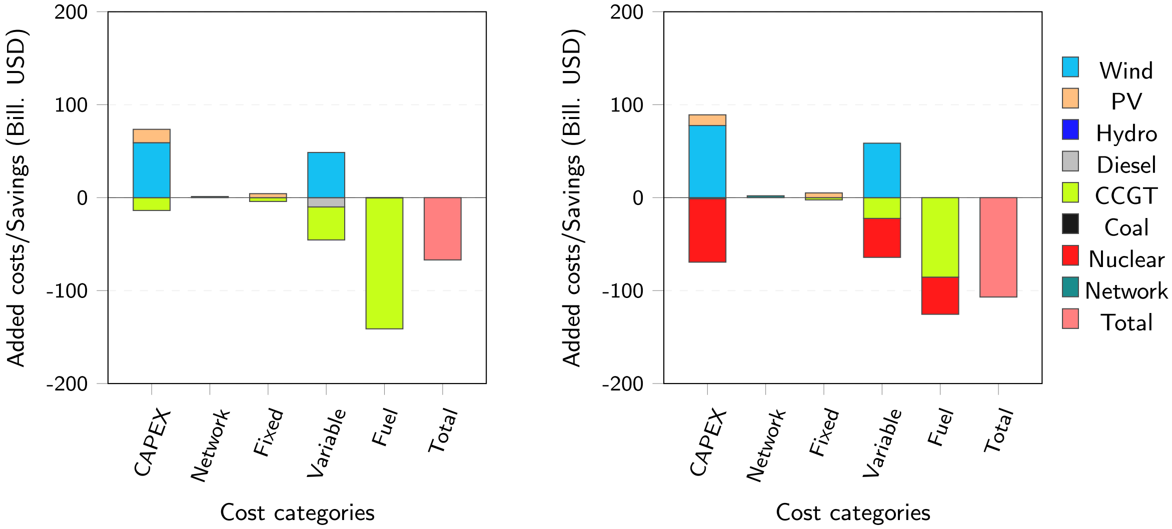
(b) RES Cap

Figure 6: Domestic power plant fleet development with and without a RES cap (*Free RES* & *RES Cap*) in the scenarios *High Dem* and *Low Fuel*

A restrained build-out of RES (*RES cap*) results in significantly higher costs (Fig. 7a and 7b). In the scenarios with low fuel costs (*Low Fuel*), while renewable energy technologies entail higher investment costs, fuel costs are mitigated in the long run. In the case of low demand growth (*Low Dem*), this results in a total of ca. USD 66.5 billion in additional costs. This corresponds to average additional outlays of USD 2.66 billion per year. In the scenario *High Dem*, a similar amount of additional costs of USD 67 billion until 2042 accrue. In the scenarios *High Fuel*, the expansion of nuclear power plant capacities results in high capital expenditures. In the long term, additional costs of around USD 175 billion until 2042 or USD 7 billion per year are borne in the case *Low Dem*. Under the *High Dem* trajectory, the cost difference amounts to ca. USD 107 billion across the model horizon.

6.2. Regional deployment of renewable energy technologies

In the following section, the sub-regional deployment of power generation capacities is reported in greater detail. In particular, the site-specific installation of renewable energy technologies, the sub-regional build-out of conventional power plants and transmission network expansion is evaluated.



(a) Low Fuel (b) High Fuel

Figure 7: Cost comparison in the case *RES Cap* under the scenarios *Low Fuel* and *High Fuel*

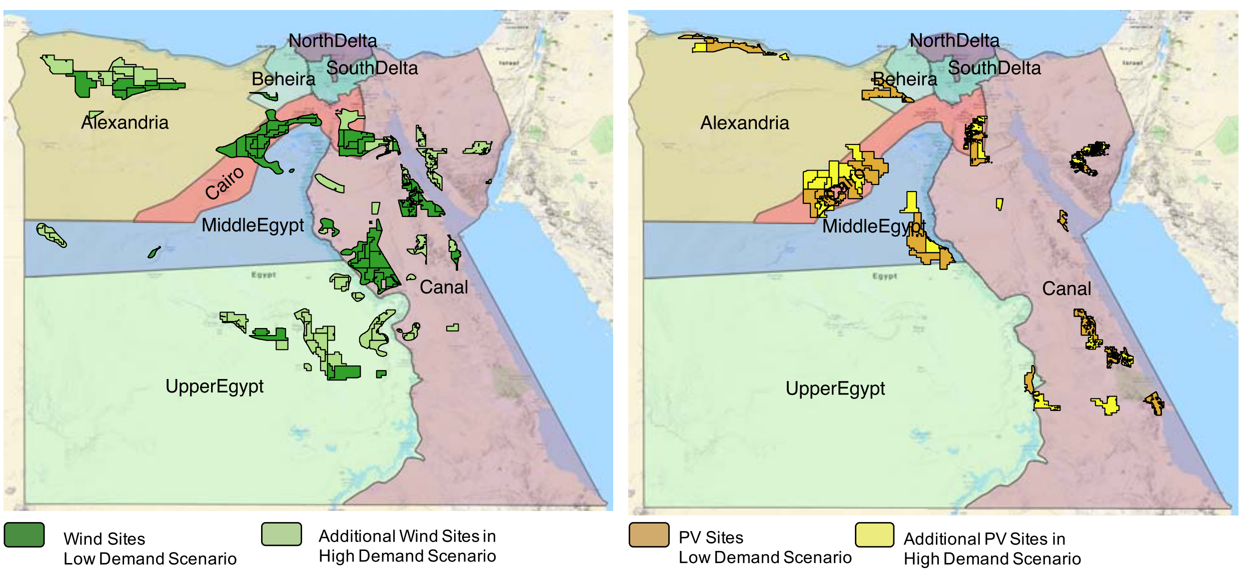


Figure 8: Development of candidate wind and PV sites in the case *Free RES*, source: own illustration

The number of sites developed across the time horizon of the model strongly depends on the imputed demand trajectory and whether the expansion of renewable technologies in constrained. While fuel costs have a limited effect on RES development, it is worth noting that in the *High Fuel* scenario a slight increase in the number of sites where deployment takes place is registered, even though in some cases the absolute generation capacity decreases. This stems from the greater diversification of site-specific deployment, as certain sites are only partially utilised. In comparison to the fuel costs, the demand trajectory has a much greater bearing on the development. Fig. 8 depicts the candidate wind and PV sites developed over the time horizon in the case *Free RES*. The exploitation of the candidate wind and PV sites in the scenarios subject to the case *RES Cap* are significantly fewer, as shown in Fig. 9.

While wind power is deployed relatively evenly throughout the country, locations for PV systems tend to be developed more in the northern part of the country, although locations in the south yield on average a higher output.

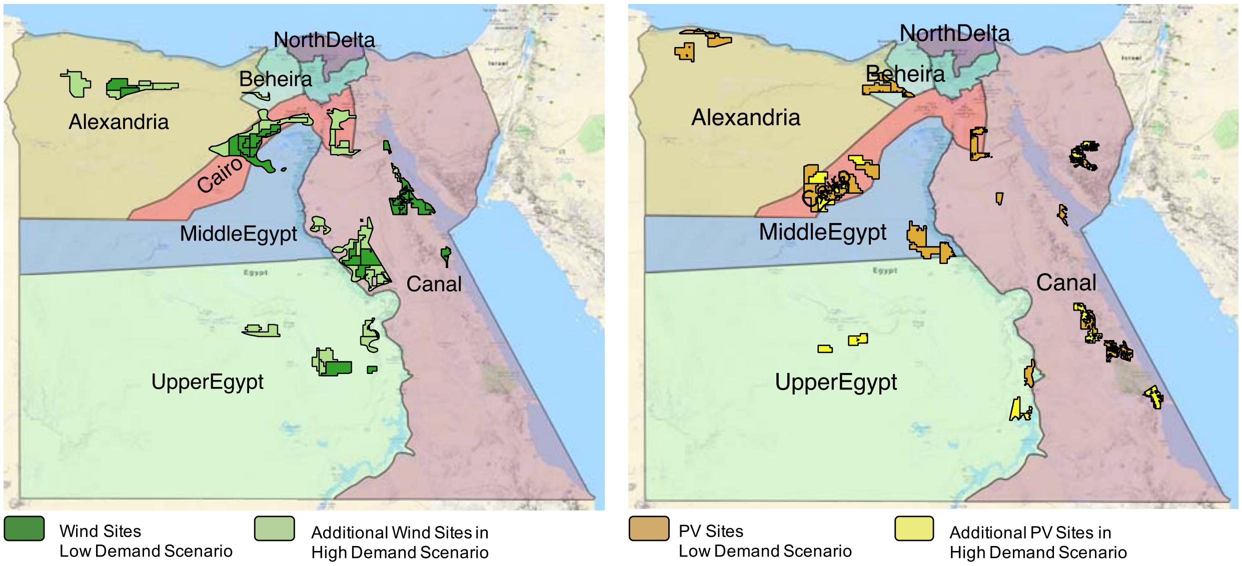
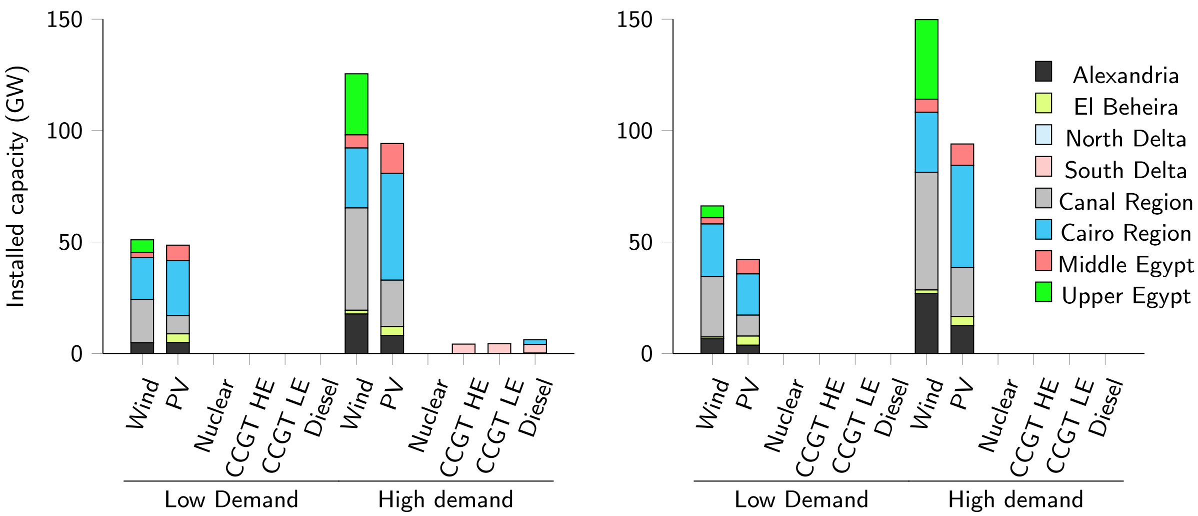


Figure 9: Development of candidate wind and PV sites in the case *RES Cap*, source: own illustration



(a) Added capacity (*Low Fuel*)

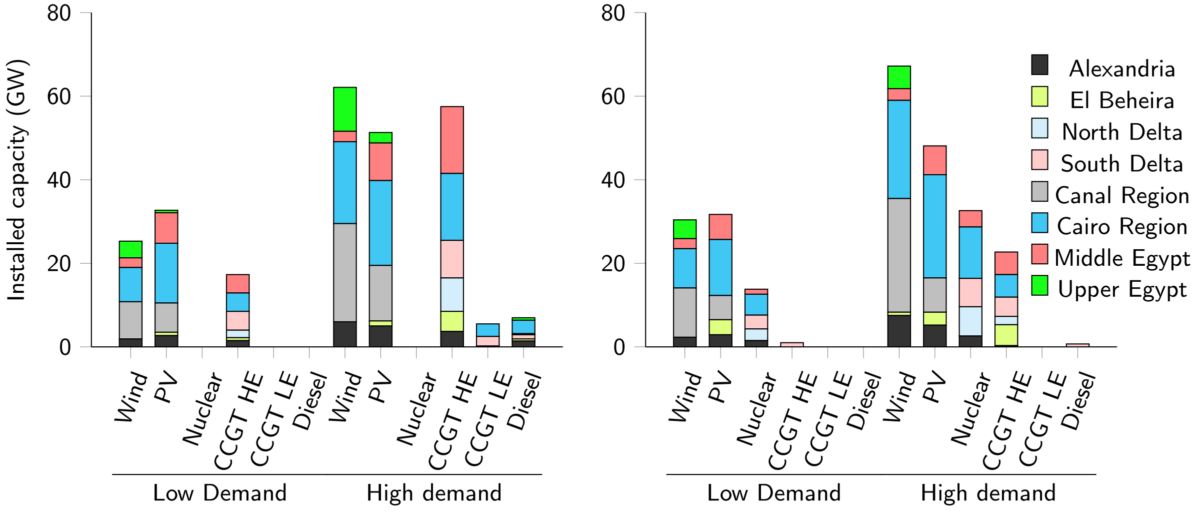
(b) Added capacity (*High Fuel*)

Figure 10: Added capacities in the case *Free RES*

For example, some PV plants in the south approach 2,500 full-load hours, almost 200 full-load hours more than a PV power plant situated on the Mediterranean coast. Due to the proximity to the load centres in the Nile Delta, however, it is economically advantageous to develop the somewhat less favourable candidate sites and thus avoid transmission losses and line costs. The locations allocated to the sub-region *Cairo* are primarily exploited.

In addition to renewable energies, conventional power plants are also built in selected sub-regions. The expansion of conventional capacities serves to primarily cover peak loads or are added in sub-regions where the potential of renewable technologies is low or non-existent. As shown in Fig. 10b, the residual demand can be covered by the existing power plant fleet in the *Low Dem* scenario. In the *High Fuel* scenario, additional wind power capacities are deployed instead of conventional capacities. Thus, as shown in Fig. 10a, no additional conventional power plants are installed even under the demand projections in the *High Dem* scenario.

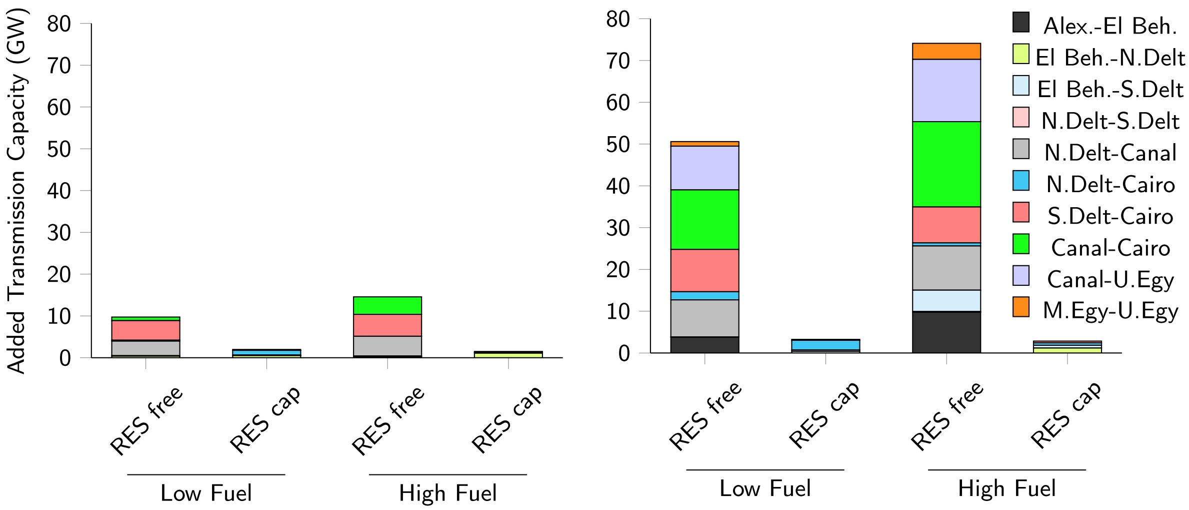
Under a restrained renewable deployment pathway (*RES Cap*), in accordance with the government's current tar-



(a) Added capacity (*Low Fuel*)

(b) Added capacity (*High Fuel*)

Figure 11: Added capacities in the case *RES Cap*



(a) Added capacity (*Low Dem*)

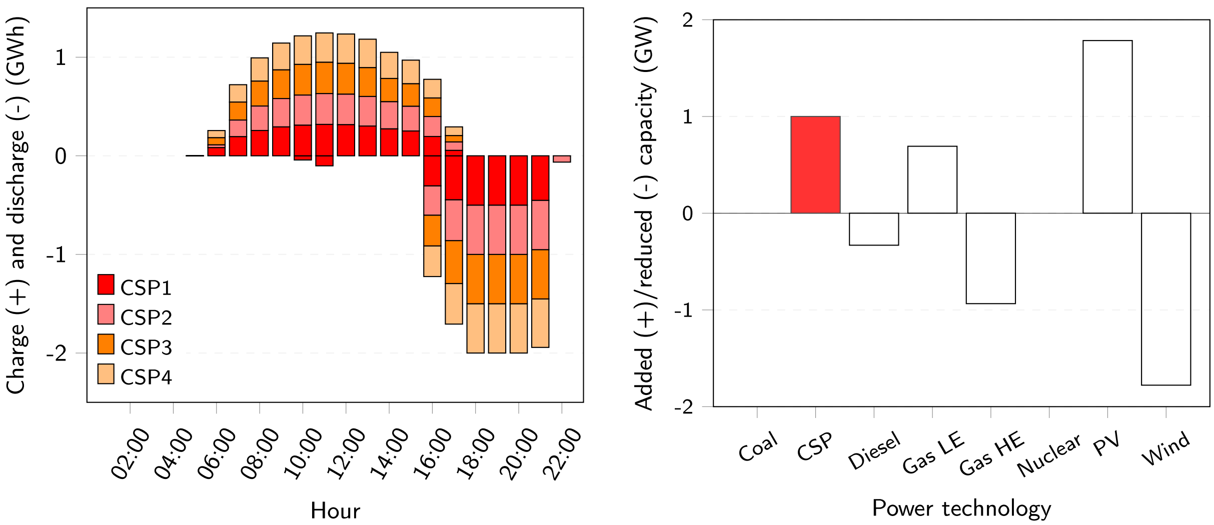
(b) Added capacity (*High Dem*)

Figure 12: Transmission capacity expansion in low and high demand scenarios

gets, significantly more conventional power capacity is required to serve the demand. These are primarily built in Cairo, Middle Egypt and Delta sub-regions. High-efficiency CCGT power plants constitute the greatest share of the conventional capacity added (Fig. 11a & 11b).

The exploitation of renewable resource potentials in areas at significant distances from urban centres leads to production deficits in some sub-regions, which must be covered by imports from sub-regions with electricity surpluses. This imbalance between sub-regions is further exacerbated with a high shares of renewable penetration.

In particular, the sub-regions Alexandria, Canal and Upper Egypt are characterised by surplus production. Electricity exchanged between the sub-regions in the final time interval (2038-2042) are displayed in Tables A.3 and A.4 in the appendix. To facilitate the delivery of the electricity to load centres a significant expansion of the capacity of the transmission grid is required. For the high demand and high fuel cost scenario transmission capacities between the sub-regions are expanded as shown in Fig. 12.



(a) CSP storage profile

(b) Δ in fleet with addition of 1 GW CSP

Figure 13: Impact of CSP capacity installation on the cost-optimal power fleet and operation profiles of candidate installations

6.3. Impact of CSP deployment

Although this study comes to the conclusion that CSP power plants are not part of a cost-optimal power fleet in any of the scenarios considered, other authors attribute great potential to this technology, e.g., [23]. Therefore, the effects of the deployment of CSP power plants on the dispatch and composition of the power fleet are discussed in more detail. Due to their heat storage capacity, CSP power plants can be utilised flexibly and thus can be deployed to cover peak loads or to compensate fluctuations in production in wind or PV power plants. To analyse this in the context of the Egyptian power system, CSP is exogenously introduced into the model. When determining the cost-optimal dispatch of the four most economically advantageous sites, the charging and discharging profiles, which are depicted in Fig. 13a, indicate that CSP is primarily dispatched in the evening hours to serve the respective daily demand peaks.

The deployment of CSP leads to a reduction in the utilisation of peak load power plants (diesel, combined cycle LE) and depending on the scenario, to a slightly increased expansion of base load power plants (combined cycle HE, nuclear power plants). In terms of renewable energy technologies, the use of CSP power plants leads to an increased expansion of PV power plants and a reduction in the wind power capacity installed (Fig. 13b).

For the installation, operation and maintenance of one gigawatt of installed CSP capacity, total costs of ca. USD 6.5 billion are incurred during the modelling period (2017-2042). Taking into account the corresponding savings obtained through its dispatch, the additional costs for the overall system range between USD 0.4 and 3.5 billion. This corresponds to additional annual costs of ca. USD 18 - 60 million per gigawatt of installed capacity.

6.4. Discussion of results

As decisions concerning the future development of the electricity sector in Egypt are made by government authorities and a pervasive market liberalisation is not planned in the near future, the central planner approach employed in the analysis seems suitable. The model, of course, abstracts from reality and exhibits several shortcomings. For instance, the model is not capable of offering insights into aspects related to security of supply. In particular, the feed-in profiles based on representative days are not suitable to capture extreme weather events. In the case of conventional power plants, neither reserve capacities nor ramp-up times are considered, which fails to capture existing inflexibilities in the system. Furthermore, the representation of the transmission network is coarse in nature and due to the absence of congestion within sub-regions, the model is incentivised to utilise remote renewable energy sites with favourable conditions to supply distant load centres. Especially in the sub-region Canal, the large north-south extension can lead to a distortion in the results. In contrast to the reference line costs used in the analysis, capital costs for transmission lines correspond to the respective voltage level. Lower transmission capacities would lead to significantly higher specific costs, which would affect the results rendered in the model. It should also be emphasised that urban centres were excluded as candidate sites for PV installations. However, the use of small-scale rooftop PV systems could significantly contribute to the local supply and have a strong impact on the results reported above.

Comparing the results of the analysis with similar studies of the future Egyptian power system, one key difference involves demand projections. Taliotis et al. [44] and Mondal et al. [28] forecast demand in 2040 at 691 TWh and 524 TWh, respectively, in the range between the high scenario of 918 TWh assumed in this paper and the baseline scenario with a low increase in demand of 434 TWh. The assumptions of Rady et al. [38] even assume a level as low as 350 TWh in 2040. Accordingly, capacity developments differ. However, all studies mentioned reach the conclusion that wind power should be utilised much more extensively in Egypt. CSP power plants have been considered to figure into the development of the power fleet, especially in somewhat older studies such as those by Kost [23] or Taliotis et al. [44], whereas in the paper at hand, similar to somewhat more recent studies by Rady et al. [38] or Mondal et al. [28], the technology does not appear to be viable for deployment in the mid-term. Utility-scale PV, on the other hand, is deployed extensively in the analysis. Its share in the power plant fleet is significantly higher than in the studies conducted by other authors. This is likely due to the differing costs and technical assumptions made about the reference technology. For instance, in the analysis, a single-axis tracking system was assumed for better use of the available solar potential, which is in line with current projects under construction. As it pertains to conventional power plant technologies, both Rady et al. [38] and Taliotis et al. [44] conclude that in terms of a cost-optimal power fleet development, coal-fired power plants are not economically viable. The authors' assessments also project gas-fired combined cycle power plants to exhibit the greatest potential for conventional technologies. However, the development of the gas price can significantly alter the results.

7. Summary and Outlook

The electricity sector in Egypt is facing major challenges. The population is growing and with increasing prosperity, per capita consumption is also growing steadily. In the past, the uptick in demand was primarily covered by natural gas capacities. Due to decreasing domestic production volumes, Egypt became dependent on gas imports in 2015. Although new gas deposits have been developed and Egypt is once again in a position to export natural gas, [35] points out that this could well be short-lived and that in the coming years export levels might experience a precipitous decline. Moreover, the established policy of fuel subsidies are increasingly burdening the national budget. The government is therefore pursuing a diversification strategy, which includes increasing the share of renewable energies to a total of 42% by 2035 while exploring the deployment of nuclear and coal-fired power plants.

To be able to evaluate the planned developments, a model-based analysis based on the open-source modelling framework OSyMOSYS was employed. The model examines the optimal capacity expansion of the power fleet up to the year 2042 under different scenarios. All existing Egyptian power plants and transmission network capacities were included in the model. Beyond the legacy capacities in the system, the potential additions of nuclear and coal-fired power plants were considered. In the case of renewable energy technologies, wind power turbines, utility-scale PV installations and CSP power plants at a total of 320 different locations were examined. For each of these sites, hourly feed-in profiles were generated based on ten years of weather data. In addition, the expansion of existing and new transmission lines between the individual sub-regions defined in the model was incorporated. Demand profiles were considered based on the construction of three seasonal representative weeks. The scenario framework applied includes uncertainties related to demand projections and reforms of fuel price subsidies as well as the level of ambition regarding the build-out of renewable energy capacities. The restrained development pathway is formulated in line with the government's current expansion targets.

