# *Complex Modeling and Analysis of the Energy Systems of Afghanistan*

Sabrina Sabella

*A thesis submitted to the faculty at the Royal Institute of Technology in partial fulfillment of the requirements for the Nordic Master's Programme in Innovative Sustainable Energy Engineering in the Division of Energy Systems Analysis.*

April 2021

KTH Royal Institute of Technology and Aalto University

# *Master of Science Thesis*

## *Complex Modeling and Analysis of the Energy Systems of Afghanistan*

Author: Sabrina Sabella

**Double Degree Master's Programme in Innovative Sustainable Energy Engineering**

Advisor at KTH: Vignesh Sridharan

Supervisor at Aalto: Mika Järvinen

Aalto University
School of Engineering

Aalto University, P.O. Box 11000, FI-00076 Aalto aaltoGraywww.aalto.fi

## Abstract

**Author**
Sabrina Sabella

**Title**
Complex Modeling and Analysis of the Energy Systems of Afghanistan

**School** School of Engineering

**Master's programme** Nordic Master Programme in Innovative Sustainable Energy Engineering

**Supervisor** Mika Järvinen

**Advisor** Vignesh Sridharan

**Level** Master's thesis **Date** 26 Apr 2021 **Pages** 30 + 10 **Language** English

**Abstract**

This Master's Thesis aimed to use quantitative analysis to explore different pathways for the sustainable development of Afghanistan. The Open Source Energy Modeling System (OSeMOSYS) was adopted to build an energy model of the country. Electricity demand projections for residential, industrial and commercial sectors were created using both a bottom-up and a top-down approach. These were then used as input data for the optimisation model. Starting from the Reference scenario, three additional scenarios were elaborated: Limit Import scenario, Renewable scenario and National Policies scenario. These showed different options of the least-cost energy mix and explored fundamental aspects to be considered for sustainable development, such as grid access, energy reliability, efficiency and costs, potential of renewable energy. In detail, the Limit Import scenario restricted electricity import up to 60% by 2050. The Renewable scenario applied the following constraints of minimum RE penetration: 20% by 2020, 30% by 2030, 40% by 2040. The National Policies scenario implemented the capacity of power plants that were already planned and commissioned by the country's future plans. The results highlighted a strong dependency on import as well as a consistent fossil-fuel baseload across all scenarios. Even if the investment costs were decreasing over time, renewables would enter the mix only if strict targets were applied. Hydro power represented the only green technology to play a bigger role in the mix. Overall, the results of this study could be used as an informative source for the national policy makers.

**Keywords** Afghanistan, energy systems, energy demand, OSeMOSYS, scenarios, optimisation

# ACKNOWLEDGMENTS

To my best friend Marcelanko, without her I would have never finished this work and I would have never believed in myself and succeeded in life as she (insistently) taught me I could have.

# CONTENTS

# LIST OF FIGURES

# LIST OF TABLES

# LIST OF ABBREVIATIONS

APSMP - Afghanistan Power Sector Master Plan
BAU - Business As Usual
dESA - The division of Energy System Analysis at KTH
ESMAP - The Energy Sector Management Assistance Program
GDP - Gross Domestic Product
GHG - Greenhouse Gas
GoA - Government of Afghanistan
LCOE - Levelized Cost of Energy
MoManI - The Model Management Infrastructure
MTF - Multi-Tier Framework
NG - Natural Gas
OnSSET - Open Source Spatial Electrification Tool
OSeMOSYS - Open Source Energy Modelling System
PP - Power Plant
PPA - Power Purchase Agreement
PV - Photovoltaics
RE - Renewables
RES - Reference Energy System
SE4ALL - Sustainable Energy for All initiative
SDGs - Sustainable Development Goals
TPES - Total primary Energy Supply

# 1. INTRODUCTION

The world's energy sector is currently going through a phase of transition towards cleaner power generation. It is fundamental to consider an equal and sustainable development of countries that have not been included in this revolution yet.
Afghanistan is one of the poorest countries in the world ($16^{th}$ poorest country in terms of GDP according to the Global Finance Magazine [Ventura, 2019]). However, its abundance and diversity in natural resources offer it the potential to become an incredible resource for both its economy and society.