The results obtained for the different scenarios considered highlight that the deployment of wind power and PV installations is preferable from an economic point of view and should be expanded to a much greater extent than currently planned by the government. Depending on the scenario, costs of ca. USD 67 billion can be saved over the entire period under consideration. Wind power should be deployed spatially throughout the country while the analysis indicates that from a system perspective PV should be installed at sites whose resource potential is less favourable, especially in the northern part of the country.

The expansion of conventional power plant capacities depends strongly on the price of natural gas. If prices remain low, combined cycle power plants will continue to be the preferred power plant technology in the future, alongside wind power and PV plants as mentioned above. Only in the scenarios where high gas prices are assumed and a restrained build-out of renewable energies is targeted, is it cost-optimal to invest in nuclear power plants. An optimal location for these would be in *Cairo* or the *Nile Delta* sub-region. The location in the *Alexandria* sub-region currently under consideration would not be optimal under the framework conditions of the model. In addition, nuclear power plants are only viable if used as baseload generation capacities and are not endowed with the flexibility to accommodate fluctuations in renewable energies. To cover peak loads, diesel generators are dispatched in some scenarios during a limited number of hours of the year. These are primarily installed in *Cairo* or the *Southern Delta* sub-region. Coal-fired power plants do not constitute part of the cost-optimal power plant fleet in any of the scenarios considered. The results thus raise questions as to the prudence of the government's plans to explore the utilisation of coal-fired power. Furthermore, the planned location in the sub-region *Canal* is not advisable due to the particularly favourable conditions for renewable energy technologies.

CSP power plants are also not deployed in any of the scenarios considered. A more detailed assessment of the utilisation of CSP, however, yields the insight that the additional costs of installation are partially offset by a reduction in fuel costs. Depending on the scenario, additional annual costs total between 18-60 USD per installed kilowatt of capacity. The results also indicate that CSP plants would in large part replace the dispatch of diesel generators when it comes to covering peak loads. The CSP plants would also lead to the expansion of PV capacities while significantly crowding out wind power investments.

The impacts on the transmission grid correlate positively with the share of variable renewable energies in the system. Thus, an ambitious expansion pathway would render substantial surpluses in the sub-regions of *Alexandria*, *Canal* and *Upper Egypt*, which must be exported to sub-regions with production deficits. This requires a substantial expansion of transmission capacities. Limiting the share of renewable energy leads to fewer disparities between sub-regions and thus less expansion of network capacities, such as those in the *Delta* sub-region.

In closing, the analysis conducted indicates from an economic point of view a more expansive deployment of wind and PV power installations is worth recommending, even when considering impacts on the transmission infrastructure. The research also suggests that adding coal-fired power plants is not economically rational. Solar thermal power plants are also not viable investments under the model conditions. However, they could contribute to decarbonisation efforts by offering tailored subsidies, as their flexibility would help substitute for particularly inefficient fossil-fuel technologies to cover peak demand levels.

Further research could extend the analysis by considering a more detailed representation of the power transmission network and its expansion as well as evaluating supply security by exploring inflexibilities in the power system and the impacts of uncertainties in the context of increased renewable energy penetration.

Acknowledgment

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

CRediT authorship contribution statement

Christoph Dallmann: Conceptualization, Methodology, Data curation, Software, Investigation, Writing- Original draft preparation, Visualization. **Matthew Schmidt:** Conceptualization, Methodology, Writing- Original draft preparation, Visualization. **Dominik Möst:** Supervision, Writing- Review.

A. Configuration of seasonal representative days

Based on the load profile forecasts for Egypt developed in Toktarova et al. [45] and applying a hierarchical clustering procedure from Kotzur et al. [24], three representative seasonal weeks with 168 hours, respectively, were derived for the years 2020, 2030 and 2040. The representative weeks derived were assigned to a season according to their chronological sequence in the year. The winter season comprises 21 weeks, a transitional season 14 weeks and the summer season 17 calendar weeks.

Demand is highest during the summer season and lowest in winter. This is attributed to the positive correlation between temperature and demand levels, in particular the extensive use of air conditioning systems [3]. In the course of each representative week, peak usage occurs in the evening hours with demand reaching its lowest levels overnight. Weekends are characterised by lower loads. Since the load profiles of individual weekdays and weekend days are almost indistinguishable, the respective day types are averaged together to create two representative days for each respective season. Based on the constructed load curves and the consumption shares of the individual sub-regions, a specific share of the total consumption for each representative hour of a modeling period is allocated to each sub-region. Considering three different seasons, two different types of days (weekday and weekend) with 24 hours each, the model consists of 144 time steps per model period. Since the model horizon includes 35 years and each model period includes five years, a total number of 1,008 time steps are considered across the entire modelling horizon.

B. Supplementary figures and tables

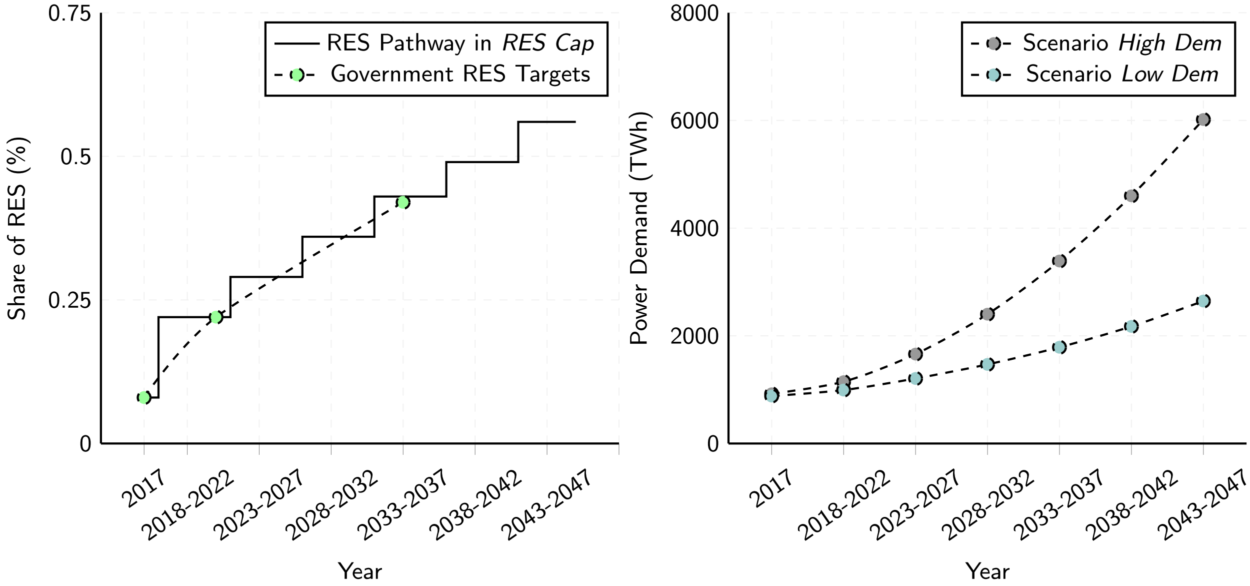
The appendix provides detailed tables and supplementary diagrams referenced but not contained in the preceding text.

Table A.1
Assumed fuel price development (USD/kWh$_{th}$) in scenarios *Fuel Low* and *Fuel High*; sources: World Bank [52], Massachusetts Institute of Technology (MIT) [26], Hussein et al. [18], Hanan [15], IEA [19], BAFA [1], Egyptian Natural Gas Holding Company [12]

	Low Fuel Scenario				*High Fuel Scenario*			
	Natural Gas	Diesel	Coal	Nuclear	Natural Gas	Diesel	Coal	Nuclear
2017	0.019	0.018	0.012	0.0062	0.036	0.018	0.012	0.0062
2022	0.021	0.034	0.012	0.0062	0.036	0.04	0.014	0.0062
2027	0.021	0.043	0.012	0.0062	0.036	0.047	0.016	0.0062
2032	0.021	0.043	0.012	0.0062	0.036	0.058	0.018	0.0062
2037	0.021	0.043	0.012	0.0062	0.036	0.069	0.019	0.0062
2042	0.021	0.043	0.012	0.0062	0.036	0.08	0.021	0.0062
2047	0.021	0.043	0.011	0.0062	0.036	0.091	0.023	0.0062

Table A.2
Techno-economic parameters of transmission lines, source: own calculations; Pletka et al. [36], World Bank [53]

Transmission line	Original Capacity (MW)	Distance (Miles)	Capital Costs (USD/MW)	Losses (%)
Alexandria - El Beheira	1,500	142	240,000	4.2
El Beheira – North Delta	0	60	110,500	4.2
El Beheira – South Delta	400	38	75,800	4.2
El Beheira – Cairo	1,500	80	142,100	4.2
North Delta – South Delta	400	73	131,100	4.2
North Delta - Canal	800	130	221,000	4.2
North Delta – Cairo	400	65	118,400	4.2
South Delta – Cairo	400	50	94,700	4.2
Canal – Cairo	1,500	90	157,900	4.2
Canal – Middle Egypt	1,500	155	260,500	4.2
Canal – Upper Egypt	0	125	213,100	4.2
Cairo – Middle Egypt	3,00	125	213,100	4.2
Middle Egypt – Upper Egypt	3,00	325	528,900	4.2



(a) RES targets and expansion pathways in *RES Cap* (b) Power demand scenarios

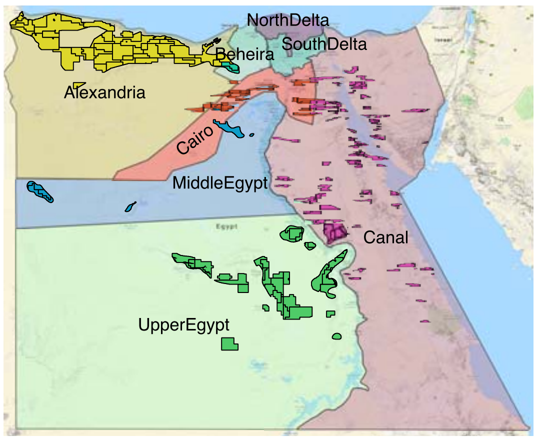
Figure A.1: *RES Cap* expansion pathway and *Low Dem* and *High Dem* power demand scenarios; sources: own calculations, [20, 34]

Table A.3
Power exchange between the sub-regions in the case of high demand (*High Dem*), high fuel costs (*High Fuel*) & no RES cap (*RES free*) in 2042, source: own calculations

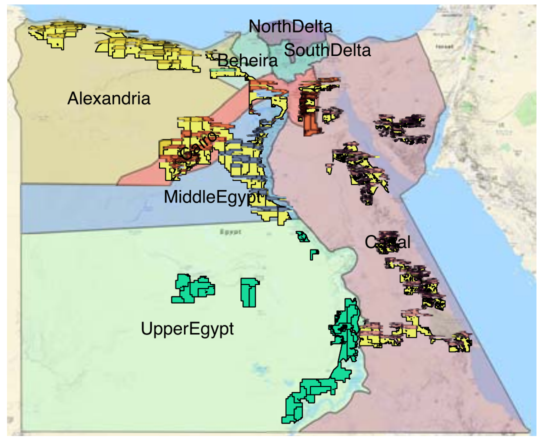
Sub-region	Export (GWh)	Import (GWh)	Net exchange (GWh)
Alexandria	68,748	0	68,748
El Beheira	31,574	70,008	-38,434
North Delta	2,641	78,678	-76,037
South Delta	92	80,131	-80,038
Canal	174,460	45,245	129,215
Cairo	52,280	97,217	-44,937
Middle Egypt	1,401	46,790	-45,389
Upper Egypt	86,872	0	86,872

Table A.4
Power exchange between the sub-regions in the case of high demand (*High Dem*), high fuel costs (*High Fuel*) & RES cap (*RES cap*) in 2042, source: own calculations

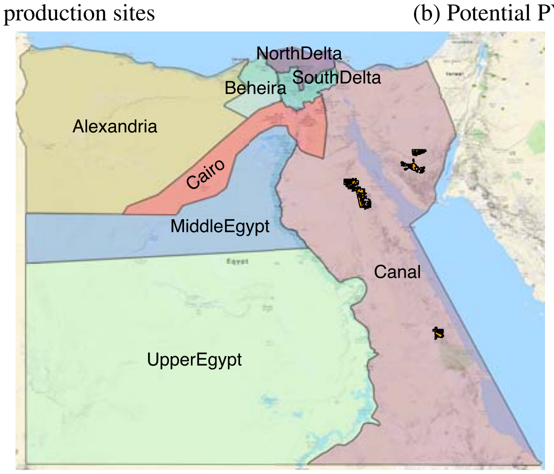
Sub-region	Export (GWh)	Import (GWh)	Net exchange (GWh)
Alexandria	4,689	502	4,187
El Beheira	3,401	15,942	-12,540
North Delta	5,526	7,656	-2,130
South Delta	5,352	2,634	2,718
Canal	12,110	2,213	9,897
Cairo	10,480	7,428	3,052
Middle Egypt	2,621	18,509	-15,888
Upper Egypt	11,762	1,058	10,704



(a) Potential wind production sites



(b) Potential PV production sites



(c) Potential CSP production sites

Figure A.2: Site and technology-specific RES potentials considered in the model

C. Model Description

The following appendix provides an overview of the sets and parameters used in the model. The equations that have been altered from or added to the original OSeMOSYS model formulation for purposes of the analysis are also depicted. The complete model code used in the paper can be accessed at: `https://doi.org/10.5281/zenodo.4437681`

C.1. List of Sets and Parameters

Set Name (abbreviation)	Set Description
Dailytimebracket (lh)	Allows for day/night differentiation, i.e., splits a single day into brackets
Daytype (ld)	Allows to model different days like weekday/weekend
Fuel (f)	Fuels enter or leave technologies
Mode of Operation (m)	Technologies might operate in different modes
Region (r)	The different (aggregated) regions considered
Season (ls)	Allows a differentiation for yearly seasons (e.g., summer/winter)
Storage (s)	The set of different storage technologies
Technology (t)	Everything that processes energy in any form is considered a technology
Timeslice (l)	Timeslices are a combination of ls, ld and lh
Year (y)	The set of the different modeled years

Parameter Name	Parameter Description
$AccumulatedAnnualDemand_{r,f,y}$	Amount of demand that can be satisfied at any time of the year, not time-slice dependent
$AvailabilityFactor_{r,t,y}$	Maximum time a technology may run in a year
$CapacityFactor_{l,t,r,y}$	Maximum time a technology may run in a time-slice
$CapacityOfOneTechnologyUnit_{r,t,y}$	Capacity of one new unit of a technology
$CapacityToActivityUnit_{r,t}$	Conversion factor of capacities [GW] into activity [PJ]. Assumes provision of 1 [GW] over one year.
$CapitalCostStorage_{r,s,y}$	Capital costs for storage technologies
$CapitalCost_{r,t,y}$	Capital cost for all technologies
$Conversionlh_{l,lh}$	Assigns DailyTimeBracket to time-slice
$Conversionld_{l,ld}$	Assigns DayType to time-slice
$Conversionls_{l,ls}$	Assigns Season to time-slice
$DaySplit_{lh,y}$	Length of a DailyTimeBracket in one day as a fraction of the year
$DaysInDayType_{ld,ls,y}$	Amount of days per week in which a DayType occurs
$DiscountRate_{r}$	Interest rate used for purposes of discounting
$FixedCost_{r,t,y}$	Fixed operational costs for a technology
$InputActivityRatio_{f,m,r,t,y}$	Describes along with OutputActivityRatio the efficiency of a technology
$OperationalLife_{r,t}$	Operational lifetime of all technologies
$OperationalLifeStorage_{r,s,y}$	Operational lifetime of storage technologies
$OutputActivityRatio_{f,m,r,t,y}$	Describes along with InputActivityRatio the efficiency of a technology
$RETagFuel_{f,r,y}$	Designates fuels that do not produce emissions
$RETagTechnology_{r,t,y}$	Designates technologies with fluctuating feed-in
$REMaxProductionTarget_{r,y}$	Upper limit on renewable technologies with fluctuating feed- in
$ResidualCapacity_{r,t,y}$	Capacities that exist in addition to the endogenously built capacities
$SpecifiedAnnualDemand_{f,r,y}$	Annual demand of fuels which are time-slice dependent.
$SpecifiedDemandProfile_{f,r,t,y}$	Assigns a share of SpecifiedAnnualDemand to the different time-slices
$StorageLevelStart_{r,s}$	Amount of stored energy at the beginning of the modeling period
$StorageMaxChargeRate_{r,s}$	Maximum amount a storage can be charged within one hour
$StorageMaxDischargeRate_{r,s}$	Maximum amount a storage can be discharged within one hour
$TechnologyFromStorage_{m,r,s,t}$	Technologies that can use a fuel from a storage
$TechnologyToStorage_{m,r,s,t}$	Technologies that can provide a fuel to a storage.
$TotalAnnualMaxCapacityInvestment_{r,t,y}$	Maximum amount of investments into a technology in a year
$TotalAnnualMinCapacityInvestment_{r,t,y}$	Minimum amount of investments into a technology in a year
$TotalAnnualMaxCapacity_{r,t,y}$	Maximum amount of used capacity in a year
$TotalAnnualMinCapacity_{r,t,y}$	Minimum amount of used capacity in a year
$TotalTechnologyAnnualActivityLowerLimit_{r,t,y}$	Minimum amount of activity in a year
$TotalTechnologyAnnualActivityUpperLimit_{r,t,y}$	Maximum amount of activity in a year
$TotalTechnologyModelPeriodActivityLowerLimit_{r,t}$	Minimum amount of activity over model period
$TotalTechnologyModelPeriodActivityUpperLimit_{r,t}$	Maximum amount of activity over model period
$TradeRoute_{f,r,rr,y}$	Designates possible trade routes between regions.
$VariableCost_{m,r,t,y}$	Variable operational costs for using a technology
$YearSplit_{l,y}$	Share of a time-slice in one year

C.2. Algebraic Formulation of Altered/Added Model Equations in OSeMOSYS

As the model horizon consists of five year periods, the cost components of the objective function are discounted accordingly:

$$VariableOperatingCosts_{r,t,y,l} = \sum_{m} RateofActivity_{r,t,y,l,m} * VariableCost_{r,t,y,m} \;\; \forall\, r,t,y \tag{3}$$

$$PeriodFixedOperatingCost_{r,t,y} = TotalCapacityAnnual_{r,t,y} * FixedCost_{r,t,y} * 5 \;\; \forall\, r,t,y \tag{4}$$

$$\begin{aligned} DiscountedOperatingCost_{r,t,y} &= (PeriodFixedOperatingCost_{r,t,y} + VariableOperatingCosts_{r,t,y})/5 \\ &* \sum_{i=0}^{4} \frac{1}{DiscountRate_{r} + 1^{(y-min(y))*5+0.5+i}} \;\; \forall\, r,t,y \end{aligned} \tag{5}$$

$$\begin{aligned} DiscountedCapitalInvestment_{r,t,y} &= CapitalCost_{r,t,y} * NewCapacity_{r,t,y}) \\ &* \frac{1}{DiscountRate_{r} + 1^{(y-min(y))*5}} \;\; \forall\, r,t,y \end{aligned} \tag{6}$$

$$\begin{aligned} SalvageValue_{r,t,y} &= NewCapacity_{r,t,y} * CapitalCost_{r,t,y}) * \frac{1 - max(p) - p + 1}{OperationalLife_{r,t}} \\ &\forall\, r,t,y \;:\; (p + OperationalLife_{t} - 1) \geq max(p) \end{aligned} \tag{7}$$

$$DiscountedSalvageValue_{r,t,y} = \frac{SalvageValue_{r,t,y}}{1 + DiscountRate_{r}^{1+(max(y)-min(y))*5}} \;\; \forall\, r,t,y \tag{8}$$

In order to reduce computational burden, the following constraints are added to the CSP storage, which entails that the storage must be emptied by the end of each $Daytype(ld)$:

$$StorageLevelDayTypeFinish_{r,s,ls,ls,y} = 0 \;\; \forall\, r,s,p \tag{9}$$

$$StorageLevelDayTypeStart_{r,s,ls,ls,y} = 0 \;\; \forall\, r,s,p \tag{10}$$

For purposes of restraining the capacity expansion of renewable energy technologies, the following constraint is implemented:

$$\begin{aligned} &\sum_{t}\sum_{f}\sum_{l}\sum_{m} RateOfActivity_{r,t,y,l,m} * OutputActivityRatio_{r,t,y,f,m} * YearSplit_{l,y} * RETagFuel_{r,y,f} \\ &\leq REMaxProductionTarget_{r,y} * \sum_{f}\sum_{l} RateofActivity_{r,t,y,l,m} * OutputActivityRatio_{r,t,y,f,m} \\ &* YearSplit_{l,y} * RETagFuel_{r,y,f} \;\; \forall\, r,y \,:\, OutputActivityRatio \neq 0 \end{aligned} \tag{11}$$

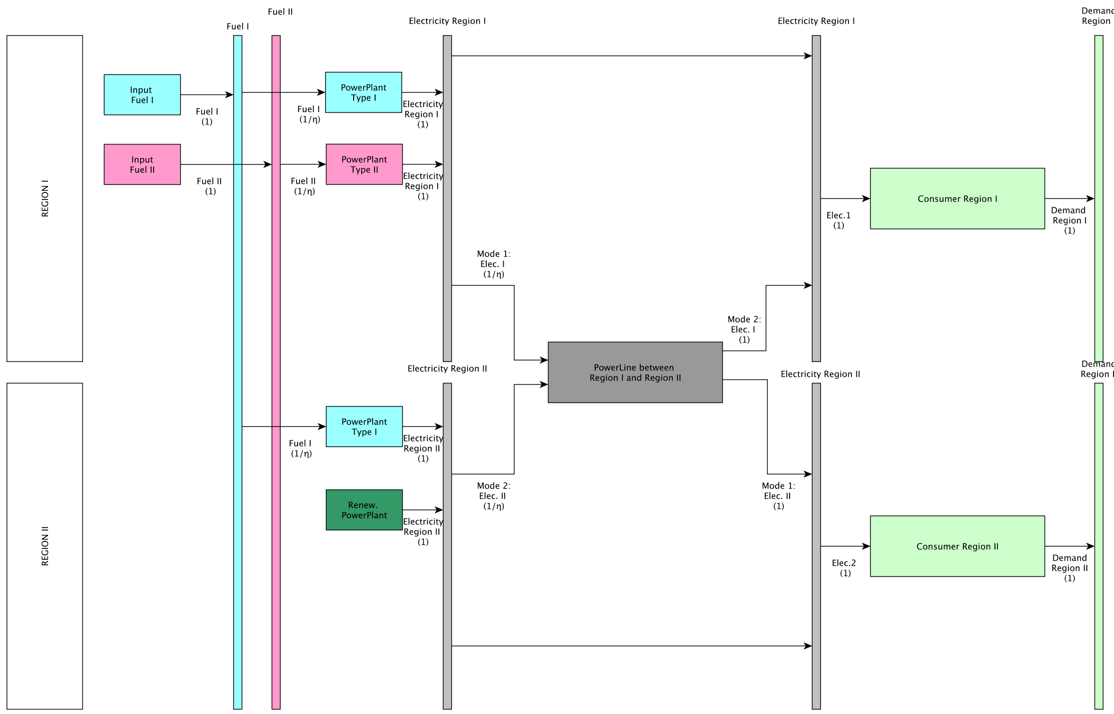


Figure A.3: Schematic representation of the model-specific mapping of sub-regional outputs via the designation of stock and flow variables

References

[1] BAFA, 2019. Drittlandskohlepreis. Technical Report. Bundesamt für Wirtschaft und Ausfuhrkontrolle. Berlin. URL: https://www.bafa.de/DE/Energie/Rohstoffe/Drittlandskohlepreis/drittlandskohlepreis{_}node.html.

[2] Bellini, E., 2019. Jordan suspends renewables auctions, new licenses for projects over 1 MW. URL: https://www.pv-magazine.com/2019/01/28/jordan-suspends-renewables-auctions-new-licenses-for-projects-over-1-mw/.

[3] Beshara, A., 2008. Energy Efficiency in the Buildings Sector : Egyptian Experience.

[4] Burandt, T., Xiong, B., Löffler, K., Oei, P.Y., 2019. Decarbonizing China's energy system – Modeling the transformation of the electricity, transportation, heat, and industrial sectors. Applied Energy doi:10.1016/j.apenergy.2019.113820.

[5] Cohen, T., Rabinovitch, A., 2018. Egyptian firm to buy $15 billion of Israeli natural gas. URL: https://de.reuters.com/article/us-israel-egypt-natgas/egyptian-firm-to-buy-15-billion-of-israeli-natural-gas-idUSKCN1G31BK.

[6] Dhakouani, A., Gardumi, F., Znouda, E., Bouden, C., Howells, M., 2017. Long-term optimisation model of the Tunisian power system. Energy 141, 550–562. doi:10.1016/j.energy.2017.09.093.

[7] Eberhard, A., Gratwick, K., 2007. From state to market and back again: Egypt's experiment with independent power projects. Energy 32, 724–738. doi:10.1016/j.energy.2006.05.003.

[8] EEHC, 2015. Ministry of Electricity & Energy 2015, The Annual Report of 2014/2015 2015. URL: http://www.moee.gov.eg/english_new/EEHC_Rep/2014-2015en.pdf.

[9] EEHC, 2016. Egyptian Electricity Holding Company Annual Report 2015/2016. Technical Report. Arab Republic of Egypt Ministry of Electricity and Renweable Energy.

[10] EEHC, 2017. Egyptian Electricity Holding Company Annual Report 2016/2017. Technical Report. Arab Republic of Egypt Ministry of Electricity and Renweable Energy. URL: http://www.moee.gov.eg/english_new/EEHC_Rep/2016-2017en.pdf.

[11] EEHC, 2019. Annual Report 2017/18. Technical Report 9. doi:10.1017/CBO9781107415324.004.

[12] Egyptian Natural Gas Holding Company, 2018. Annual Report 20017-2018. Technical Report 9. URL: http://www.egas.com.eg/docs/pdf/EGASAnnualReport2018EN.pdf, doi:10.1017/CBO9781107415324.004.

[13] EIA, 2016. Capital Cost Estimates for Utility Scale Electricity Generating Plants. US Department of Energy, Energy Information Administration. US Department of Energy, Energy Information Administration. , 141URL: https://www.eia.gov/analysis/studies/powerplants/capitalcost/pdf/capcost_assumption.pdf.

[14] European Commission Joint Research Centre (JRC), 2019. Photovoltaic Geographical Information System. URL: https://re.jrc.ec.europa.eu/pvg_tools/es/tools.html.

[15] Hanan, M., 2019. Egypt lifts fuel subsidies, completely announces new prices. URL: https://www.egypttoday.com/Article/1/72448/Egypt-lifts-fuel-subsidies-completely-announces-new-prices.

[16] Heaps, C., 2016. Long-range Energy Alternatives Planning (LEAP) system. Stockholm Environment Institute. URL: https://www.energycommunity.org/default.asp?action=license.

[17] Howells, M., Rogner, H., Strachan, N., Heaps, C., Huntington, H., Kypreos, S., Hughes, A., Silveira, S., DeCarolis, J., Bazillian, M., Roehrl, A., 2011. OSeMOSYS: The Open Source Energy Modeling System: An introduction to its ethos, structure and development. Energy Policy 39, 5850–5870. doi:10.1016/j.enpol.2011.06.033.

[18] Hussein, N.S., Abokersh, M., Kost, C., Schlegl, T., 2016. Electricity Cost From Renewable Energy Technologies in Egypt. Technical Report December. Frauenhofer Institute for Solar Energy Systems ISE. URL: https://www.ise.fraunhofer.de/content/dam/ise/en/documents/publications/studies/Dec2016_Fraunhofer-ISE_LCOE_Renewable_Energy_Technologies_EN_v20_ns.pdf.

[19] IEA, 2019. Energy prices and taxes. First quarter 2019 ed., International Energy Agency, Paris.

[20] IRENA, 2018. International Renewable Energy Agency. Renewable Power Generation Costs in 2017. URL: https://www.irena.org/publications/2018/Jan/Renewable-power-generation-costs-in-2017.

[21] IRENA, LBNL, 2015. Africa Renewable Energy Zones. Technical Report.

[22] Kosmopoulos, P., Kazadzis, S., El-Askary, H., 2018. The Solar Atlas of Egypt. Technical Report. URL: http://geocradle.eu/, doi:10.1017/CBO9781107415324.004, arXiv:arXiv:1011.1669v3.

[23] Kost, C., 2015. Renewable energy in North Africa: Modeling of future electricity scenarios and the impact on manufacturing and employment. Fraunhofer Verlag. URL: http://publica.fraunhofer.de/documents/N-356362.html.

[24] Kotzur, L., Markewitz, P., Robinius, M., Stolten, D., 2018. Impact of different time series aggregation methods on optimal energy system design. Renewable Energy 117, 474–487. URL: https://www.sciencedirect.com/science/article/pii/S0960148117309783, doi:10.1016/J.RENENE.2017.10.017.

[25] Lopion, P., Markewitz, P., Stolten, D., Robinius, M., 2019. Cost uncertainties in energy system optimization models: A quadratic programming approach for avoiding penny switching effects. Energies 12. doi:10.3390/en12204006.

[26] Massachusetts Institute of Technology (MIT), 2018. The Future of Nuclear Energy in a Carbon-Constrained World. Technical Report. Massachusetts Institute of Technology. Cambridge (MA). URL: http://energy.mit.edu/wp-content/uploads/2018/09/The-Future-of-Nuclear-Energy-in-a-Carbon-Constrained-World.pdf, doi:10.1021/es50002a013.

[27] Middle East Eye, 2019. Egypt lowers fuel prices following wave of protests. URL: https://www.middleeasteye.net/news/egypt-lowers-fuel-prices-following-spat-protests.

[28] Mondal, M.A.H., Ringler, C., Al-Riffai, P., Eldidi, H., Breisinger, C., Wiebelt, M., 2019a. Long-term optimization of Egypt's power sector: Policy implications. Energy 166, 1063–1073. URL: https://doi.org/10.1016/j.energy.2018.10.158, doi:10.1016/j.energy.2018.10.158.

[29] Mondal, M.A.H., Ringler, C., Al-Riffai, P., Eldidi, H., Breisinger, C., Wiebelt, M., 2019b. Long-term optimization of Egypt's power sector: Policy implications. Energy 166, 1063–1073. URL: https://doi.org/10.1016/j.energy.2018.10.158, doi:10.1016/j.energy.2018.10.158.

[30] Mortensen, N., Said Said, U., Badger, J., 2006. Wind atlas for egypt, in: Proceedings of the Third Middle East-North Africa Renewable Energy Conference (on CD-ROM).

[31] Moura, G., Howells, M., Legey, L., 2015. A Brazilian Perspective on Power Systems Investment and Integration in South America – using SAMBA (South America Model Base). Review 85. doi:10.20955/r.85.67.

[32] New & Renewable Energy Authority Egypt, 2016. Strategic Environmental & Social Assessment : Final Report. Technical Report February. URL: https://www.miga.org/sites/default/files/archive/Documents/SPGDisclosures/BenbanStrategicEnvironmentalandSocialAssessment-Feb2016-FinalReport.pdf.

[33] Niu, S., Jia, Y., Wang, W., He, R., Hu, L., Liu, Y., 2013. Electricity consumption and human development level: A comparative analysis based on panel data for 50 countries. International Journal of Electrical Power & Energy Systems 53, 338–347. URL: https://www.sciencedirect.com/science/article/abs/pii/S0142061513002263?via{%}3Dihub, doi:10.1016/J.IJEPES.2013.05.024.

[34] NREA, 2018. Renewable Energy Annual Report , 3–37.

[35] Ouki, M., 2018. Egypt - a return to a balanced gas market?:. Technical Report. Oxford Institute for Energy Studies. URL: https://www.oxfordenergy.org/publications/egypt-return-balanced-gas-market/, doi:10.26889/9781784671129.

[36] Pletka, R., Khangura, J., Rawlines, A., Waldren, E., Wilson, D., 2014. Capital Costs for Transmission and Substations. Western Electricity Coordinating Council , 35.

[37] Pothecary, S., 2016. Egypt agrees to international arbitration for PV projects but slashes FITs. URL: https://www.pv-magazine.com/2016/09/07/egypt-agrees-to-international-arbitration-for-pv-projects-but-slashes-fits_100026027/.

[38] Rady, Y.Y., Rocco, M.V., Serag-Eldin, M.A., Colombo, E., 2018. Modelling for power generation sector in Developing Countries: Case of Egypt. Energy 165, 198–209. URL: https://doi.org/10.1016/j.energy.2018.09.089, doi:10.1016/j.energy.2018.09.089.

[39] Reuters, 2019. Egypt lowers fuel prices for first time as part of IMF-backed pricing mechanism. URL: http://news.trust.org/item/20191004073715-pe9ql/.

[40] ROSATOM, 2019. Egypt's Dabaa nuclear plant granted site permit. URL: http://www.rosatom.ru/en/press-centre/industry-in-media/egypt-s-dabaa-nuclear-plant-granted-site-permit/?sphrase_id=913741.

[41] Shouman, E.R., El Shenawy, E.T., Khattab, N.M., 2016. Market financial analysis and cost performance for photovoltaic technology through international and national perspective with case study for Egypt. Renewable and Sustainable Energy Reviews 57, 540–549. URL: http://dx.doi.org/10.1016/j.rser.2015.12.074, doi:10.1016/j.rser.2015.12.074.

[42] Staffell, I., Pfenninger, S., 2016. Using bias-corrected reanalysis to simulate current and future wind power output. Energy 114, 1224–1239. URL: http://dx.doi.org/10.1016/j.energy.2016.08.068, doi:10.1016/j.energy.2016.08.068.

[43] Taliotis, C., Rogner, H., Ressl, S., Howells, M., Gardumi, F., 2017. Natural gas in Cyprus: The need for consolidated planning. Energy Policy 107, 197–209. doi:10.1016/j.enpol.2017.04.047.

[44] Taliotis, C., Shivakumar, A., Ramos, E., Howells, M., Mentis, D., Sridharan, V., Broad, O., Mofor, L., 2016. An indicative analysis of invest-

ment opportunities in the African electricity supply sector - Using TEMBA (The Electricity Model Base for Africa). Energy for Sustainable Development 31, 50–66. URL: http://dx.doi.org/10.1016/j.esd.2015.12.001, doi:10.1016/j.esd.2015.12.001.

[45] Toktarova, A., Gruber, L., Hlusiak, M., Bogdanov, D., Breyer, C., 2019. Long term load projection in high resolution for all countries globally. International Journal of Electrical Power and Energy Systems 111, 160–181. URL: https://doi.org/10.1016/j.ijepes.2019.03.055, doi:10.1016/j.ijepes.2019.03.055.

[46] Trieb, F., Schillings, C., Pregger, T., O'Sullivan, M., 2012. Solar electricity imports from the Middle East and North Africa to Europe. Energy Policy 42, 341–353. URL: https://www.sciencedirect.com/science/article/abs/pii/S030142151100989X, doi:10.1016/J.ENPOL.2011.11.091.

[47] United Nations, Department of Economic and Social Affairs, P.D.., 2019. Probabilistic Population Projections Rev. 1 based on the World Population. Technical Report.

[48] Urban, F., Benders, R.M., Moll, H.C., 2007. Modelling energy systems for developing countries. Energy Policy 35, 3473–3482. URL: https://doi.org/10.1016/j.enpol.2006.12.025, doi:10.1016/j.enpol.2006.12.025.

[49] Verme, P., 2017. Subsidy Reforms in the Middle East and North Africa Region: A Review. doi:10.1007/978-3-319-52926-4_1.

[50] Welsch, M., Hermann, S., Howells, M., Rogner, H.H., Young, C., Ramma, I., Bazilian, M., Fischer, G., Alfstad, T., Gielen, D., Le Blanc, D., Röhrl, A., Steduto, P., Müller, A., 2014. Adding value with CLEWS - Modelling the energy system and its interdependencies for Mauritius. Applied Energy 113, 1434–1445. URL: http://dx.doi.org/10.1016/j.apenergy.2013.08.083, doi:10.1016/j.apenergy.2013.08.083.

[51] Willis, B., 2018. Building Benban: Inside Egypt´s 1.6gw Solar Park. PV Tech URL: https://www.ibvogt.com/home/building-benban.html.

[52] World Bank, 2014. International Bank for Reconstruction and Development Project Appraisal Document on a Proposed Loan to the Arab Republic of Egypt for an Egypt Household Natural Gas Connection Project URL: http://documents.worldbank.org/curated/en/903171468024860655/pdf/PAD9350PAD0P14010Box385274B00OUO090.pdf.

[53] World Bank, 2017. Electricity Transmission Network Egypt. URL: https://datacatalog.worldbank.org/dataset/egypt-electricity-transmission-network-2017.

[54] World Bank, 2019. World Development Indicators. Technical Report.

[55] World Nuclear Association, 2019. Decommissioning Nuclear Facilities. URL: https://www.world-nuclear.org/information-library/nuclear-fuel-cycle/nuclear-wastes/decommissioning-nuclear-facilities.aspx.

Highlights

~~MENA countries between~~ Between path dependencies and renewable energy potentials: A case study of the Egyptian power system

Christoph Dallmann,Matthew Schmidt,Dominik Möst

- Cost-optimal future development of the Egyptian power plant fleet
- Inclusion of renewable potentials for 320 sites across Egypt
- Regional power production disparities and implications for the domestic transmission network

~~MENA countries between~~ Between path dependencies and renewable energy potentials: A case study of the Egyptian power system

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ARTICLE INFO

Keywords:
Renewable energy
MENA countries
Egyptian power system
OseMOSYS
Energy systems modelling
Energy transition pathways

ABSTRACT

Egypt's power system is facing major changes. Rising demand, scarcity of fossil resources and the falling capital costs of solar and wind energy technologies pose the potential to fundamentally remake the national power fleet. Against this backdrop, the paper at hand investigates potential pathways of the domestic power system with a particular focus on regional deployment and associated impacts on the transmission network. To this end, the open-source modelling framework OSeMOSYS was adapted and deployed. The analysis evaluates eight different sub-regions and renewable potentials for 320 sites across Egypt. The study concludes that wind and PV installations prove to be cost-competitive and capable of shouldering a large share of projected demand growth, while their regional deployment should take required grid investments into consideration. The results also indicate that a restrained expansion of renewable energy technologies targeted by the government proves to be more costly than a more aggressive deployment pathway.

1. Introduction

The electricity sector in Egypt is facing major challenges. Due to a growing population and rising per capita income, the country's electricity demand is rapidly increasing [47, 54]. While substantial investments in new power plant capacities have made it possible to reduce the incidence of large-scale power outages, an increasing shortage of access to fossil energy resources and ageing infrastructure continue to pose problems for the domestic electricity supply [9, 20, 41]. Today the country primarily relies on natural gas as a feedstock for power generation. While the country's natural gas reserves are technically large enough to cover domestic demand, in recent years, the production volume in some gas fields has declined as Egypt's demand has continued to rise. Since 2015, the former gas exporting country has been forced to buy more expensive natural gas on the world market or to switch to other sources. Recently developed gas fields in the Mediterranean Sea, some of which are significant in size, are not expected to keep pace with long-term forecasts of domestic energy demand growth [35]. The energy sector in Egypt is strongly regulated. Extensive subsidies to the energy sector have led to distorted market prices, inefficient consumption levels and heavy burdens on the national budget. Since 2014, the subsidies have been gradually reduced, but this has partly led to public opposition and protests in an already politically tense environment [27, 39].

Considering these recent developments and the forecasted growth in power demand, Egypt urgently needs to extensively expand its power plant fleet in the most cost-efficient manner possible. Renewable energy technologies that exploit the domestic endowment of wind and solar resources figure to play a decisive role in this respect, as conditions are very favourable for their deployment by global standards [30, 22]. The government has therefore set forth plans to increase the share of renewable energies in the power mix to 42% by 2042. In order to analyse possible development paths of the Egyptian electricity sector and to assess the cost-efficiency of the government's plans, the paper at hand develops and deploys a comprehensive power market model tailored to the Egyptian power system based on the open-source modelling framework OSeMOSYS [17]. Eight sub-regions with 429 capacity expansion options are examined. In terms of renewable technologies, site-specific hourly feed-in profiles are utilised, offering a high-resolution assessment of potential locations for wind and solar capacity build-out. Disaggregating the country into various sub-regions, potential impacts on the transmission grid and expansion requirements are analysed. In line with government plans, the cost-efficiency of introducing coal-fired or nuclear capacities is also evaluated in a scenario framework. Using the

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model setup, the analysis addresses questions concerning the cost-efficient composition of the domestic power fleet in the year 2042 with a particular focus on the spatial allocation of renewable energy capacities as well as providing a broad estimate of the impact on the transmission network of an increased penetration of renewable energy in the power system.

The remainder of the paper is organised as follows: Section 2 provides a brief overview of the current structure of the Egyptian power fleet and the respective expansion targets set by the government. Section 3 examines the extant literature on model-based analyses of the future of the Egyptian power system and highlights the contribution of the paper at hand. Section 4 details the input data of the model and its structure as well as the associated scenario framework. Section 5 reports selected results of the scenarios considered. Section 6 discusses the limitations of the model and compares the reported results with similar published studies. Section 7 closes the paper with a summary of the analysis performed and provides a brief outlook on potential extensions of the research.

2. Current structure of the Egyptian power fleet and expansion targets

2.1. Structural characteristics of the Eyptian power system

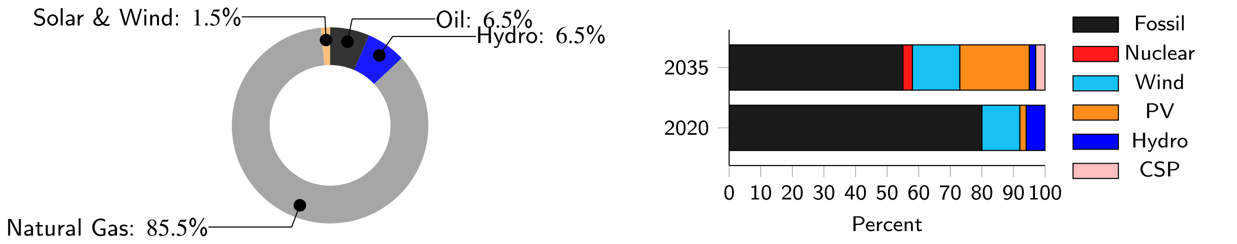
The electricity sector in Egypt is strongly regulated and mostly owned by the government. Although the various sub-sectors of generation, transmission and distribution have been separated in organisational terms over the years, they still continue to operate under the auspices of the Ministry of Electricity and Energy (MOEE). Utilities are run by distribution network operators. Due to their monopoly position, they are subject to regulation. The conventional fleet of the electricity industry is managed by the Egyptian Electricity Holding Company (EEHC). It comprises five regionally separate generation companies and one generation company responsible for the country's hydropower plants. The New and Renewable Energy Authority (NREA) is responsible for the build-out of renewable energy technologies.

With a market share of 94%, the state-owned power companies produce the overwhelming majority of domestic electricity (EEHC, 2019). The remainder is generated by independent power producers (IPPs) or companies operating under the Build, Own, Operate & Transmit principle (BOOT). These are contractually obligated to transfer all production assets to the respective government authority after a period of use of 20 years [7]. With the progressive opening of the market, a significantly higher share of non-governmental entities are anticipated to be actively involved in the future. In its current composition, the electricity sector is dominated by fossil energy carriers. As depicted in Fig. 1a, 85.5% of electricity was generated from natural gas, 6.5% from oil products, 6.5% from hydropower and a mere 1.5% from solar and wind power in 2018. This underscores the current dependency of the domestic power system on natural gas as a fuel source.

The transmission system operator is responsible for the operation and development of the high and extra-high voltage transmission network in the country. Due to the concentration of the population along the Nile, the transmission grid is characterised by a well-developed north-south connection and does not exhibit an extensively branched structure. Although there are connections to the neighbouring countries of Jordan and Libya, as well as a planned power line to Saudi Arabia, cross-border trade is virtually non-existent with a total market share of ca. 0.1%. Large industrial consumers can purchase electricity at the high or extra-high voltage level directly from the grid operator. In total, these purchases comprise a share of ca. 15% of total market volume [11].

The vast majority of power is acquired by the nine distribution system operators and sold at the distribution grid level. Since about half of the total demand is consumed by private households, they have a major influence on the daily load curve. The peak of a typical load curve is therefore in the evening hours when most people return from work. Due to the extensive use of air conditioning systems, electricity demand and temperature are positively correlated. This contributes significantly to the sharp increase in demand during the hot summer months.

In order to deploy a optimisation model based on a cost-minimisation approach and thus facilitate the assessment of the current energy policy outlook of the Egyptian government against a cost-optimal generation portfolio, the analysis abstracts from the current realities of the Egyptian electricity sector and assumes a perfectly competitive market environment.



(a) Share of primary energy sources

(b) Generation capacity expansion targets (in %)

Figure 1: Share of primary energy sources in Egypt's power generation mix in 2018 and the energy-specific generation capacity expansion of the MOEE, source: [11, 34]

2.2. Expansion targets for the Egyptian power fleet

The development of Egypt's power fleet is organised by the Ministry of Electricity and Energy on the basis of five-year plans. The seventh five-year plan ended in 2017. In order to promote self-sufficiency and in so doing prevent potential supply bottlenecks, the government agency has been pursuing a diversification strategy. One component of this strategy involves the increased exploitation of domestic renewable resources. Sites for renewable technologies have been identified and tendering rounds have been organised. In total, projects for wind power plants amounting to 2.3 gigawatts (GW) and photovoltaic (PV) plants amounting to 3.3 GW are currently in the process of being built [32, 34]. According to the government's long-term targets, as illustrated in Fig. 1b, the share of renewable energies is set to increase to 20% by 2022 and 42% by 2035.

Due to the steep increase in demand forecasted, an additional build-out of conventional power capacities is planned. Thus, the ninth five-year plan envisages the construction of new fossil-based generation capacities including coal-fired power plants and in accordance with its long-term diversification strategy even a nuclear power plant [11, 40].

3. Literature overview and research contribution

3.1. Energy system modelling and the global South

Energy system modelling has increasingly been used to identify cost-efficient expansion pathways in individual countries and regions. Most of the models are developed in industrialised countries and are only conditionally suitable for use in countries of the global South due to the differing requirements [48]. To better meet the requirements of these countries, the MARKAL modelling platform was developed on behalf of the International Energy Agency (IEA). MARKAL, like its successor TIMES, has been used worldwide for numerous studies. Mondal et al. [28], for example, investigate potential natural gas shortages and greenhouse gas emissions in Egypt. Although MARKAL or TIMES are free of charge to use, their usage requires access to proprietary software, e.g. programming language and solver.

This can constitute a particular obstacle for ~~guuunancially~~ financially disadvantaged countries or institutions. For this reason, the Open Source Energy Modelling System (OSeMOSYS) and the Long Range Energy Alternatives Planning System (LEAP) based on it were developed under the direction of the Royal Institute of Technology Stockholm (KTH) [17]. LEAP, on the other hand, is only freely available for institutions of the global South [16]. To this date, the modelling frameworks have been deployed in the development of a large number of energy system models. In preparation for the Conference on Sustainable Development (Rio+20), the United Nations modelled interactions between global climate, land, energy and water systems in the CLEWS model based on OSeMOSYS [50]. With respect to individual countries and regions, applications include, e.g., network expansion and generation capacity planning in South America [31], the development of pathways for greenhouse gas reductions in China [4] and the assessment of renewable energy potentials in Tunisia [6].

3.2. Overview of assessments of future pathways of the Eyptian power system

OSeMOSYS also formed the basis for the TEMBA project, in which the development of the power sector of Egypt and 45 other African countries is investigated. The study's conclusions suggest that the countries could profit from further intertwining their power systems and becoming more interconnected. The study assumes a slowly growing demand and an increase in generation capacities in Egypt to ca. 200 gigawatts (GW) with a demand of approx. 690

terawatt hours (TWh) by 2040 [43]. Using the *RESilion* model, Kost [23] evaluates the development of the power system in North African countries and an enhanced interconnection with Europe. A significant increase in the renewable share in the electricity mix of up to 72% is identified as most cost-efficient. Concentrated Solar Power (CSP) power plants play a significant role in the future power provision, comprising a share of 33% in the region's future power mix. Egypt is divided into three load zones in the study. A total of 14 specific regions are considered for renewable capacity additions. In a study conducted by Mondal et al. [28], power demand is assumed to increase to 524 TWh by 2040. Depending on the share of renewable technologies, between 91 and 120 GW of generation capacity is required to meet load requirements. Wind power, in particular, but also in some cases PV power plants, play a prominent role in achieving the emission reduction targets. CSP power plants hardly figure into the future power fleet. In Rady et al. [38], Egypt is also considered as a single region. Similar to this study, the analysis of the Egyptian electricity sector is conducted with a model based on OSeMOSYS. The availability of renewable energy technologies was determined on the basis of annual averages. With an increase in demand up to 350 TWh in 2040, an expansion of 110 GW of capacity is projected. To ensure a cost-efficient build-out, the expansion of wind power capacities is particularly recommended. Coal-fired, nuclear and CSP power plants are also considered as potential investment options, but are not added in any of the scenarios considered.

3.3. Research contribution

In comparison to previous work on the future development of the Egyptian power system, the paper at hand employs an enhanced spatial and temporal resolution. In addition, the study is carried out with updated cost forecasts. In comparison with somewhat older studies such as Kost [23], capital costs of PV and CSP power plants have developed much differently than previously assumed. By looking at the various sub-regions within the country, ~~regions~~ sub-regions with differing consumption profiles are examined in detail, unlike in the studies by Taliotis et al. [44], Rady et al. [38], Mondal et al. [28]. This allows for a more detailed assessment of the spatial allocation of future power plants and their potentials as well as associated transmission network expansion requirements. For renewable power technologies, spatial locations and capacity installations are derived. This is performed on the basis of individual hourly feed-in values and thus also in much greater detail than in the above-mentioned studies. This work, therefore, enables not only the identification of general nation-wide trends, but also the delineation of specific developments for individual ~~regions~~ sub-regions in the country.

4. Model set-up and adaptations

The model deployed for the following analysis is largely based on the model code of OSeMOSYS~~.~~ 2017_11_08. Based on various technology and site-specific techno-economic data parameters, the cost-efficient deployment of generation and transmission capacity and the dispatch of electricity to serve an inelastic demand is computed over the time horizon of the model. Model results offer insights into the cost-optimal composition of the domestic power fleet, the transmission network, the corresponding shares of renewable energy technologies and fossil resource requirements. The model is a bottom-up model that is sector-specific and thus does not represent macroeconomic relationships and feedback loops. In terms of the representation of the power system, it should be noted that for the research at hand, technology-specific emissions are not considered. Furthermore, reserve capacities and ancillary services are not represented in the model. Each individual sub-region is modelled as a single node, meaning transmission costs or congestion within sub-regions are neglected. Transmission capacities between the sub-regions are modelled as net transfer capacities.

In order to reduce computational burden, three representative seasonal weeks were derived in an hourly resolution and then recombined to form work and weekend days. The year 2017 is adopted as the base year for the analysis. Investment periods are modelled in five year time steps. This was done by making corresponding adjustments to the ~~objective function of the~~ OSeMOSYS code. The five-year investment periods correspond to the Egyptian government's five-year plans for the development of the electricity system. In order to be able to assess medium-term developments, the model horizon runs 25 years to the year 2042. To deal with the end-of-horizon problem of energy system investment models, the model is run for an additional investment period. The output pertaining to the last period is not reported.

The objective function minimises the net present cost of the power system to serve an inelastic demand. This is

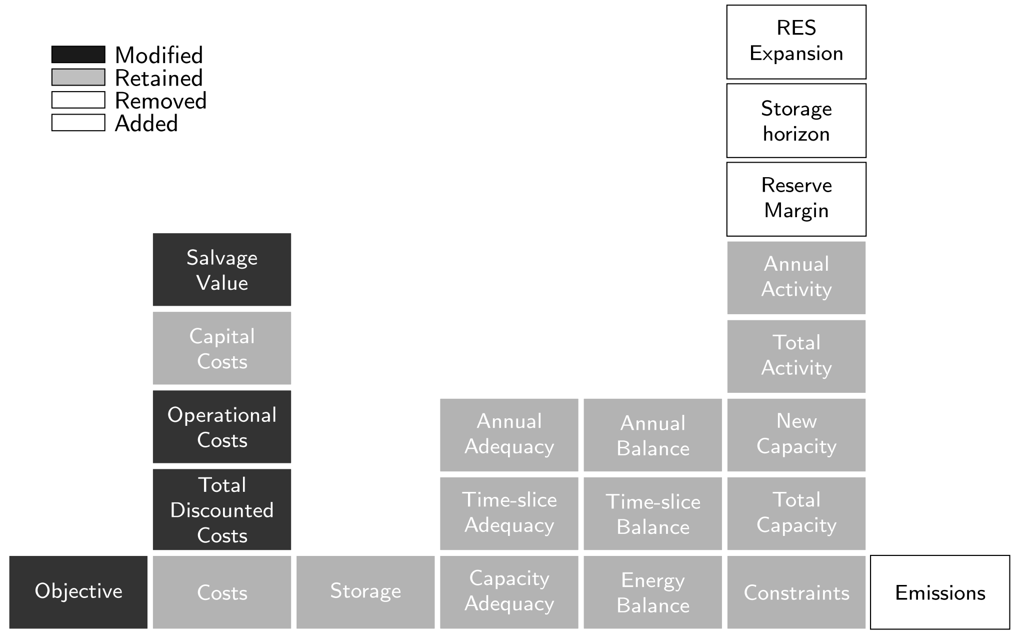


Figure 2: Adaptations made to the base structure of OSeMOSYS, source: based on Howells et al. [17]

done by summing up the total discounted costs of each *technology (t)* in each model ~~*period*~~ *year* (~~*p*~~*y*):

$$minimize \sum_{r} \sum_{t} \sum_{\cancel{p}y} TotalDiscountedCosts_{\cancel{t,p}r,t,y} \tag{1}$$

Technologies (t) comprise all elements that are capable of processing or generating the variable fuel such as a primary energy carrier or electricity. In order to reduce the computational ~~effort~~ burden of the model, ~~the region function of OSEMOSYS was omitted and an allocation of the~~ Egypt constitutes a single region for the built-in region set. The sub-regions of Egypt are mapped to specific stock and flow variables ~~was assigned to the different subregions by means of indices~~as is shown in Fig. A.3 in the appendix.

Costs comprise those associated with the construction ($\cancel{DiscountedCapitalInvestment_{t,p}}$ $DiscountedCapitalInvestment_{r,t,y}$) of new technology capacities and their corresponding dispatch ($\cancel{DiscountedOperatingCost_{t,p}}$ $DiscountedOperatingCost_{r,t,y}$):

$$\begin{aligned} TotalDiscountedCosts_{r,t,y} &= DiscountedOperatingCost_{r,t,y} \\ &+ DiscountedCapitalInvestment_{r,t,y} \\ &- DiscountedSalvageValue_{r,t,y} \qquad \forall\, t, y \end{aligned} \tag{2}$$

These parameters are specified for each respective year ~~, technology, and region~~ (y) and technology (t) considered in the model. The investment in and dispatch of a non-storage technology is associated with capital costs, which are annuitised according to the capacity installed, as well as operational costs for each technology, which are composed of variable and fixed cost shares. Annual operating costs are discounted with respect to the base year to make costs comparable. Furthermore, the salvage value ($\cancel{DiscountedSalvageValue_{t,p}}$ $DiscountedSalvageValue_{r,t,y}$) of the respective technologies that have exceeded their operational life or have been replaced is incorporated in the objective function. The salvage value is based on the ~~year of installment~~commissioning year, operational lifetime and imputed discount rate. A linear depreciation method is applied.

As displayed in Fig. 2, the base structure of OSeMOSYS has been slightly modified for the analysis conducted in the paper.

- **CSP storage**: Unlike pumped storage power plants, heat generated in CSP power plants cannot be stored for an unlimited period of time. Due to the simplified assumption that the storages must be emptied at the end of each representative day type, i.e., at the transition from work day to weekend day or vice versa, balancing of the storage level over the entire modelling period is no longer necessary, which considerably reduces the computational burden of the model. This is applicable irrespective of the specific season.
- **RES expansion cap**: A further adaptation made to the model involves the exogenously determined minimum shares of RES capacity. An additional constraint which applies both to the flows, whose share is to be determined, and the corresponding technologies is introduced into the model.

5. Data input and scenario framework

5.1. Configuration of sub-regions and seasonal representative days

The model distinguishes between eight sub-regions, which are based on the network areas of the distribution system operators. Their service areas define the respective model ~~regions~~ sub-regions as depicted in Fig. 3. Northern and southern network areas around Cairo are combined into one sub-region. Historical data indicate that the distribution of total national demand amongst the network areas has remained relatively constant in recent years [8, 9, 10, 11]. The entire country has access to electricity and the level of urbanization has held steady at around 45% for the past decade [33]. For the analysis, therefore, the distribution of total demand between the sub-regions is assumed to remain constant over the modelling horizon.

The availability of renewable energy sources is subject to temporal variability. It is therefore prudent to consider temporal fluctuations in their generation output as well as the temporal characteristics of domestic load profiles. In order to reduce computational burden while accounting for seasonal and hourly fluctuations, representative days are constructed based on the load profile forecasts for Egypt developed in Toktarova et al. [45] by applying a hierarchical clustering procedure from Kotzur et al. [24] (see Appendix A for a more elaborate explanation).

5.2. Specification of renewable energy sites and potentials

In order to provide for a more disaggregated assessment of renewable energy expansion pathways in Egypt, the research conducted makes use of site and technology-specific potentials reported in the Multi-criteria Analysis for Planning Renewable Energy (MapRE) project. This study identifies and evaluates concrete sites for wind, PV and solar thermal technologies in a large number of African countries based on certain sustainability criteria related to cost-efficiency as well as social and environmental impacts. Using geodata provided by governmental and non-governmental organisations potential areas were determined by using thresholds or exclusion criteria like settlements or infrastructurally developed areas. The potential areas were divided into zones vary in size between 30 km^2 and 1,000 km^2 by the extent of spatial homogeneity in resource quality [21].

Using the tool published by MapRE, the attributes of the individual zones are recalculated. While the geodata from MapRE were used, investment and operating cost assumptions are updated in accordance with recent technical and economic developments. In addition to technical capacity and production potential based on weather data, other factors relevant to the choice of location are identified and evaluated. With a weighting of 50%, the levelized cost of electricity (LCOE) is given the greatest consideration. The distance to load centers is included in the evaluation with 15% and the transmission connection, population density and competing site usage with 10%, respectively. The last criterion considered is road access, which is attributed a weight of 5%.

The potential sites are assigned to the Egyptian sub-regions and integrated into the model. The exact number of potential sites considered is determined by repeated model runs until either the potential of a sub-region is exhausted or additional locations do not alter the results within the period under consideration. In total, a number of 165 wind sites, 150 PV sites and five CSP sites are assessed in the analysis (see Fig. A.2 in the appendix).

5.3. Power plant technologies

The expansion of the various power plant technologies depends largely on availabilities and the development of economic parameters. Due to the wide variety of data assumptions used in the literature, fuel prices and cost data vary depending on the source used. A large share of the data used is sourced from Hussein et al. [18]. In the case of coal-fired and nuclear power plants, assumptions are taken from other sources [13, 26]. Due to repeated attacks on pipeline infrastructure in the past as well as legal irregularities in tenders for large-scale PV plants, investors demand considerable risk premiums [5, 37]. Based on the work of Hussein et al. [18], an average weighted cost of capital (WACC) of 10% is assumed. All calculations were made in US-Dollar and an inflation rate of 1% is used.

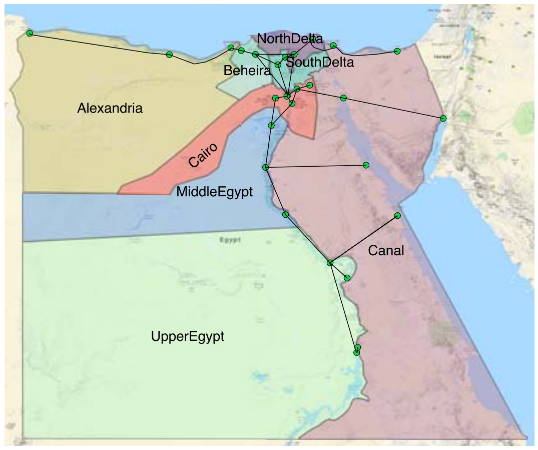


Figure 3: Regional representation of Egypt based on network areas of distribution system with simplified representation of transmission grid

5.3.1. Conventional power fleet

As displayed in Fig. 1a, the current conventional power fleet is primarily comprised of natural gas-fired power plants, including gas turbines, steam turbines and combined cycle power plants. A total of ca. 51 GW of natural gas-based power plants were in operation in 2017. While recent builds achieve overall efficiencies of up to 55 %, a share of older power plants dating back to the 1980s are still in operation, some of which operate with significantly poorer efficiency factors [11].

Diesel generators are characterised by high operational flexibility and low investment costs. However, fuel costs are significantly higher than other technologies. In Egypt, they are therefore used either as reserve capacity in case of power outages, to cover peak loads or in island operation. However, as grid expansion progresses, an increasing number of remote locations have been connected to the grid and existing diesel generators are no longer needed to cover base loads. Currently, a total of 600 MW in grid operation and 185 MW in island operation are installed in Egypt (EEHC, 2019).

As previously stated, the Egyptian government is currently pursuing plans to diversify its power plant fleet. This includes both plans to build a coal-fired power plant as well as well as explore the utilisation of nuclear power. To assess the cost efficiency of these plans, both technologies are integrated into the model as investment options. All relevant techno-economic parameters for the conventional power technologies are listed in Table 1.

Table 1
Techno-economic parameters of new-build conventional power plant technologies, source: [13, 18, 26, 55]

Technology	Overnight capital costs (USD/kW)	Fixed costs (USD/kW)	Variable costs (USD/MWh)	Efficiency factor (%)	Lifetime (years)
Existing (NG-based)	-	22	20	specific	30
CCGT (high)	1,050	22	20	55	30
CCGT (low)	750	22	20	45	30
Diesel	160	30	4.6	35	30
Hard coal	3,636	42	46	39	40
Nuclear	4,850	-	15.1	43	40

5.3.2. Renewable energy technologies

The production of renewable energy technologies is highly weather-dependent. Therefore, site and technology-specific capacity factors are derived.

Wind energy capacity: The evaluation of site conditions indicates that for most sites in Egypt class III turbines are most suitable. A Vestas V150 wind turbine with a capacity of 4.5 MW and a hub height of 145 metres was employed as the reference turbine. Respective cost parameters were sourced from Hussein et al. [18]. In order to render site-specific feed-in profiles, capacity factors were constructed using simulations of the hourly power output as in Staffell and Pfenninger [42]. The simulated hourly capacity factors of the reference plant at the respective sites were averaged over a period of ten years (2007-2016). The hourly feed-in values were then converted to conform to the representative days by applying a hierarchical clustering algorithm. The production profiles of the representative days is largely dependent on the distance from the coast. While coastal locations exhibit ~~an evenly production output~~steady generation levels, sites in the interior of the country are characterised by day-night variations.

PV capacity: Desert makes up a large part of the territory of Egypt. These areas are characterised by high solar irradiation and are also neither populated nor otherwise used, making them ideal locations for utility-scale PV plants. As a note, distributed behind-the-meter PV installations are not considered in the analysis conducted. One example of such a power plant is the Benban solar park. The solar power plant, which is currently under construction, will be the largest contiguous PV plant in the world with 1.8 GW of installed peak capacity at the time of completion [32]. In the model, it constitutes the reference power plant for future projects. To improve the capacity factor at the location, plans foresee the deployment of a single-axis tracking system [51].Based on investment costs of USD 1.35 million/MWp in 2016, Hussein et al. [18] projects a cost reduction to USD 1.08 million/MWp by 2020, falling further to USD 0.79 million/MWp by 2035. The hourly capacity factors for the individual sites were derived using simulated production profiles over the period from 2007-2016. The hourly capacity factors were subsequently transformed into representative seasonal days as per the process for the capacity factors of wind generation. Due to the higher levels of irradiation in the south of the country, larger yields are generated than on the Mediterranean coast, especially in the winter months.

CSP capacity: The prospect of exploiting the solar resources in the desert areas of MENA regions to deploy significant capacities of CSP power plants has long been the topic of energy policy discussions [46, 23]. In particular, the ability to integrate high temperature heat storage to temporally shift production, affording it baseload properties, constitutes a significant advantage over other renewable technologies. The resource potential, however, has failed to materialise in Egypt as currently no significant CSP power plants have been installed to date. Due to limited installed capacity worldwide, its technical development has yet to progress the likes of other RES technologies and capital costs remain relatively high [20]. The most widespread type of construction is one that consists of a solar collector made up of parabolic mirrors and a steam turbine to generate electricity. As this technology continues to develop, Hussein et al. [18] assume a cost reduction of ca. USD 1 million/MW to USD 4.2 million/MW between 2016 and 2035. This forms the basis for the cost assumptions applied in the model analysis.

Unlike the capacity factors derived for wind and PV sites, the output of CSP sites is based on the site-specific capacity and annual power output determined in the MapRE project (see Sec. 5.2). The output is distributed across the year according to the respective DNI values over a ten year period from 2007-2016 [14]. The specific cost assumptions made for the respective RES technologies are provided in Table 2.

Table 2
Economic parameters of new-build renewable energy technologies, source: [18]

Technology	Overnight capital costs (USD/kW)	Fixed costs (USD/kW)	Variable costs (USD/MWh)	Lifetime (years)
Wind turbines	1,350	0	18	20
Utility-scale PV (base year)	1,350	24	18	25
CSP plant (base year)	5,225	22	20	30

5.3.3. Transmission network

As explained above, OSeMOSYS is in its basic structure a market model, in which the transmission network is not explicitly represented. It does, however, provide for a simplified representation of transmission capacities between separate ~~regions~~sub-regions. As the cost of infrastructure expansion measures could be an inhibiting factor for integrating high penetration levels of RES, as recent examples in countries, e.g. Jordan, where the tendering of RES projects was halted due concerns over the state of the electrical grid, investigating broad impacts on the transmission network is important [2].

Based on geodata of the current transmission grid, the line distances between existing substations were derived and used as a basis for determining net transfer capacities [53]. In the simplified network representation, transit transmission lines across certain sub-regions are included. Candidate capacities are added between the El Beheira and North Delta sub-regions as well as between Canal and Upper Egypt. Transmission capacities of existing lines as well as the capital costs for candidate connections were determined using Pletka et al. [36]. As a reference, the costs of constructing a 500 kV single line with a maximum transmission capacity of 1,500 MW were used. In line with the linear optimisation approach, incremental extensions of candidate connections are permissible. The respective techno-economic parameters employed for the transmission network can be found in Table A.2.

5.4. Scenario framework

In order to investigate and compare various pathways the power system in Egypt could potentially take as well as represent inherent uncertainties, a scenario framework is adopted. The framework includes three sets of drivers including future demand growth, the subsidisation of fuel prices and the restrictive nature of RES expansion. A graphical representation of the scenario framework is displayed in Fig. 4.

- **Demand growth**: Power demand in Egypt has been growing steadily. This can be attributed on the one hand to a rapidly growing population and on the other to rising per capita income [47, 54]. Future projections of demand growth are, however, subject to uncertainty. Demand forecasts in the literature adopt different assumptions. For example, IRENA [20] assumes a complete correlation of economic growth and energy demand. A stable growth rate of 4% per year is assumed. This would correspond to an increase in demand of up to ca. 434 TWh by 2040. This trajectory was taken as the basis for the scenario *Low Dem*. However, if the average increase in consumption in recent years is taken as a basis for the projection, an annual increase of ca. 7.4% is expected, which corresponds to a total demand increase to 940 TWh by 2040. This trajectory is assumed in the scenario *High Dem*. The demand ~~scenarios are depited~~ trajectories used reflect the broad range of demand forecasts for Egypt employed in the extant literature (cf. [44, 38, 29]. It should be noted that the demand is modelled at an aggregate level, i.e., individual demand sectors are not explicitly considered, since the focus of the paper lies in evaluating impacts at a systems level. The demand scenarios are depicted in Fig. A.1b in the appendix.

- **Fuel prices and subsidy reforms**
  In order to analyse the influence of changes in fuel costs, especially considering the established policy of heavy subsidisation and current reforms being undertaken, two scenarios are considered for the respective energy sources [49]. The scenario sets consist of a low and high price development. As the primary energy source in the current electricity mix, natural gas can currently only be substituted to a limited extent. Supply costs therefore have a direct influence on system costs. In addition, the government has been engaged in cutting subsidies for natural gas [35]. With this in mind, the low price scenario is based on the assumption that fuel costs will initially rise due to a rollback of subsidies. The assumption is made that in the long-term Egypt will be able to secure natural gas at the price of recently contracted gas from Israel. For the high price scenario, a figure for the opportunity costs of export losses due to government subsidies is assumed [52]. Price assumptions for the other relevant fossil fuels are provided in Table A.1 in the appendix.

- **RES expansion**: Due to the penny-switching nature of linear optimisation models, i.e., a complete switch to other technologies through marginal variations in the corresponding investment costs, the increasingly favourable conditions for the deployment of RES technologies in Egypt can lead to an expansion of these technologies that in light of production capacity and technical restrictions is unrealistic [25]. Furthermore, considering potential challenges with respect to the grid infrastructure as well as issues related to supply security, it is safe to assume that these concerns are likely to curb the pace at which RES expansion is feasible. Thus, two scenarios are contrasted to compare the economic implications of a restrained build-out of renewable energy capacities. In the first, *Free RES*, the cost-optimal expansion of capacity without an exogenous limitation is considered. The alternative expansion scenario, *RES Cap* introduces a constraint on the renewable share of the total electricity mix according to the government's current policy targets. The envisaged targets for the years 2022 and 2035 are adopted as the reference expansion pathway [34]. This corresponds to an increase of 7% in each modelling period. The expansion pathway assumed in the case *RES Cap* is depicted in Fig. A.1a in the appendix.

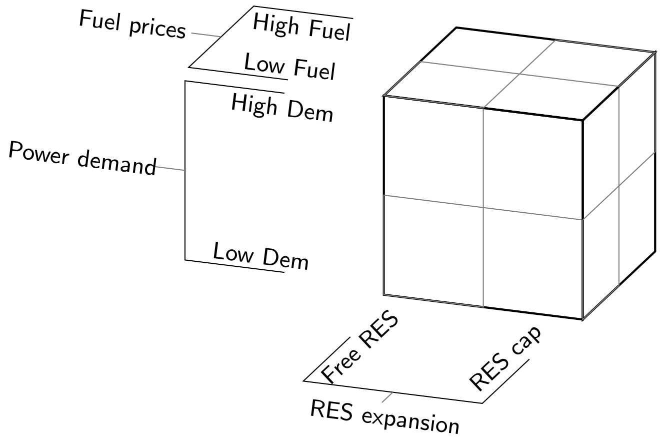


Figure 4: Analysis framework consisting of eight scenario combinations

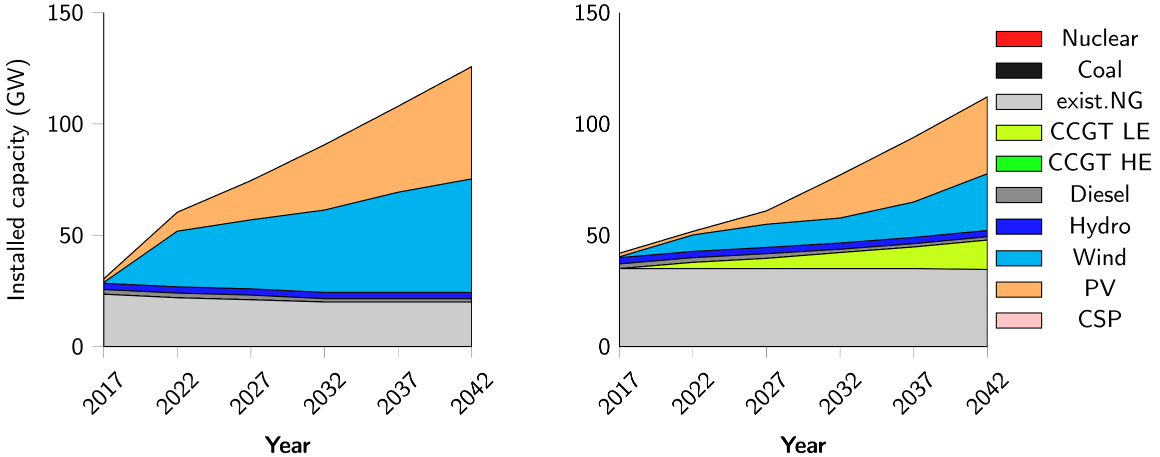
6. Results and discussion

This section provides an overview of the model results of the scenarios evaluated. First, more general developments and nation-wide results are reported. Subsequently, selected results pertaining to developments in specific sub-regions and technologies are presented and discussed.

6.1. Domestic power fleet development

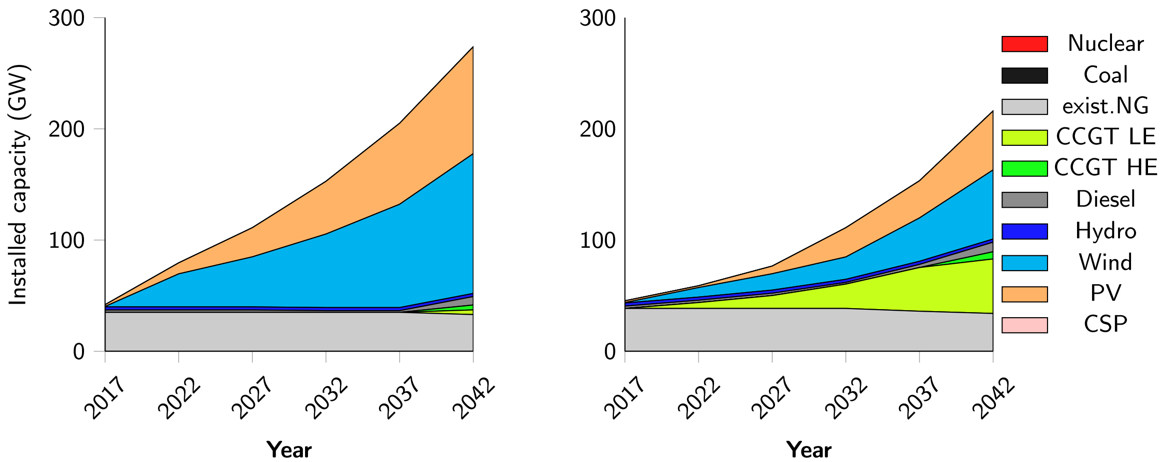
The model analysis clearly indicates that both wind and PV technologies have a significant role to play in the development of the domestic power fleet. Hence, both renewable energy technologies compose a high share of the cost-optimal power plant fleet in all scenarios. Absent an exogenous limitation (*Free RES*), the exploitation of renewable sources is almost sufficient to completely cover increases in power demand. If the share of renewable energies is limited *RES Cap*, conventional power plants will continue to rely on natural gas as a source of energy at low cost (*Low Fuel*), while only in the case of high energy costs (*High Fuel*), nuclear power capacity is added. Diesel generators are also used to cover peak loads. Neither coal-fired power or CSP plants are deployed in any of the scenarios examined.

The extent of the capacity expansion up to 2042 largely depends on the assumed demand trajectory and limits put on the share of renewable capacities in the power plant fleet. Under the *Low Dem* trajectory, a capacity build-out of ca. 130 GW in the *Free RES* case and 110 GW in the *RES Cap* case is realised. These results hold for both high (*High Fuel*) and low price (*Low Fuel*) scenarios. The individual composition in the *Low Fuel* case is displayed in Fig. 5a and 5b. Assuming a strong increase in demand levels (*High Dem*), the power plant fleet is expanded to 275 GW in the *RES Free* and *Low Fuel* and to 284 GW in the *High Fuel* scenario. Limiting the share of renewable power capacity (*RES Cap*) reduces the installed fleet capacity to 216 GW in the case *Low Fuel* and to 221 GW under the scenario *High Fuel*. The individual capacity shares of the respective power generation technologies in the *Low Fuel* scenario are depicted in Fig. 6a and 6b.



(a) Free RES (b) RES Cap

Figure 5: Domestic power plant fleet development with and without a RES cap (*Free RES* & *RES Cap*) in the scenarios *Low Dem* and *Low Fuel*



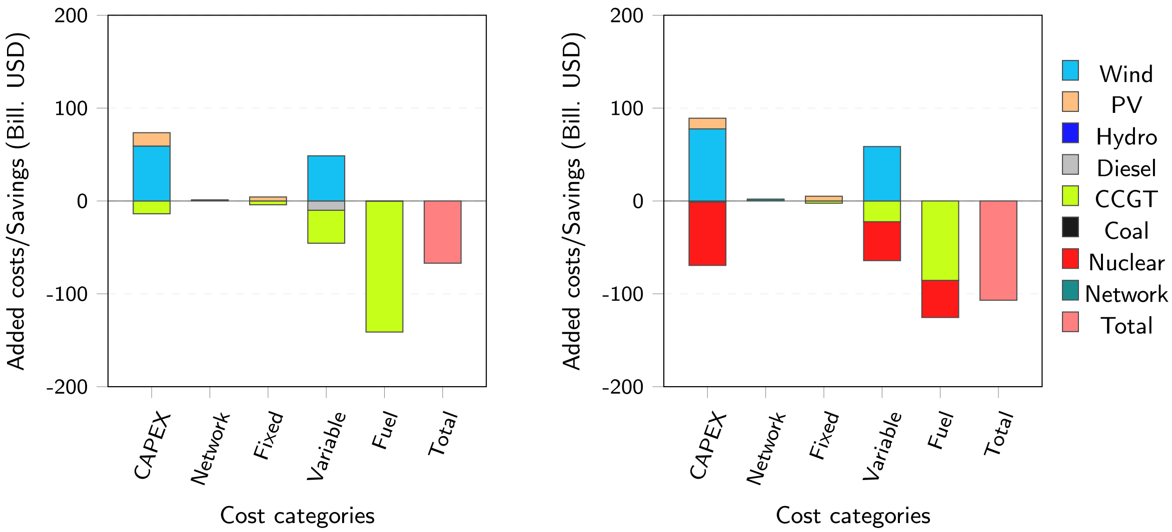
(a) RES Free (b) RES Cap

Figure 6: Domestic power plant fleet development with and without a RES cap (*Free RES* & *RES Cap*) in the scenarios *High Dem* and *Low Fuel*

A restrained build-out of RES (*RES cap*) results in significantly higher costs (Fig. 7a and 7b). In the scenarios with low fuel costs (*Low Fuel*), while renewable energy technologies entail higher investment costs, fuel costs are mitigated in the long run. In the case of low demand growth (*Low Dem*), this results in a total of ca. USD 66.5 billion in additional costs. This corresponds to average additional outlays of USD 2.66 billion per year. In the scenario *High Dem*, a similar amount of additional costs of USD 67 billion until 2042 accrue. In the scenarios *High Fuel*, the expansion of nuclear power plant capacities results in high capital expenditures. In the long term, additional costs of around USD 175 billion until 2042 or USD 7 billion per year are borne in the case *Low Dem*. Under the *High Dem* trajectory, the cost difference amounts to ca. USD 107 billion across the model horizon.

6.2. Regional deployment of renewable energy technologies

In the following section, the ~~regional~~ sub-regional deployment of power generation capacities is reported in greater detail. In particular, the site-specific installation of renewable energy technologies, the ~~regional~~ sub-regional build-out of conventional power plants and transmission network expansion is evaluated.



(a) Low Fuel

(b) High Fuel

Figure 7: Cost comparison in the case *RES Cap* under the scenarios *Low Fuel* and *High Fuel*

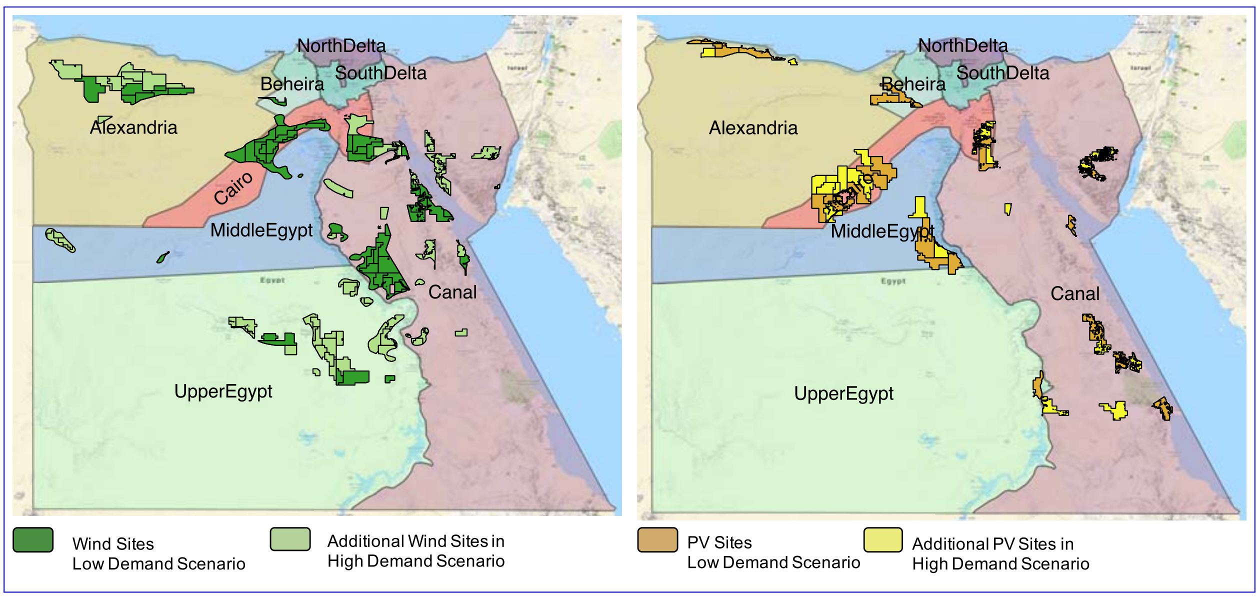


Figure 8: Development of candidate wind and PV sites in the case *Free RES*, source: own illustration

The number of sites developed across the time horizon of the model strongly depends on the imputed demand trajectory and whether the expansion of renewable technologies in constrained. While fuel costs have a limited effect on RES development, it is worth noting that in the *High Fuel* scenario a slight increase in the number of sites where deployment takes place is registered, even though in some cases the absolute generation capacity decreases. This stems from the greater diversification of site-specific deployment, as certain sites are only partially utilised. In comparison to the fuel costs, the demand trajectory has a much greater bearing on the development. Fig. 8 depicts the candidate wind and PV sites developed over the time horizon in the case *Free RES*. The exploitation of the candidate wind and PV sites in the scenarios subject to the case *RES Cap* are significantly fewer, as shown in Fig. 9.

While wind power is deployed relatively evenly throughout the country, locations for PV systems tend to be developed more in the northern part of the country, although locations in the south yield on average a higher output.

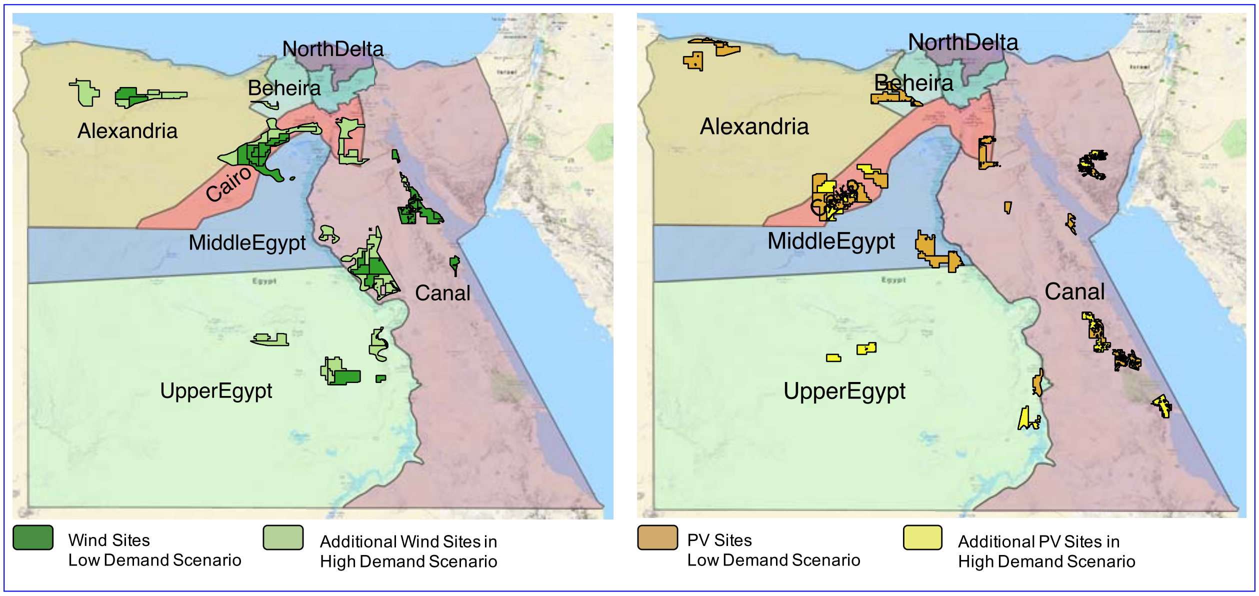
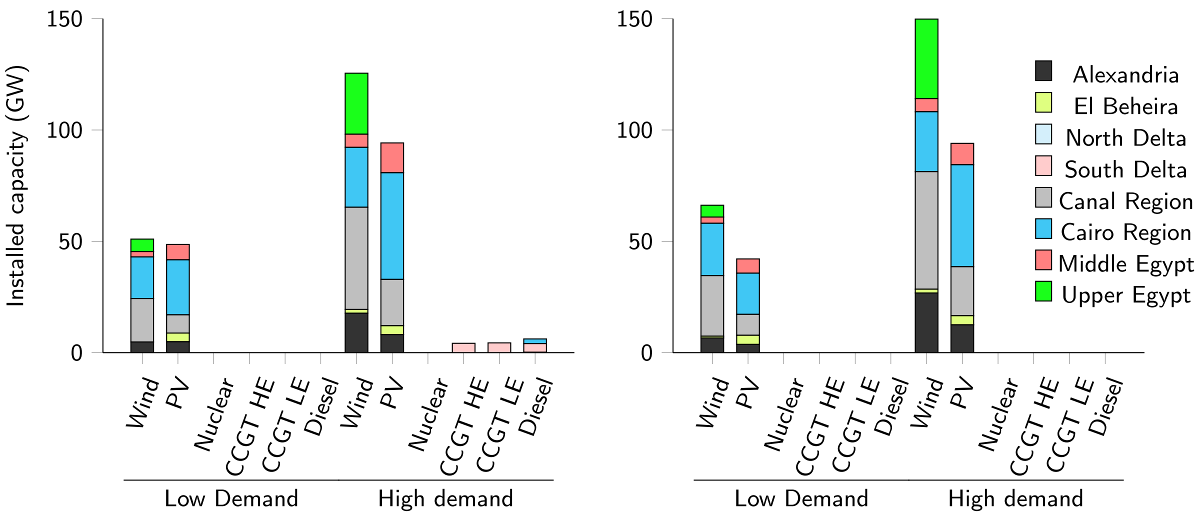


Figure 9: Development of candidate wind and PV sites in the case *RES Cap*, source: own illustration



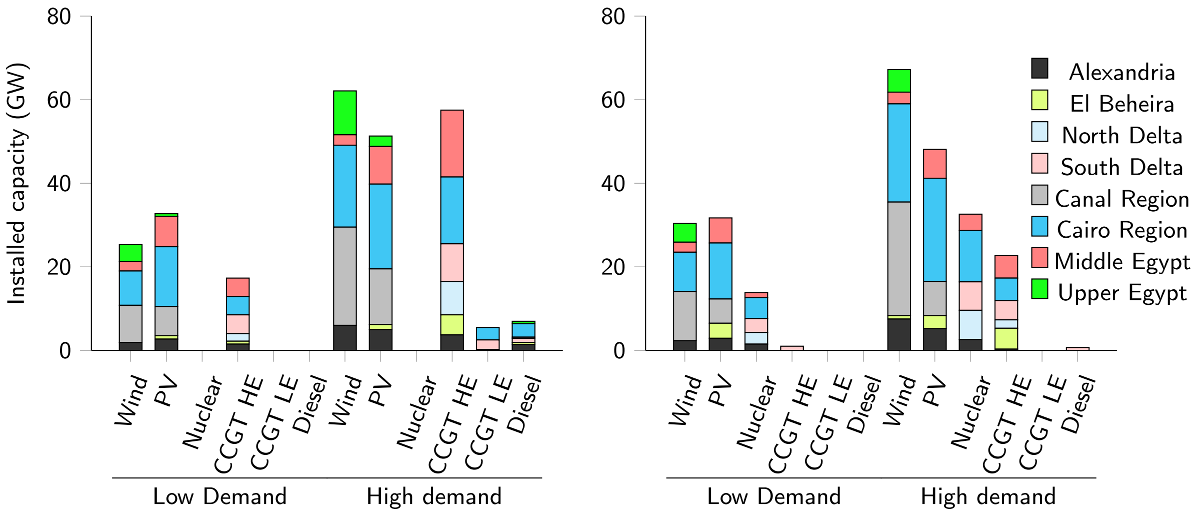
(a) Added capacity (*Low Fuel*)

(b) Added capacity (*High Fuel*)

Figure 10: Added capacities in the case *Free RES*

For example, some PV plants in the south approach 2,500 full-load hours, almost 200 full-load hours more than a PV power plant situated on the Mediterranean coast. Due to the proximity to the load centres in the Nile Delta, however, it is economically advantageous to develop the somewhat less favourable candidate sites and thus avoid transmission losses and line costs. The locations allocated to the sub-region *Cairo* are primarily exploited.

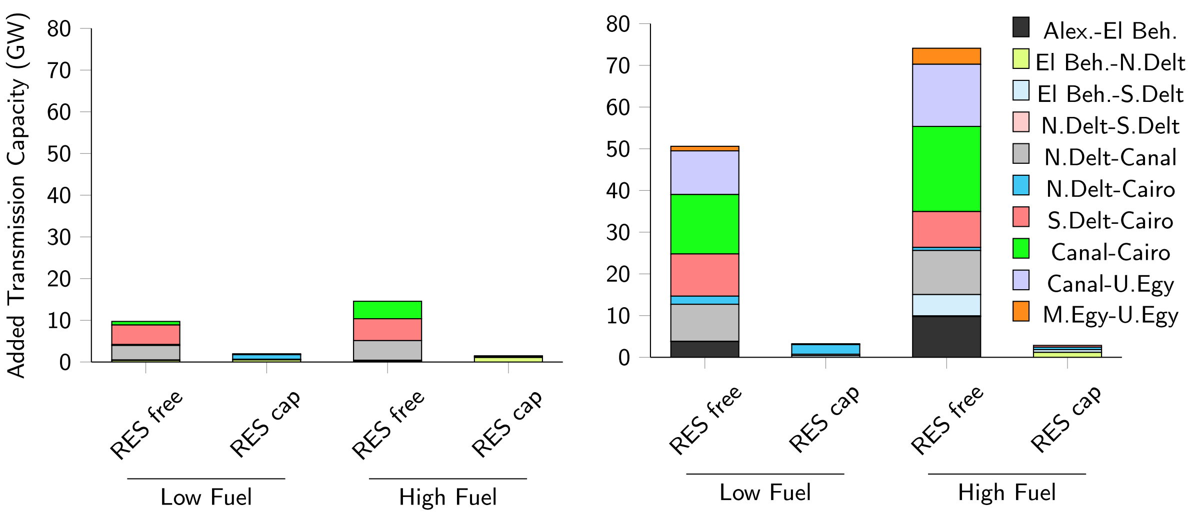
In addition to renewable energies, conventional power plants are also built in selected sub-regions. The expansion of conventional capacities serves to primarily cover peak loads or are added in ~~regions~~ sub-regions where the potential of renewable technologies is low or non-existent. As shown in Fig. 10b, the residual demand can be covered by the existing power plant fleet in the *Low Dem* scenario. In the *High Fuel* scenario, additional wind power capacities are deployed instead of conventional capacities. Thus, as shown in Fig. 10a, no additional conventional power plants are installed even under the demand projections in the *High Dem* scenario.



(a) Added capacity (*Low Fuel*)

(b) Added capacity (*High Fuel*)

Figure 11: Added capacities in the case *RES Cap*



(a) Added capacity (*Low Dem*)

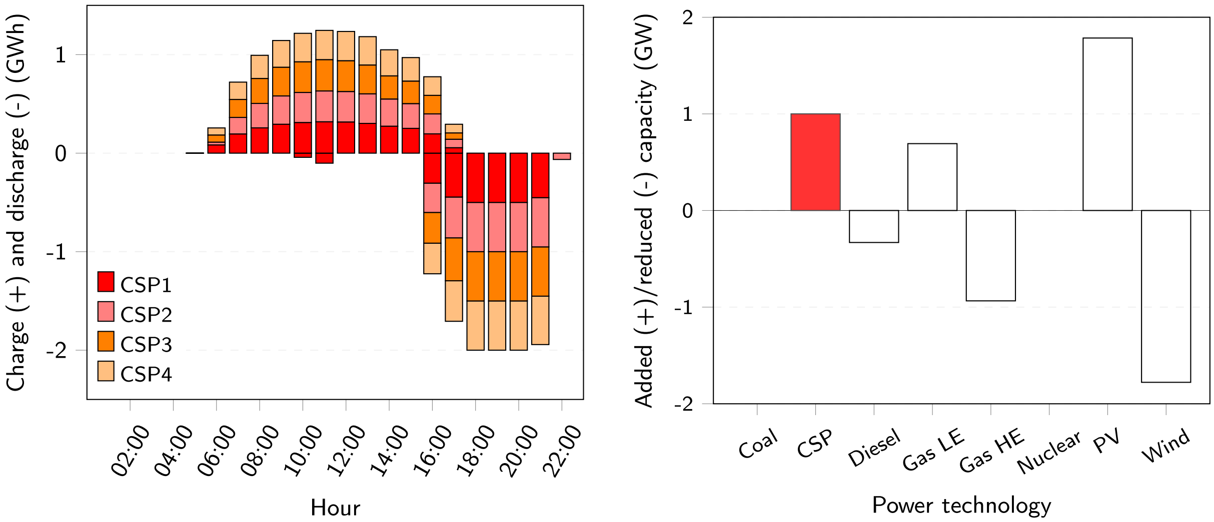
(b) Added capacity (*High Dem*)

Figure 12: Transmission capacity expansion in low and high demand scenarios

Under a restrained renewable deployment pathway (*RES Cap*), in accordance with the government's current targets, significantly more conventional power capacity is required to serve the demand. These are primarily built in Cairo, Middle Egypt and Delta sub-regions. High-efficiency CCGT power plants constitute the greatest share of the conventional capacity added (Fig. 11a & 11b).

The exploitation of renewable resource potentials in areas at significant distances from urban centres leads to production deficits in some ~~regions~~sub-regions, which must be covered by imports from ~~regions~~ sub-regions with electricity surpluses. This imbalance between ~~regions~~ sub-regions is further exacerbated with a high shares of renewable penetration.

In particular, the sub-regions Alexandria, Canal and Upper Egypt are characterised by ~~a power production surplus . Power volumes~~ surplus production. Electricity exchanged between the sub-regions in the final time interval (2038-2042) are displayed in Tables A.3 and A.4 in the appendix. To facilitate the delivery of the electricity to load centres



(a) CSP storage profile

(b) Δ in fleet with addition of 1 GW CSP

Figure 13: Impact of CSP capacity installation on the cost-optimal power fleet and operation profiles of candidate installations

a significant expansion of the capacity of the transmission grid is required. For ~~a~~ the high demand and high fuel ~~costs the transmission capacity is~~ cost scenario transmission capacities between the sub-regions are expanded as shown in Fig.12.

6.3. Impact of CSP deployment

Although this study comes to the conclusion that CSP power plants are not part of a cost-optimal power fleet in any of the scenarios considered, other authors attribute great potential to this technology, e.g., [23]. Therefore, the effects of the deployment of CSP power plants on the dispatch and composition of the power fleet are discussed in more detail. Due to their heat storage capacity, CSP power plants can be utilised flexibly and thus can be deployed to cover peak loads or to compensate fluctuations in production in wind or PV power plants. To analyse this in the context of the Egyptian power system, CSP is exogenously introduced into the model. When determining the cost-optimal dispatch of the four most economically advantageous sites, the charging and discharging profiles, which are depicted in Fig. 13a, indicate that CSP is primarily dispatched in the evening hours to serve the respective daily demand peaks.

The deployment of CSP leads to a reduction in the utilisation of peak load power plants (diesel, combined cycle LE) and depending on the scenario, to a slightly increased expansion of base load power plants (combined cycle HE, nuclear power plants). In terms of renewable energy technologies, the use of CSP power plants leads to an increased expansion of PV power plants and a reduction in the wind power capacity installed (Fig. 13b).

For the installation, operation and maintenance of one gigawatt of installed CSP capacity, total costs of ca. USD 6.5 billion are incurred during the modelling period (2017-2042). Taking into account the corresponding savings obtained through its dispatch, the additional costs for the overall system range between USD 0.4 and 3.5 billion. This corresponds to additional annual costs of ca. USD 18 - 60 million per gigawatt of installed capacity.

6.4. Discussion of results

As decisions concerning the future development of the electricity sector in Egypt are made by government authorities and a pervasive market liberalisation is not planned in the near future, the central planner approach employed in the analysis seems suitable. The model, of course, abstracts from reality and exhibits several shortcomings. For instance, the model is not capable of offering insights into aspects related to security of supply. In particular, the feed-in profiles based on representative days are not suitable to capture extreme weather events. In the case of conventional power plants, neither reserve capacities nor ramp-up times are considered, which fails to capture existing inflexibilities in the system. Furthermore, the representation of the transmission network is coarse in nature and due to the absence of congestion within sub-regions, the model is incentivised to utilise remote renewable energy sites with favourable conditions to supply distant load centres. Especially in the sub-region Canal, the large north-south extension can lead to a distortion in the results. In contrast to the reference line costs used in the analysis, capital costs for transmission lines correspond to the respective voltage level. Lower transmission capacities would lead to significantly higher specific costs, which would affect the results rendered in the model. It should also be emphasised that urban centres were excluded as candidate sites for PV installations. However, the use of small-scale rooftop PV systems could significantly contribute to the local supply and have a strong impact on the results reported above.

Comparing the results of the analysis with similar studies of the future Egyptian power system, one key difference involves demand projections. Taliotis et al. [44] and Mondal et al. [28] forecast demand in 2040 at 691 TWh and 524 TWh, respectively, in the range between the high scenario of 918 TWh assumed in this paper and the baseline scenario with a low increase in demand of 434 TWh. The assumptions of Rady et al. [38] even assume a level as low as 350 TWh in 2040. Accordingly, capacity developments differ. However, all studies mentioned reach the conclusion that wind power should be utilised much more extensively in Egypt. CSP power plants have been considered to figure into the development of the power fleet, especially in somewhat older studies such as those by Kost [23] or Taliotis et al. [44], whereas in the paper at hand, similar to somewhat more recent studies by Rady et al. [38] or Mondal et al. [28], the technology does not appear to be viable for deployment in the mid-term. Utility-scale PV, on the other hand, is deployed extensively in the analysis. Its share in the power plant fleet is significantly higher than in the studies conducted by other authors. This is likely due to the differing costs and technical assumptions made about the reference technology. For instance, in the analysis, a single-axis tracking system was assumed for better use of the available solar potential, which is in line with current projects under construction. As it pertains to conventional power plant technologies, both Rady et al. [38] and Taliotis et al. [44] conclude that in terms of a cost-optimal power fleet development, coal-fired power plants are not economically viable. The authors' assessments also project gas-fired combined cycle power plants to exhibit the greatest potential for conventional technologies. However, the development of the gas price can significantly alter the results.

7. Summary and Outlook

The electricity sector in Egypt is facing major challenges. The population is growing and with increasing prosperity, per capita consumption is also growing steadily. In the past, the uptick in demand was primarily covered by natural gas capacities. Due to decreasing domestic production volumes, Egypt ~~has become~~ became dependent on gas imports in 2015. Although new gas deposits have been developed and Egypt is once again in a position to export natural gas, [35] points out that this could well be short-lived and that in the coming years export levels might experience a precipitous decline. Moreover, the established policy of fuel subsidies are increasingly burdening the national budget. The government is therefore pursuing a diversification strategy, which includes increasing the share of renewable energies to a total of 42% by 2035 while exploring the deployment of nuclear and coal-fired power plants.

To be able to evaluate the planned developments, a model-based analysis based on the open-source modelling framework OSyMOSYS was employed. The model examines the optimal capacity expansion of the power fleet up to the year 2042 under different scenarios. All existing Egyptian power plants and transmission network capacities were included in the model. Beyond the legacy capacities in the system, the potential additions of nuclear and coal-fired power plants were considered. In the case of renewable energy technologies, wind power turbines, utility-scale PV installations and CSP power plants at a total of 320 different locations were examined. For each of these sites, hourly feed-in profiles were generated based on ten years of weather data. In addition, the expansion of existing and new transmission lines between the individual sub-regions defined in the model was incorporated. Demand profiles were considered based on the construction of three seasonal representative weeks. The scenario framework applied includes uncertainties related to demand projections and reforms of fuel price subsidies as well as the level of ambition regarding the build-out of renewable energy capacities. The restrained development pathway is formulated in line with the government's current expansion targets.

The results obtained for the different scenarios considered highlight that the deployment of wind power and PV installations is preferable from an economic point of view and should be expanded to a much greater extent than currently planned by the government. Depending on the scenario, costs of ca. USD 67 billion can be saved over the entire period under consideration. Wind power should be deployed spatially throughout the country while the analysis indicates that from a system perspective PV should be installed at sites whose resource potential is less favourable, especially in the northern part of the country.

The expansion of conventional power plant capacities depends strongly on the price of natural gas. If prices remain low, combined cycle power plants will continue to be the preferred power plant technology in the future, alongside wind power and PV plants as mentioned above. Only in the scenarios where high gas prices are assumed and a restrained build-out of renewable energies is targeted, is it cost-optimal to invest in nuclear power plants. An optimal location for these would be in *Cairo* or the *Nile Delta* ~~region~~sub-region. The location in the *Alexandria* ~~region~~ sub-region currently under consideration would not be optimal under the framework conditions of the model. In addition, nuclear power plants are only viable if used as baseload generation capacities and are not endowed with the flexibility to accommodate fluctuations in renewable energies. To cover peak loads, diesel generators are ~~dispatached~~ dispatched in some scenarios during a limited number of hours of the year. These are primarily installed in *Cairo* or the *Southern Delta* ~~region~~sub-region. Coal-fired power plants do not constitute part of the cost-optimal power plant fleet in any of the scenarios considered. The results thus raise questions as to the ~~usefulness~~ prudence of the government's plans to explore the utilisation of coal-fired power. Furthermore, the planned location in the sub-region *Canal* is not advisable due to the particularly favourable conditions for renewable energy technologies.

CSP power plants are also not deployed in any of the scenarios considered. A more detailed assessment of the utilisation of CSP, however, yields the insight that the additional costs of installation are partially offset by a reduction in fuel costs. Depending on the scenario, additional annual costs total between 18-60 USD per installed kilowatt of capacity. The results also indicate that CSP plants would in large part replace the dispatch of diesel generators when it comes to covering peak loads. The CSP plants would also lead to the expansion of PV capacities while significantly crowding out wind power investments.

The impacts on the transmission grid correlate positively with the share of variable renewable energies in the system. Thus, an ambitious expansion pathway would render substantial surpluses in the sub-regions of *Alexandria*, *Canal* and *Upper Egypt*, which must be exported to sub-regions with production deficits. This requires a substantial expansion of transmission capacities. Limiting the share of renewable energy leads to fewer disparities between sub-regions and thus less expansion of network capacities, such as those in the *Delta* ~~region~~sub-region.

In closing, the analysis conducted indicates from an economic point of view a more expansive deployment of wind and PV power installations is worth recommending, even when considering impacts on the transmission infrastructure. The research also suggests that adding coal-fired power plants is not economically rational. Solar thermal power plants are also not viable investments under the model conditions. However, they could contribute to decarbonisation efforts by offering tailored subsidies, as their flexibility would help substitute for particularly inefficient fossil-fuel technologies to cover peak demand levels.

Further research could extend the analysis by considering a more detailed representation of the power transmission network and its expansion as well as evaluating supply security by exploring inflexibilities in the power system and the impacts of uncertainties in the context of increased renewable energy penetration.

Acknowledgment

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

CRediT authorship contribution statement

Christoph Dallmann: Conceptualization, Methodology, Data curation, Software, Investigation, Writing- Original draft preparation, Visualization. **Matthew Schmidt:** Conceptualization, Methodology, Writing- Original draft preparation, Visualization. **Dominik Möst:** Supervision, Writing- Review.

A. Configuration of seasonal representative days

Based on the load profile forecasts for Egypt developed in Toktarova et al. [45] and applying a hierarchical clustering procedure from Kotzur et al. [24], three representative seasonal weeks with 168 hours, respectively, were derived for the years 2020, 2030 and 2040. The representative weeks derived were assigned to a season according to their chronological sequence in the year. The winter season comprises 21 weeks, a transitional season 14 weeks and the summer season 17 calendar weeks.

Demand is highest during the summer season and lowest in winter. This is attributed to the positive correlation between temperature and demand levels, in particular the extensive use of air conditioning systems [3]. In the course of each representative week, peak usage occurs in the evening hours with demand reaching its lowest levels overnight. Weekends are characterised by lower loads. Since the load profiles of individual weekdays and weekend days are almost indistinguishable, the respective day types are averaged together to create two representative days for each respective season. Based on the constructed load curves and the consumption shares of the individual sub-regions, a specific share of the total consumption for each representative hour of a modeling period is allocated to each sub-region. Considering three different seasons, two different types of days (weekday and weekend) with 24 hours each, the model consists of 144 time steps per model period. Since the model horizon includes 35 years and each model period includes five years, a total number of 1,008 time steps are considered across the entire modelling horizon.

B. Supplementary figures and tables

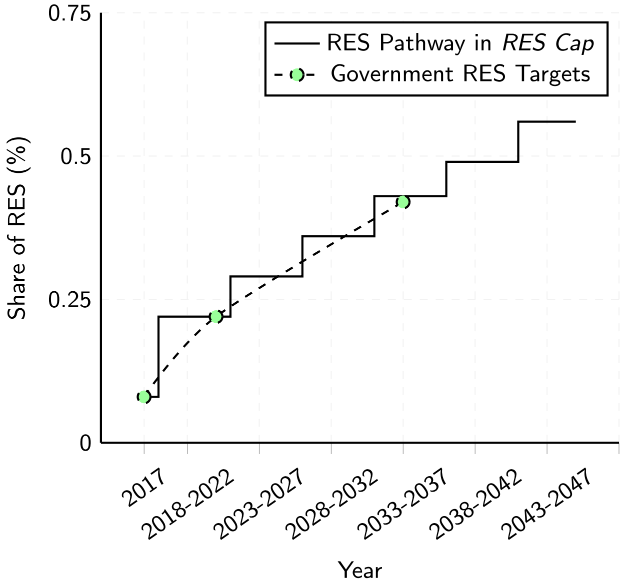
The appendix provides detailed tables and supplementary diagrams referenced but not contained in the preceding text.

Table A.1
Assumed fuel price development (USD/kWh$_{th}$) in scenarios *Fuel Low* and *Fuel High*; sources: World Bank [52], Massachusetts Institute of Technology (MIT) [26], Hussein et al. [18], Hanan [15], IEA [19], BAFA [1], Egyptian Natural Gas Holding Company [12]

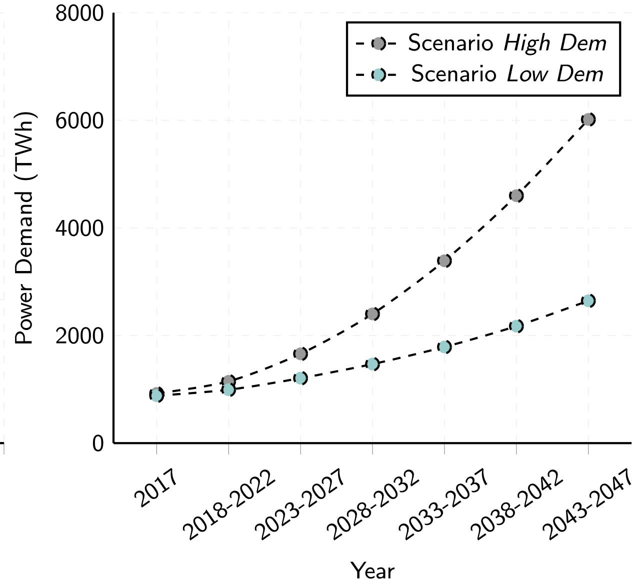
	Low Fuel Scenario				*High Fuel Scenario*			
	Natural Gas	Diesel	Coal	Nuclear	Natural Gas	Diesel	Coal	Nuclear
2017	0.019	0.018	0.012	0.0062	0.036	0.018	0.012	0.0062
2022	0.021	0.034	0.012	0.0062	0.036	0.04	0.014	0.0062
2027	0.021	0.043	0.012	0.0062	0.036	0.047	0.016	0.0062
2032	0.021	0.043	0.012	0.0062	0.036	0.058	0.018	0.0062
2037	0.021	0.043	0.012	0.0062	0.036	0.069	0.019	0.0062
2042	0.021	0.043	0.012	0.0062	0.036	0.08	0.021	0.0062
2047	0.021	0.043	0.011	0.0062	0.036	0.091	0.023	0.0062

Table A.2
Techno-economic parameters of transmission lines, source: own calculations; Pletka et al. [36], World Bank [53]

Transmission line	Original Capacity (MW)	Distance (Miles)	Capital Costs (USD/MW)	Losses (%)
Alexandria - El Beheira	1,500	142	240,000	4.2
El Beheira – North Delta	0	60	110,500	4.2
El Beheira – South Delta	400	38	75,800	4.2
El Beheira – Cairo	1,500	80	142,100	4.2
North Delta – South Delta	400	73	131,100	4.2
North Delta - Canal	800	130	221,000	4.2
North Delta – Cairo	400	65	118,400	4.2
South Delta – Cairo	400	50	94,700	4.2
Canal – Cairo	1,500	90	157,900	4.2
Canal – Middle Egypt	1,500	155	260,500	4.2
Canal – Upper Egypt	0	125	213,100	4.2
Cairo – Middle Egypt	3,00	125	213,100	4.2
Middle Egypt – Upper Egypt	3,00	325	528,900	4.2



(a) RES targets and expansion pathways in *RES Cap*



(b) Power demand scenarios

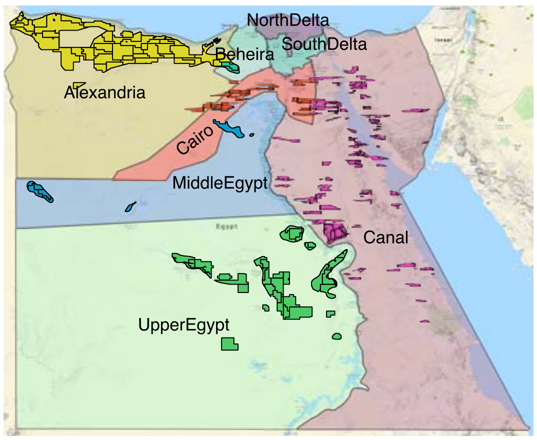
Figure A.1: *RES Cap* expansion pathway and *Low Dem* and *High Dem* power demand scenarios; sources: own calculations, [20, 34]

Table A.3
Power exchange between the sub-regions in the case of high demand (*High Dem*), high fuel costs (*High Fuel*) & no RES cap (*RES free*) in 2042, source: own calculations

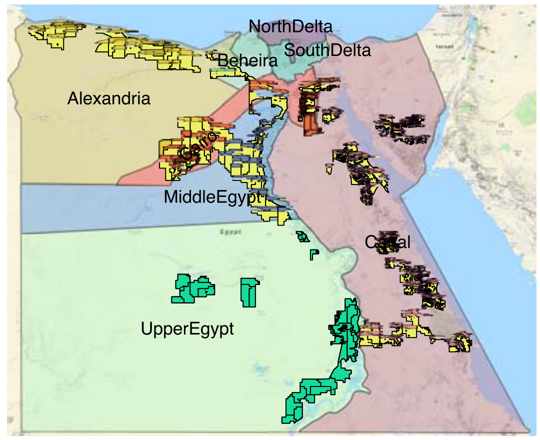
Sub-region	Export (GWh)	Import (GWh)	Net exchange (GWh)
Alexandria	68,748	0	68,748
El Beheira	31,574	70,008	-38,434
North Delta	2,641	78,678	-76,037
South Delta	92	80,131	-80,038
Canal	174,460	45,245	129,215
Cairo	52,280	97,217	-44,937
Middle Egypt	1,401	46,790	-45,389
Upper Egypt	86,872	0	86,872

Table A.4
Power exchange between the sub-regions in the case of high demand (*High Dem*), high fuel costs (*High Fuel*) & RES cap (*RES cap*) in 2042, source: own calculations

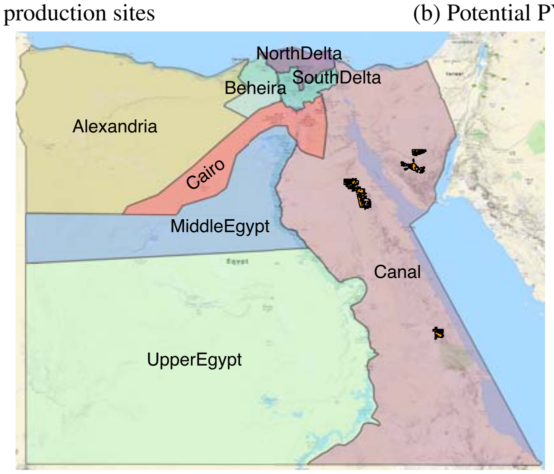
Sub-region	Export (GWh)	Import (GWh)	Net exchange (GWh)
Alexandria	4,689	502	4,187
El Beheira	3,401	15,942	-12,540
North Delta	5,526	7,656	-2,130
South Delta	5,352	2,634	2,718
Canal	12,110	2,213	9,897
Cairo	10,480	7,428	3,052
Middle Egypt	2,621	18,509	-15,888
Upper Egypt	11,762	1,058	10,704



(a) Potential wind production sites



(b) Potential PV production sites



(c) Potential CSP production sites

Figure A.2: Site and technology-specific RES potentials considered in the model

563 # C. Model Description

564 The following appendix provides an overview of the sets and parameters used in the model. The equations that have
565 been altered from or added to the original OSeMOSYS model formulation for purposes of the analysis are also depicted.
566 The complete model code used in the paper can be accessed at: https://doi.org/10.5281/zenodo.4437681

567 ## C.1. List of Sets and Parameters

Set Name (abbreviation)	Set Description
Dailytimebracket (lh)	Allows for day/night differentiation, i.e., splits a single day into brackets
Daytype (ld)	Allows to model different days like weekday/weekend
Fuel (f)	Fuels enter or leave technologies
Mode of Operation (m)	Technologies might operate in different modes
Region (r)	The different (aggregated) regions considered
Season (ls)	Allows a differentiation for yearly seasons (e.g., summer/winter)
Storage (s)	The set of different storage technologies
Technology (t)	Everything that processes energy in any form is considered a technology
Timeslice (l)	Timeslices are a combination of ls, ld and lh
Year (y)	The set of the different modeled years

Parameter Name	Parameter Description
$AccumulatedAnnualDemand_{r,f,y}$	Amount of demand that can be satisfied at any time of the year, not time-slice dependent
$AvailabilityFactor_{r,t,y}$	Maximum time a technology may run in a year
$CapacityFactor_{l,t,r,y}$	Maximum time a technology may run in a time-slice
$CapacityOfOneTechnologyUnit_{r,t,y}$	Capacity of one new unit of a technology
$CapacityToActivityUnit_{r,t}$	Conversion factor of capacity units into activity units
$CapitalCostStorage_{r,s,y}$	Capital costs for storage technologies
$CapitalCost_{r,t,y}$	Capital cost for all technologies
$Conversionlh_{l,lh}$	Assigns DailyTimeBracket to time-slice
$Conversionld_{l,ld}$	Assigns DayType to time-slice
$Conversionls_{l,ls}$	Assigns Season to time-slice
$DaySplit_{lh,y}$	Length of a DailyTimeBracket in one day as a fraction of the year
$DaysInDayType_{ld,ls,y}$	Amount of days per week in which a DayType occurs
$DiscountRate_{r}$	Interest rate used for purposes of discounting
$FixedCost_{r,t,y}$	Fixed operational costs for a technology
$InputActivityRatio_{f,m,r,t,y}$	Describes along with OutputActivityRatio the efficiency of a technology
$OperationalLife_{r,t}$	Operational lifetime of all technologies
$OperationalLifeStorage_{r,s,y}$	Operational lifetime of storage technologies
$OutputActivityRatio_{f,m,r,t,y}$	Describes along with InputActivityRatio the efficiency of a technology
$RETagFuel_{f,r,y}$	Designates fuels that do not produce emissions
$RETagTechnology_{r,t,y}$	Designates technologies with fluctuating feed-in
$REMaxProductionTarget_{r,y}$	Upper limit on renewable technologies with fluctuating feed- in
$ResidualCapacity_{r,t,y}$	Capacities that exist in addition to the endogenously built capacities
$SpecifiedAnnualDemand_{f,r,y}$	Annual demand of fuels which are time-slice dependent
$SpecifiedDemandProfile_{f,r,t,y}$	Assigns a share of SpecifiedAnnualDemand to the different time-slices
$StorageLevelStart_{r,s}$	Amount of stored energy at the beginning of the modeling period
$StorageMaxChargeRate_{r,s}$	Maximum amount a storage can be charged within one hour
$StorageMaxDischargeRate_{r,s}$	Maximum amount a storage can be discharged within one hour
$TechnologyFromStorage_{m,r,s,t}$	Technologies that can use a fuel from a storage
$TechnologyToStorage_{m,r,s,t}$	Technologies that can provide a fuel to a storage
$TotalAnnualMaxCapacityInvestment_{r,t,y}$	Maximum amount of investments into a technology in a year
$TotalAnnualMinCapacityInvestment_{r,t,y}$	Minimum amount of investments into a technology in a year
$TotalAnnualMaxCapacity_{r,t,y}$	Maximum amount of used capacity in a year
$TotalAnnualMinCapacity_{r,t,y}$	Minimum amount of used capacity in a year
$TotalTechnologyAnnualActivityLowerLimit_{r,t,y}$	Minimum amount of activity in a year
$TotalTechnologyAnnualActivityUpperLimit_{r,t,y}$	Maximum amount of activity in a year
$TotalTechnologyModelPeriodActivityLowerLimit_{r,t}$	Minimum amount of activity over model period
$TotalTechnologyModelPeriodActivityUpperLimit_{r,t}$	Maximum amount of activity over model period
$TradeRoute_{f,r,rr,y}$	Designates possible trade routes between regions
$VariableCost_{m,r,t,y}$	Variable operational costs for using a technology
$YearSplit_{l,y}$	Share of a time-slice in one year

C.2. Algebraic Formulation of Altered/Added Model Equations in OSeMOSYS

As the model horizon consists of five year periods, the cost components of the objective function are discounted accordingly:

$$VariableOperatingCosts_{r,t,y,l} = \sum_{m} RateofActivity_{r,t,y,l,m} * VariableCost_{r,t,y,m} \quad \forall\, r,t,y \tag{3}$$

$$PeriodFixedOperatingCost_{r,t,y} = TotalCapacityAnnual_{r,t,y} * FixedCost_{r,t,y} * 5 \quad \forall\, r,t,y \tag{4}$$

$$\begin{aligned} DiscountedOperatingCost_{r,t,y} &= (PeriodFixedOperatingCost_{r,t,y} + VariableOperatingCosts_{r,t,y})/5 \\ &* \sum_{i=0}^{4} \frac{1}{DiscountRate_r + 1^{(y-min(y))*5+0.5+i}} \quad \forall\, r,t,y \end{aligned} \tag{5}$$

$$\begin{aligned} DiscountedCapitalInvestment_{r,t,y} &= CapitalCost_{r,t,y} * NewCapacity_{r,t,y}) \\ &* \frac{1}{DiscountRate_r + 1^{(y-min(y))*5}} \quad \forall\, r,t,y \end{aligned} \tag{6}$$

$$\begin{aligned} SalvageValue_{r,t,y} &= NewCapacity_{r,t,y} * CapitalCost_{r,t,y}) * \frac{1 - max(p) - p + 1}{OperationalLife_{r,t}} \\ &\forall\, r,t,y \; : (p + OperationalLife_t - 1) \geq max(p) \end{aligned} \tag{7}$$

$$DiscountedSalvageValue_{r,t,y} = \frac{SalvageValue_{r,t,y}}{1 + DiscountRate_r^{1+(max(y)-min(y))*5}} \quad \forall\, r,t,y \tag{8}$$

In order to reduce computational burden, the following constraints are added to the CSP storage, which entails that the storage must be emptied by the end of each $Daytype(ld)$:

$$StorageLevelDayTypeFinish_{r,s,ls,ls,y} = 0 \quad \forall\, r,s,p \tag{9}$$

$$StorageLevelDayTypeStart_{r,s,ls,ls,y} = 0 \quad \forall\, r,s,p \tag{10}$$

For purposes of restraining the capacity expansion of renewable energy technologies, the following constraint is implemented::

$$\begin{aligned} &\sum_{t}\sum_{f}\sum_{l}\sum_{m} RateOfActivity_{r,t,y,l,m} * OutputActivityRatio_{r,t,y,f,m} * YearSplit_{l,y} * RETagFuel_{r,y,f} \\ &\leq REMaxProductionTarget_{r,y} * \sum_{f}\sum_{l} RateofActivity_{r,t,y,l,m} * OutputActivityRatio_{r,t,y,f,m} \\ &* YearSplit_{l,y} * RETagFuel_{r,y,f} \quad \forall\, r,y : OutputActivityRatio \neq 0 \end{aligned} \tag{11}$$

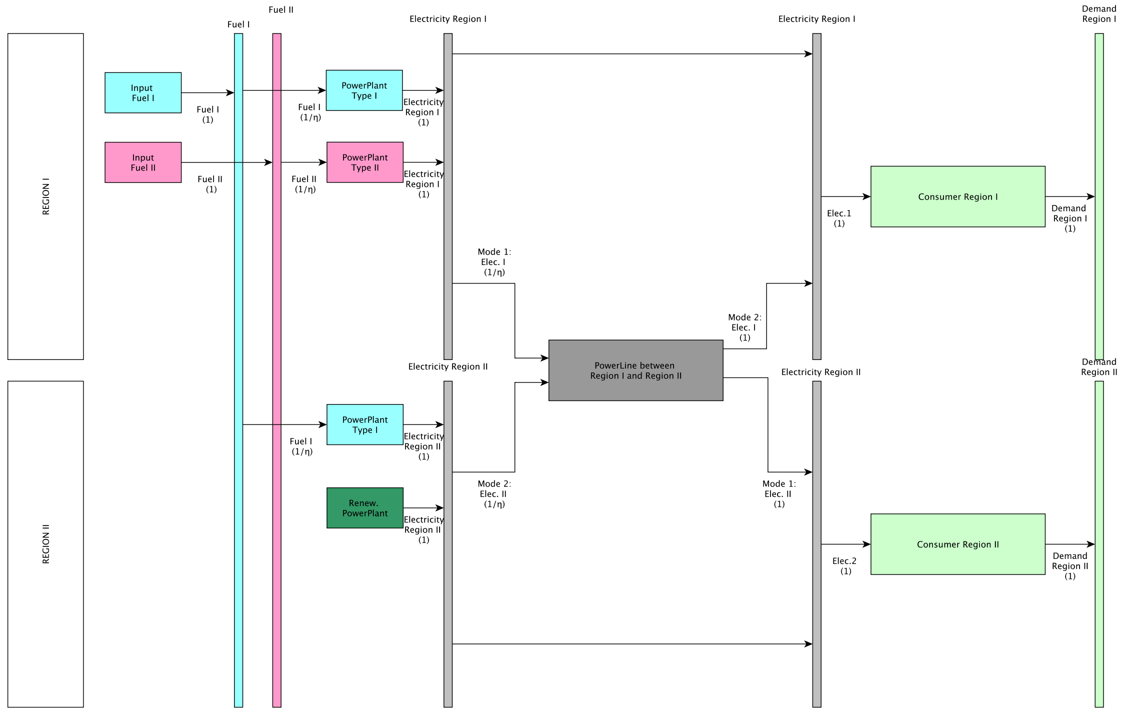


Figure A.3: Schematic representation of the model-specific mapping of sub-regional outputs via the designation of stock and flow variables

References

[1] BAFA, 2019. Drittlandskohlepreis. Technical Report. Bundesamt für Wirtschaft und Ausfuhrkontrolle. Berlin. URL: https://www.bafa.de/DE/Energie/Rohstoffe/Drittlandskohlepreis/drittlandskohlepreis{_}node.html.

[2] Bellini, E., 2019. Jordan suspends renewables auctions, new licenses for projects over 1 MW. URL: https://www.pv-magazine.com/2019/01/28/jordan-suspends-renewables-auctions-new-licenses-for-projects-over-1-mw/.

[3] Beshara, A., 2008. Energy Efficiency in the Buildings Sector : Egyptian Experience.

[4] Burandt, T., Xiong, B., Löffler, K., Oei, P.Y., 2019. Decarbonizing China's energy system – Modeling the transformation of the electricity, transportation, heat, and industrial sectors. Applied Energy doi:10.1016/j.apenergy.2019.113820.

[5] Cohen, T., Rabinovitch, A., 2018. Egyptian firm to buy $15 billion of Israeli natural gas. URL: https://de.reuters.com/article/us-israel-egypt-natgas/egyptian-firm-to-buy-15-billion-of-israeli-natural-gas-idUSKCN1G31BK.

[6] Dhakouani, A., Gardumi, F., Znouda, E., Bouden, C., Howells, M., 2017. Long-term optimisation model of the Tunisian power system. Energy 141, 550–562. doi:10.1016/j.energy.2017.09.093.

[7] Eberhard, A., Gratwick, K., 2007. From state to market and back again: Egypt's experiment with independent power projects. Energy 32, 724–738. doi:10.1016/j.energy.2006.05.003.

[8] EEHC, 2015. Ministry of Electricity & Energy 2015, The Annual Report of 2014/2015 2015. URL: http://www.moee.gov.eg/english_new/EEHC_Rep/2014-2015en.pdf.

[9] EEHC, 2016. Egyptian Electricity Holding Company Annual Report 2015/2016. Technical Report. Arab Republic of Egypt Ministry of Electricity and Renweable Energy.

[10] EEHC, 2017. Egyptian Electricity Holding Company Annual Report 2016/2017. Technical Report. Arab Republic of Egypt Ministry of Electricity and Renweable Energy. URL: http://www.moee.gov.eg/english_new/EEHC_Rep/2016-2017en.pdf.

[11] EEHC, 2019. Annual Report 2017/18. Technical Report 9. doi:10.1017/CBO9781107415324.004.

[12] Egyptian Natural Gas Holding Company, 2018. Annual Report 20017-2018. Technical Report 9. URL: http://www.egas.com.eg/docs/pdf/EGASAnnualReport2018EN.pdf, doi:10.1017/CBO9781107415324.004.

[13] EIA, 2016. Capital Cost Estimates for Utility Scale Electricity Generating Plants. US Department of Energy, Energy Information Administration. US Department of Energy, Energy Information Administration. , 141URL: https://www.eia.gov/analysis/studies/powerplants/capitalcost/pdf/capcost_assumption.pdf.

[14] European Commission Joint Research Centre (JRC), 2019. Photovoltaic Geographical Information System. URL: https://re.jrc.ec.europa.eu/pvg_tools/es/tools.html.

[15] Hanan, M., 2019. Egypt lifts fuel subsidies, completely announces new prices. URL: https://www.egypttoday.com/Article/1/72448/Egypt-lifts-fuel-subsidies-completely-announces-new-prices.

[16] Heaps, C., 2016. Long-range Energy Alternatives Planning (LEAP) system. Stockholm Environment Institute. URL: https://www.energycommunity.org/default.asp?action=license.

[17] Howells, M., Rogner, H., Strachan, N., Heaps, C., Huntington, H., Kypreos, S., Hughes, A., Silveira, S., DeCarolis, J., Bazillian, M., Roehrl, A., 2011. OSeMOSYS: The Open Source Energy Modeling System: An introduction to its ethos, structure and development. Energy Policy 39, 5850–5870. doi:10.1016/j.enpol.2011.06.033.

[18] Hussein, N.S., Abokersh, M., Kost, C., Schlegl, T., 2016. Electricity Cost From Renewable Energy Technologies in Egypt. Technical Report December. Frauenhofer Institute for Solar Energy Systems ISE. URL: https://www.ise.fraunhofer.de/content/dam/ise/en/documents/publications/studies/Dec2016_Fraunhofer-ISE_LCOE_Renewable_Energy_Technologies_EN_v20_ns.pdf.

[19] IEA, 2019. Energy prices and taxes. First quarter 2019 ed., International Energy Agency, Paris.

[20] IRENA, 2018. International Renewable Energy Agency. Renewable Power Generation Costs in 2017. URL: https://www.irena.org/publications/2018/Jan/Renewable-power-generation-costs-in-2017.

[21] IRENA, LBNL, 2015. Africa Renewable Energy Zones. Technical Report.

[22] Kosmopoulos, P., Kazadzis, S., El-Askary, H., 2018. The Solar Atlas of Egypt. Technical Report. URL: http://geocradle.eu/, doi:10.1017/CBO9781107415324.004, arXiv:arXiv:1011.1669v3.

[23] Kost, C., 2015. Renewable energy in North Africa: Modeling of future electricity scenarios and the impact on manufacturing and employment. Fraunhofer Verlag. URL: http://publica.fraunhofer.de/documents/N-356362.html.

[24] Kotzur, L., Markewitz, P., Robinius, M., Stolten, D., 2018. Impact of different time series aggregation methods on optimal energy system design. Renewable Energy 117, 474–487. URL: https://www.sciencedirect.com/science/article/pii/S0960148117309783, doi:10.1016/J.RENENE.2017.10.017.

[25] Lopion, P., Markewitz, P., Stolten, D., Robinius, M., 2019. Cost uncertainties in energy system optimization models: A quadratic programming approach for avoiding penny switching effects. Energies 12. doi:10.3390/en12204006.

[26] Massachusetts Institute of Technology (MIT), 2018. The Future of Nuclear Energy in a Carbon-Constrained World. Technical Report. Massachusetts Institute of Technology. Cambridge (MA). URL: http://energy.mit.edu/wp-content/uploads/2018/09/The-Future-of-Nuclear-Energy-in-a-Carbon-Constrained-World.pdf, doi:10.1021/es50002a013.

[27] Middle East Eye, 2019. Egypt lowers fuel prices following wave of protests. URL: https://www.middleeasteye.net/news/egypt-lowers-fuel-prices-following-spat-protests.

[28] Mondal, M.A.H., Ringler, C., Al-Riffai, P., Eldidi, H., Breisinger, C., Wiebelt, M., 2019a. Long-term optimization of Egypt's power sector: Policy implications. Energy 166, 1063–1073. URL: https://doi.org/10.1016/j.energy.2018.10.158, doi:10.1016/j.energy.2018.10.158.

[29] Mondal, M.A.H., Ringler, C., Al-Riffai, P., Eldidi, H., Breisinger, C., Wiebelt, M., 2019b. Long-term optimization of Egypt's power sector: Policy implications. Energy 166, 1063–1073. URL: https://doi.org/10.1016/j.energy.2018.10.158, doi:10.1016/j.energy.2018.10.158.

[30] Mortensen, N., Said Said, U., Badger, J., 2006. Wind atlas for egypt, in: Proceedings of the Third Middle East-North Africa Renewable Energy Conference (on CD-ROM).

[31] Moura, G., Howells, M., Legey, L., 2015. A Brazilian Perspective on Power Systems Investment and Integration in South America – using SAMBA (South America Model Base). Review 85. doi:10.20955/r.85.67.

[32] New & Renewable Energy Authority Egypt, 2016. Strategic Environmental & Social Assessment : Final Report. Technical Report February. URL: https://www.miga.org/sites/default/files/archive/Documents/SPGDisclosures/BenbanStrategicEnvironmentalandSocialAssessment-Feb2016-FinalReport.pdf.

[33] Niu, S., Jia, Y., Wang, W., He, R., Hu, L., Liu, Y., 2013. Electricity consumption and human development level: A comparative analysis based on panel data for 50 countries. International Journal of Electrical Power & Energy Systems 53, 338–347. URL: https://www.sciencedirect.com/science/article/abs/pii/S0142061513002263?via{%}3Dihub, doi:10.1016/J.IJEPES.2013.05.024.

[34] NREA, 2018. Renewable Energy Annual Report , 3–37.

[35] Ouki, M., 2018. Egypt - a return to a balanced gas market?:. Technical Report. Oxford Institute for Energy Studies. URL: https://www.oxfordenergy.org/publications/egypt-return-balanced-gas-market/, doi:10.26889/9781784671129.

[36] Pletka, R., Khangura, J., Rawlines, A., Waldren, E., Wilson, D., 2014. Capital Costs for Transmission and Substations. Western Electricity Coordinating Council , 35.

[37] Pothecary, S., 2016. Egypt agrees to international arbitration for PV projects but slashes FITs. URL: https://www.pv-magazine.com/2016/09/07/egypt-agrees-to-international-arbitration-for-pv-projects-but-slashes-fits_100026027/.

[38] Rady, Y.Y., Rocco, M.V., Serag-Eldin, M.A., Colombo, E., 2018. Modelling for power generation sector in Developing Countries: Case of Egypt. Energy 165, 198–209. URL: https://doi.org/10.1016/j.energy.2018.09.089, doi:10.1016/j.energy.2018.09.089.

[39] Reuters, 2019. Egypt lowers fuel prices for first time as part of IMF-backed pricing mechanism. URL: http://news.trust.org/item/20191004073715-pe9ql/.

[40] ROSATOM, 2019. Egypt's Dabaa nuclear plant granted site permit. URL: http://www.rosatom.ru/en/press-centre/industry-in-media/egypt-s-dabaa-nuclear-plant-granted-site-permit/?sphrase_id=913741.

[41] Shouman, E.R., El Shenawy, E.T., Khattab, N.M., 2016. Market financial analysis and cost performance for photovoltaic technology through international and national perspective with case study for Egypt. Renewable and Sustainable Energy Reviews 57, 540–549. URL: http://dx.doi.org/10.1016/j.rser.2015.12.074, doi:10.1016/j.rser.2015.12.074.

[42] Staffell, I., Pfenninger, S., 2016. Using bias-corrected reanalysis to simulate current and future wind power output. Energy 114, 1224–1239. URL: http://dx.doi.org/10.1016/j.energy.2016.08.068, doi:10.1016/j.energy.2016.08.068.

[43] Taliotis, C., Rogner, H., Ressl, S., Howells, M., Gardumi, F., 2017. Natural gas in Cyprus: The need for consolidated planning. Energy Policy 107, 197–209. doi:10.1016/j.enpol.2017.04.047.

[44] Taliotis, C., Shivakumar, A., Ramos, E., Howells, M., Mentis, D., Sridharan, V., Broad, O., Mofor, L., 2016. An indicative analysis of invest-

ment opportunities in the African electricity supply sector - Using TEMBA (The Electricity Model Base for Africa). Energy for Sustainable Development 31, 50–66. URL: http://dx.doi.org/10.1016/j.esd.2015.12.001, doi:10.1016/j.esd.2015.12.001.

[45] Toktarova, A., Gruber, L., Hlusiak, M., Bogdanov, D., Breyer, C., 2019. Long term load projection in high resolution for all countries globally. International Journal of Electrical Power and Energy Systems 111, 160–181. URL: https://doi.org/10.1016/j.ijepes.2019.03.055, doi:10.1016/j.ijepes.2019.03.055.

[46] Trieb, F., Schillings, C., Pregger, T., O'Sullivan, M., 2012. Solar electricity imports from the Middle East and North Africa to Europe. Energy Policy 42, 341–353. URL: https://www.sciencedirect.com/science/article/abs/pii/S030142151100989X, doi:10.1016/J.ENPOL.2011.11.091.

[47] United Nations, Department of Economic and Social Affairs, P.D.., 2019. Probabilistic Population Projections Rev. 1 based on the World Population. Technical Report.

[48] Urban, F., Benders, R.M., Moll, H.C., 2007. Modelling energy systems for developing countries. Energy Policy 35, 3473–3482. URL: https://doi.org/10.1016/j.enpol.2006.12.025, doi:10.1016/j.enpol.2006.12.025.

[49] Verme, P., 2017. Subsidy Reforms in the Middle East and North Africa Region: A Review. doi:10.1007/978-3-319-52926-4_1.

[50] Welsch, M., Hermann, S., Howells, M., Rogner, H.H., Young, C., Ramma, I., Bazilian, M., Fischer, G., Alfstad, T., Gielen, D., Le Blanc, D., Röhrl, A., Steduto, P., Müller, A., 2014. Adding value with CLEWS - Modelling the energy system and its interdependencies for Mauritius. Applied Energy 113, 1434–1445. URL: http://dx.doi.org/10.1016/j.apenergy.2013.08.083, doi:10.1016/j.apenergy.2013.08.083.

[51] Willis, B., 2018. Building Benban: Inside Egypt´s 1.6gw Solar Park. PV Tech URL: https://www.ibvogt.com/home/building-benban.html.

[52] World Bank, 2014. International Bank for Reconstruction and Development Project Appraisal Document on a Proposed Loan to the Arab Republic of Egypt for an Egypt Household Natural Gas Connection Project URL: http://documents.worldbank.org/curated/en/903171468024860655/pdf/PAD9350PAD0P14010Box385274B00OUO090.pdf.

[53] World Bank, 2017. Electricity Transmission Network Egypt. URL: https://datacatalog.worldbank.org/dataset/egypt-electricity-transmission-network-2017.

[54] World Bank, 2019. World Development Indicators. Technical Report.

[55] World Nuclear Association, 2019. Decommissioning Nuclear Facilities. URL: https://www.world-nuclear.org/information-library/nuclear-fuel-cycle/nuclear-wastes/decommissioning-nuclear-facilities.aspx.

Figure 1

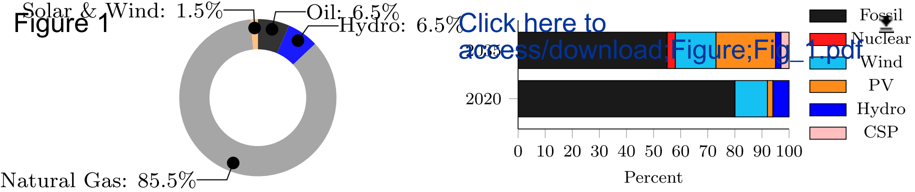
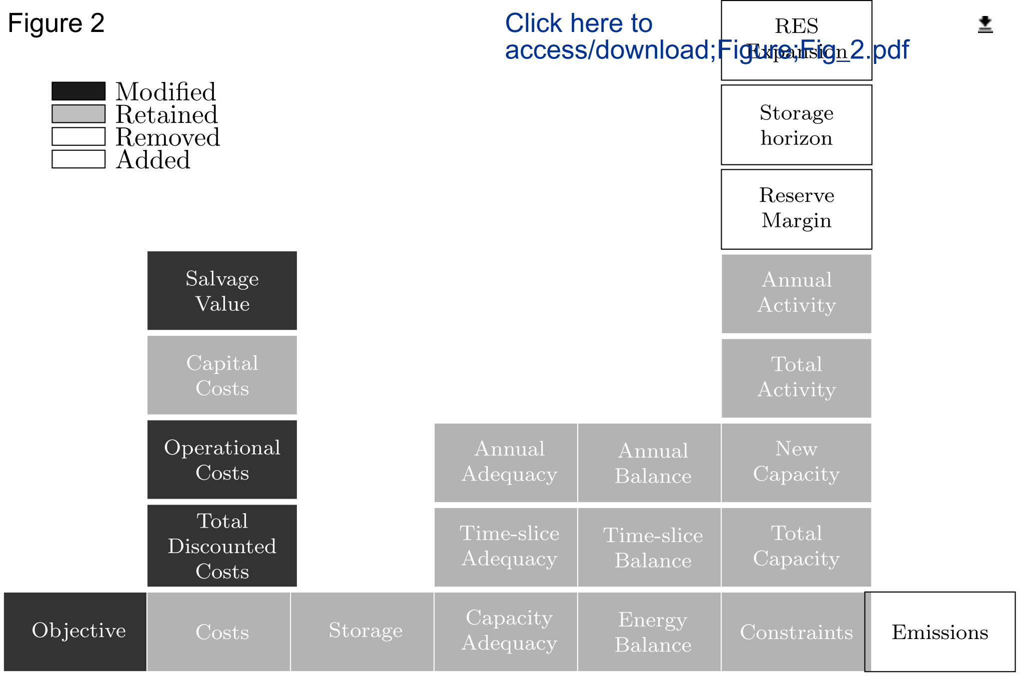
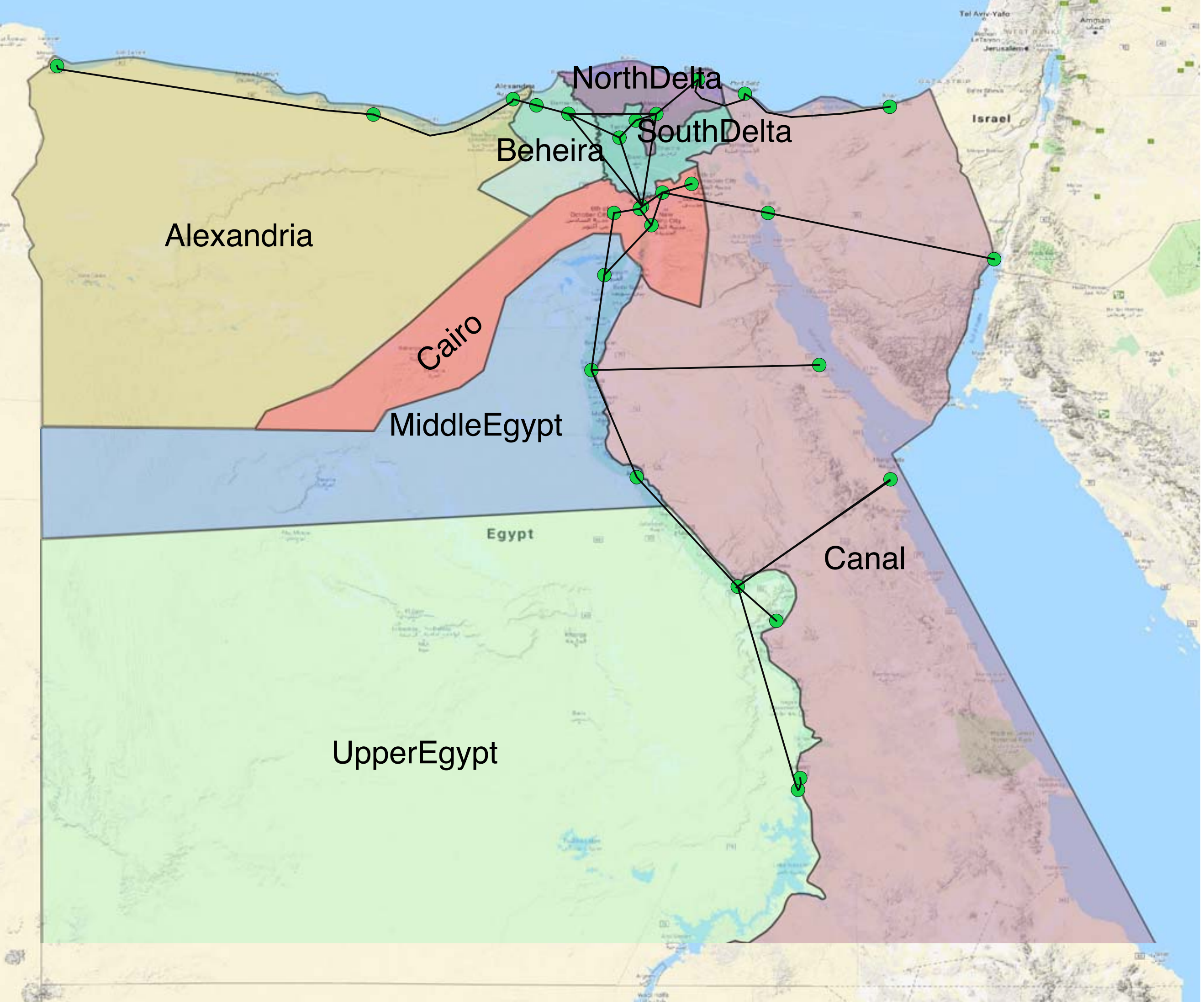

Solar & Wind: 1.5%
Oil: 6.5%
Hydro: 6.5%
Natural Gas: 85.5%
2020
0
10
20
30
40
50
60
70
80
90
100
Percent
Fossil
Nuclear
Wind
PV
Hydro
CSP

Figure 2


Modified
Retained
Removed
Added
RES
Expansion
Storage horizon
Reserve Margin
Salvage Value
Annual Activity
Capital Costs
Total Activity
Operational Costs
Annual Adequacy
Annual Balance
New Capacity
Total Discounted Costs
Time-slice Adequacy
Time-slice Balance
Total Capacity
Objective
Costs
Storage
Capacity Adequacy
Energy Balance
Constraints
Emissions



NorthDelta
SouthDelta
Beheira
Alexandria
Cairo
MiddleEgypt
Egypt
Canal
UpperEgypt
Israel

Figure 4

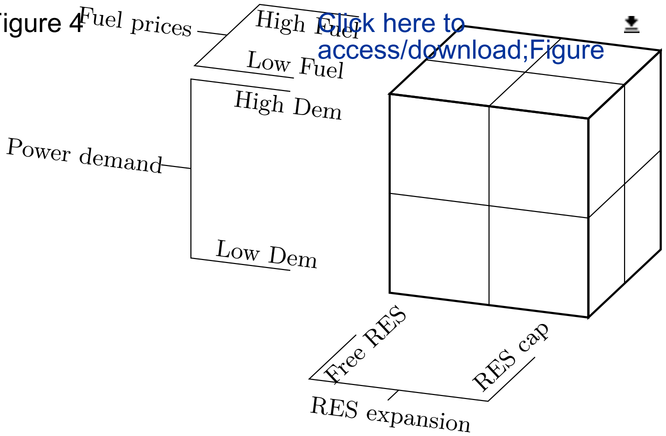

Fuel prices
High Fuel
Low Fuel
Power demand
High Dem
Low Dem
Free RES
RES cap
RES expansion

Figure 5

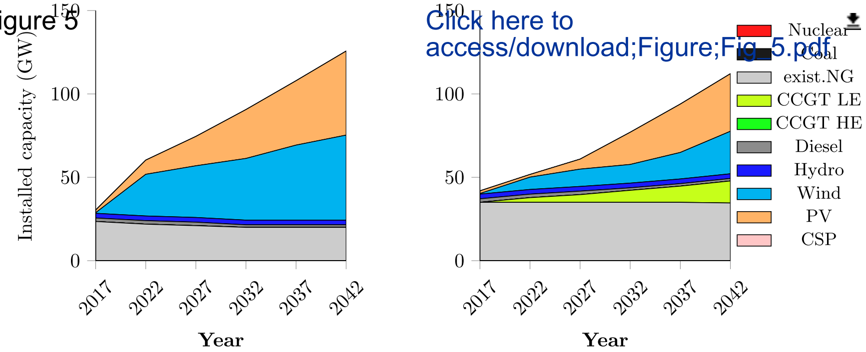
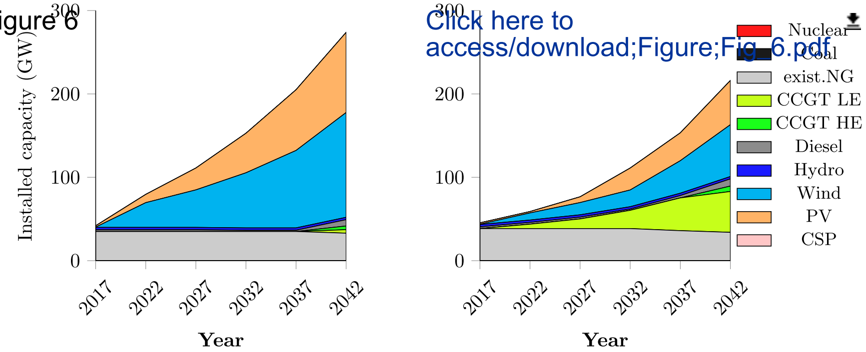

150
100
50
0
Installed capacity (GW)
2017
2022
2027
2032
2037
2042
Year
150
100
50
0
2017
2022
2027
2032
2037
2042
Year
Nuclear
Coal
exist.NG
CCGT LE
CCGT HE
Diesel
Hydro
Wind
PV
CSP

Figure 6



Installed capacity (GW)
0
100
200
300
2017
2022
2027
2032
2037
2042
Year
Nuclear
Coal
exist.NG
CCGT LE
CCGT HE
Diesel
Hydro
Wind
PV
CSP

Figure 7

Click here to access/download;Figure;Fig_7.pdf

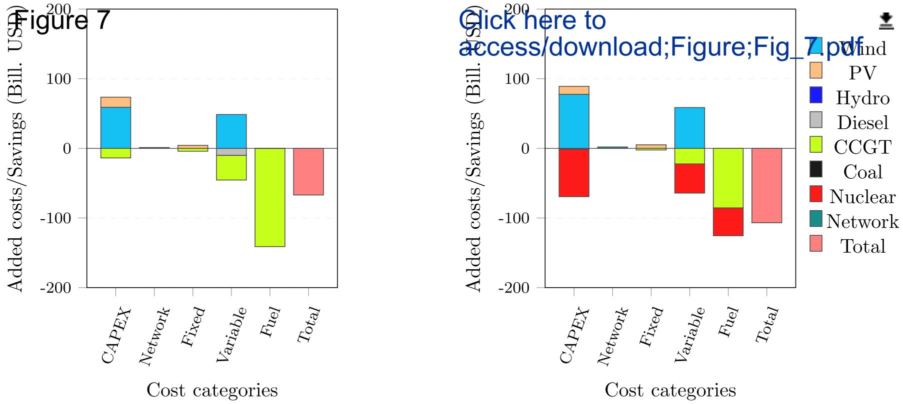


Figure 8

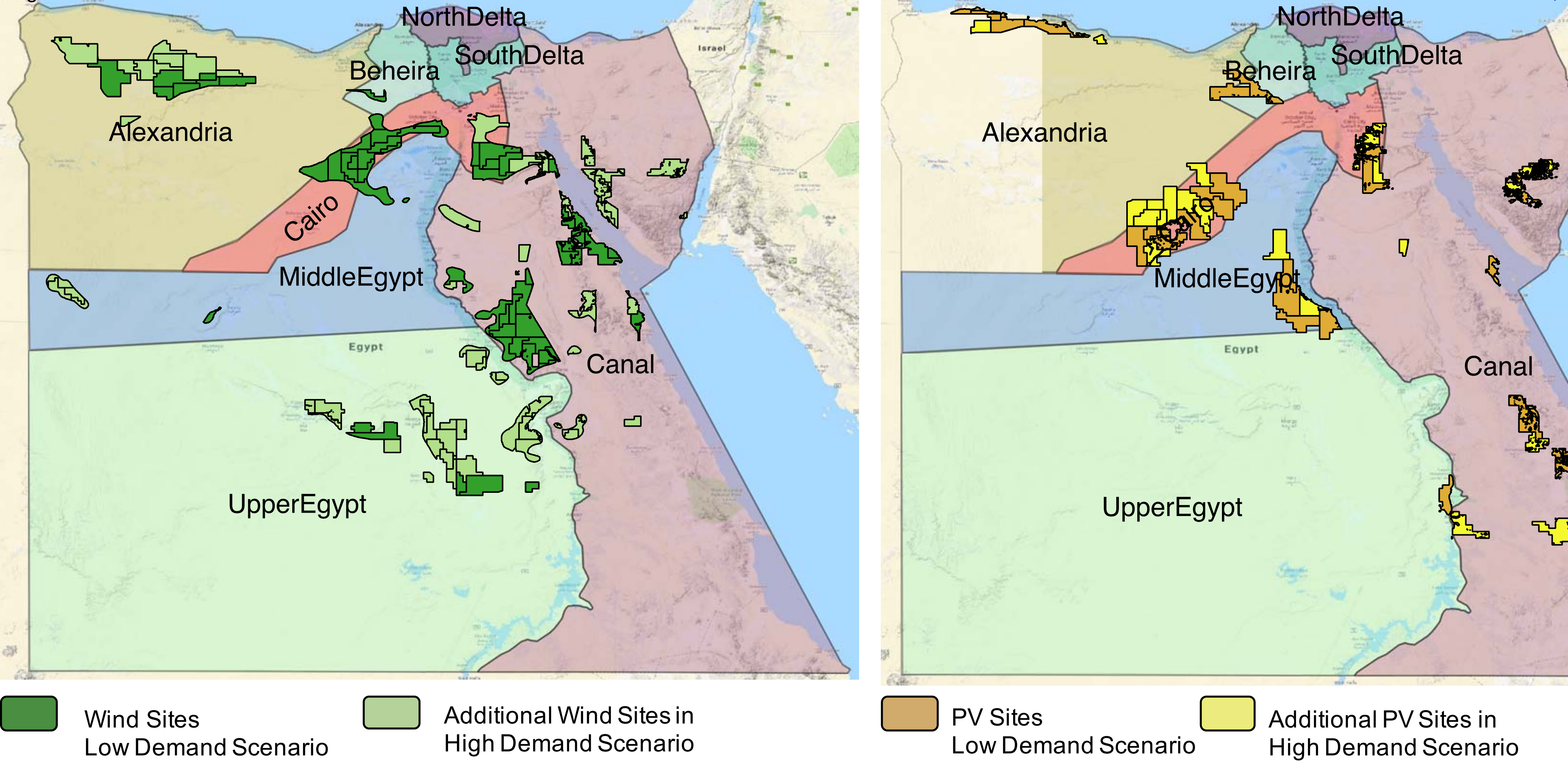
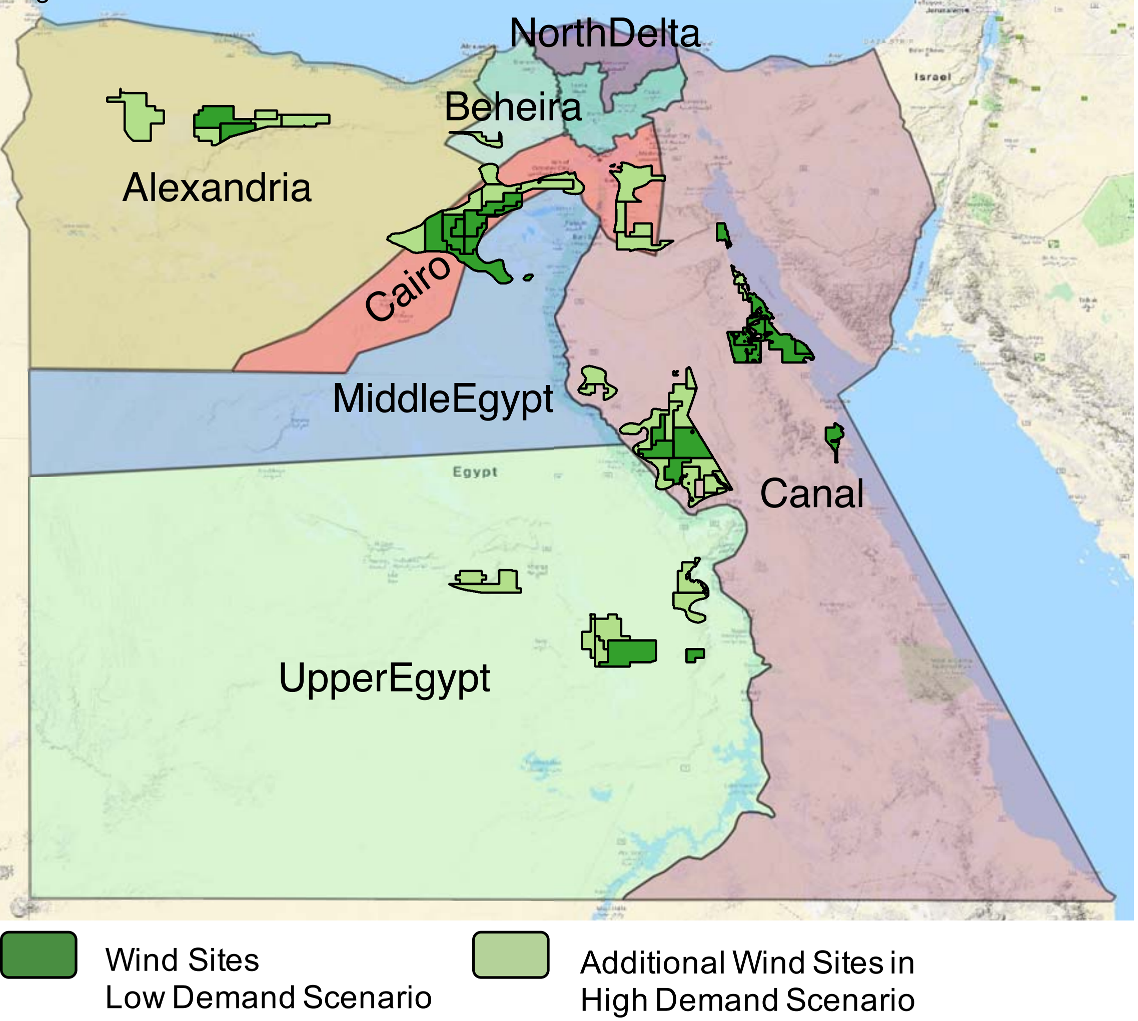

NorthDelta
SouthDelta
Beheira
Alexandria
Cairo
MiddleEgypt
Canal
UpperEgypt
Israel
Egypt
Wind Sites
Low Demand Scenario
Additional Wind Sites in
High Demand Scenario
PV Sites
Low Demand Scenario
Additional PV Sites in
High Demand Scenario

Figure 9


NorthDelta
Beheira
Alexandria
Cairo
MiddleEgypt
Canal
UpperEgypt
Wind Sites
Low Demand Scenario
Additional Wind Sites in
High Demand Scenario

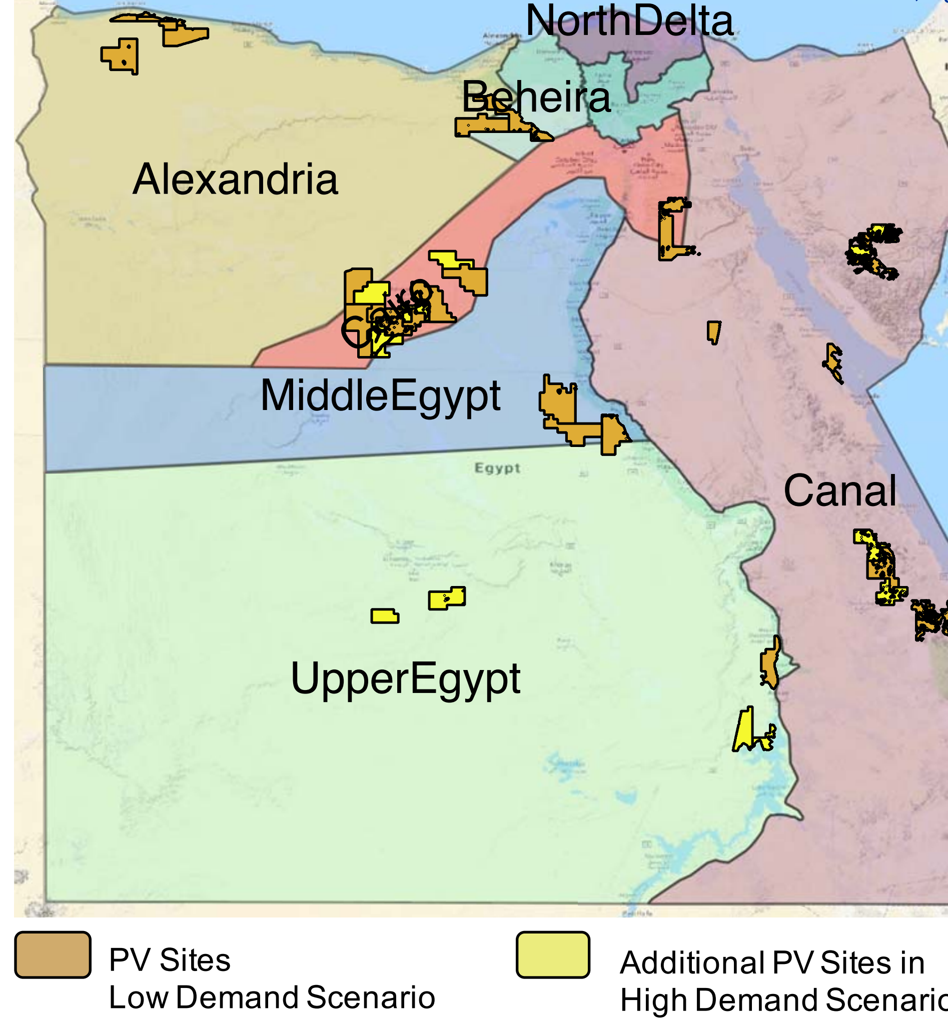
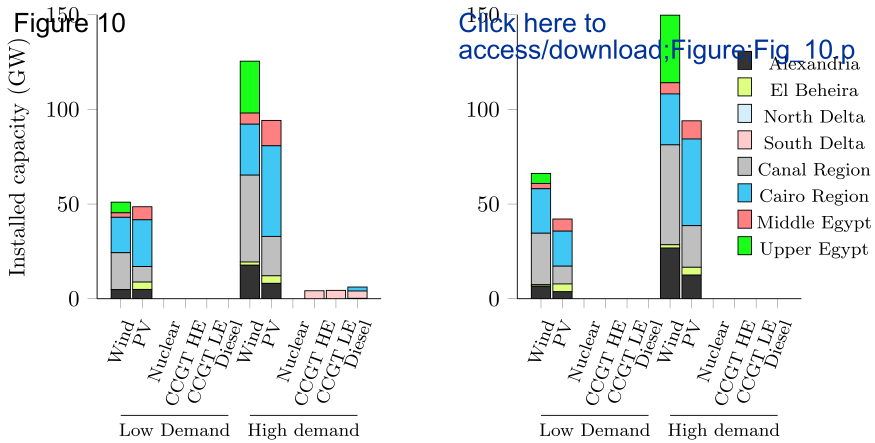

NorthDelta
Beheira
Alexandria
Cairo
MiddleEgypt
Canal
UpperEgypt
PV Sites
Low Demand Scenario
Additional PV Sites in
High Demand Scenario

Figure 10



Installed capacity (GW)
150
100
50
0
Wind
PV
Nuclear
CCGT HE
CCGT LE
Diesel
Low Demand
High demand
Alexandria
El Beheira
North Delta
South Delta
Canal Region
Cairo Region
Middle Egypt
Upper Egypt

Figure 11

Click here to access/download;Figure;Fig_11.p

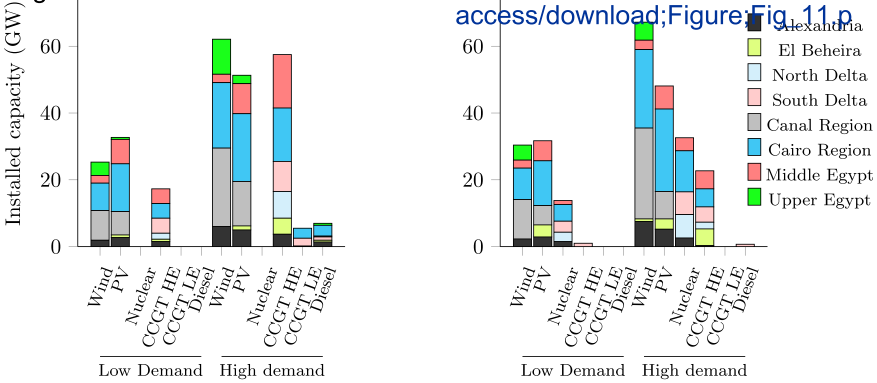


Figure 12

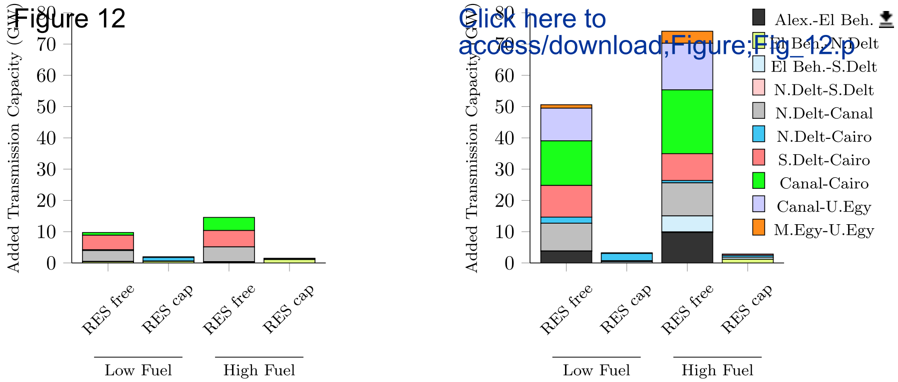

Added Transmission Capacity (GW)
0
10
20
30
40
50
60
70
80
RES free
RES cap
RES free
RES cap
Low Fuel
High Fuel
Alex.-El Beh.
El Beh.-N.Delt
El Beh.-S.Delt
N.Delt-S.Delt
N.Delt-Canal
N.Delt-Cairo
S.Delt-Cairo
Canal-Cairo
Canal-U.Egy
M.Egy-U.Egy

Figure 13

Click here to access/download;Figure;Fig_13.p

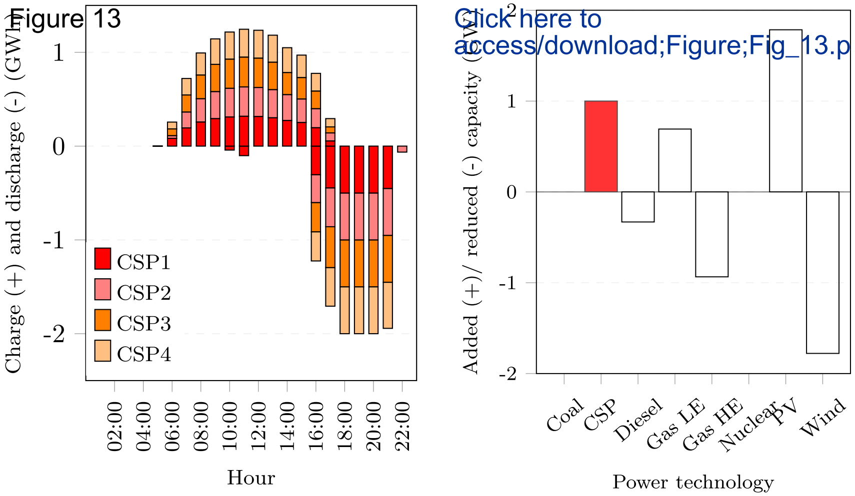


Figure A.1

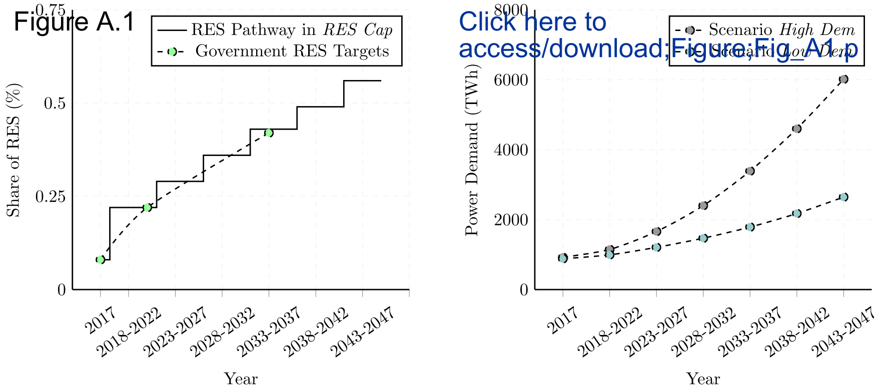
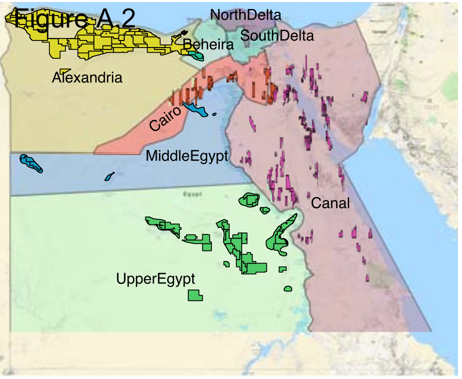
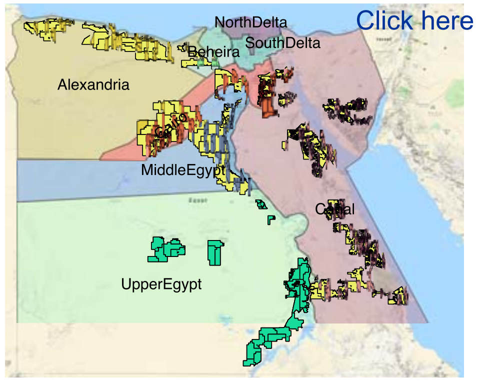

RES Pathway in *RES Cap*
Government RES Targets
Share of RES (%)
0.75
0.5
0.25
0
2017
2018-2022
2023-2027
2028-2032
2033-2037
2038-2042
2043-2047
Year
Scenario *High Dem*
Power Demand (TWh)
8000
6000
4000
2000
0
2017
2018-2022
2023-2027
2028-2032
2033-2037
2038-2042
2043-2047
Year

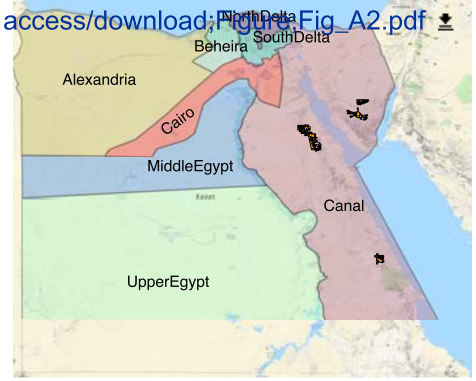
Figure A.2



(a) Potential wind production sites

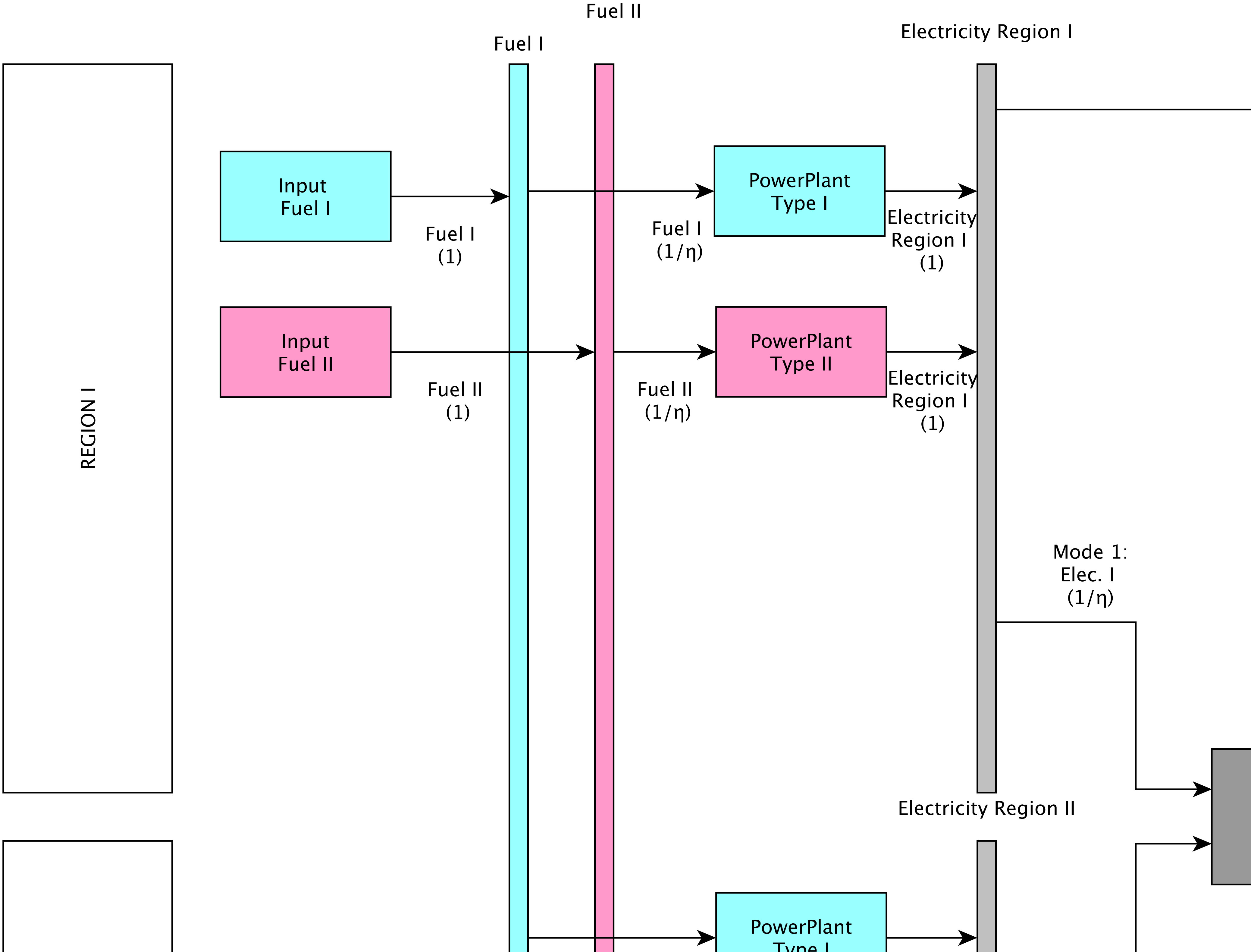


(b) Potential PV production sites



(c) Potential CSP production sites

Figure A.3



Fuel I
Fuel II
Electricity Region I
REGION I
Input Fuel I
Input Fuel II
Fuel I (1)
Fuel II (1)
Fuel I (1/η)
Fuel II (1/η)
PowerPlant Type I
PowerPlant Type II
Electricity Region I (1)
Electricity Region I (1)
Mode 1: Elec. I (1/η)
Electricity Region II