## *1.1 Country Context*

Afghanistan has endured over 40 years of uninterrupted war and its consequences on the current state of the country's economy and society are immense. Their dependency from economic assistance from other countries is so high, that the current level of annual aid is almost the same amount as the country's GDP, and it is unlikely that this level of support will still be sustained in the future.[Goepner, 2018]

Afghanistan's access to the grid electricity is among the lowest in the world [Korkovelos et al., 2017]. While in urban areas, around 89% of the population has access to a few hours per day of uninterrupted supply of electricity, only 11% of the rural Afghan population is connected to the power grid. [The World Bank, 2018] Considering that 75% of the population lives in rural areas [The World Bank, 2021], overall, only 29.7% of the households receives power directly from the grid.[Central Statistics Organization, 2016]

In 2015, 78% of the total electricity consumption in Afghanistan was imported from neighboring countries, such as Tajikistan, Turkmenistan, Uzbekistan, and Iran. [Irving and Meier, 2012] Even though imports have helped the growth of Afghanistan's electricity consumption, they are not synchronized between each other. As a result, the transmission system is fragmented, composed of isolated grids supplied by different power systems. [Asian Development Bank, 2012] Securing the stability and reliability of the supplies is one of the greatest challenges and priorities for the Afghan government.[Aminjonov, 2016]

Afghanistan has a deficient electricity connection and poor self-sufficiency, whereas it presents excessive energy resources on its territory. In the demand projection, presented in chapter 3, the demand is estimated to be around 3500 MW in 2032. The country has the potential to install 23,000 MW of hydro-power, 67,000 MW of wind-power, and 222,000 MW of solar power production capacities.[The World Bank, 2018] Thus, renewable technologies could not only fulfill Afghanistan own electricity demand, but could be exported to other countries [Rostami et al., 2017].

Integrating renewables (RE) in the electricity supply would be another unique challenge for the country. However, for the success of these undertakings, Afghanistan needs to overcome several limitations such as security and political risks, technical barriers, commercial risks, financing barriers, gaps in the legal and regulatory framework, and to find new sources of growth for the long-term stability.[The Asia Foundation, 2016]

## 1.2 Research Question

The thesis work aims to answer the following research question: *'What are the possible different pathways for the future development of Afghanistan's energy sector, which could positively affect both the economy and the society?'*

## 1.3 Objective

The key objective of this work is to use different energy scenarios that could indicate the most convenient and feasible pathways for the future of Afghanistan. A time frame from 2019 until 2050 is considered. A Multi-Criteria Analysis is conducted to assess the impact that each scenario has on the economic and social aspects of the country.

## 1.4 Scope and Limitations

The energy model covers the whole Afghanistan's territory.
The scope is narrowed to the analysis of electricity generation and demand, thus even thermal units such as coal and gas are assumed to be generating electricity only. The demand used in the model is not covering the total energy demand of the country, since it is limited to the residential, commercial, and industrial sectors only. Emissions and energy storage options are not considered in the modeling, which indeed limit the use of this study, for example for carbon emissions policies.

# 2. LITERATURE REVIEW

Several studies have been conducted regarding the energy situation in Afghanistan and its future development.

A work regarding planning electrification in Afghanistan has been developed by the division of Energy System Analysis (dESA)at KTH [Korkovelos et al., 2017]. The study focuses on the capture of quantitative data used on a geospatial modeling platform called OnSSET (Open Source Spatial Electrification Tool). Afghanistan presents a huge diversity in terms of demography, terrain types, wealth levels, resource availability, and access to infrastructure. Because of this, gathering multiple data into a unique software, surely can ease the creation of an electrification project for the country. The results of the study indicate that the most efficient and cost-effective way to achieve the electrification goals for the country, are to pursue decentralized and centralized electrification in a complementary manner. DESA study manages to identify the most optimal and affordable solution to increase the electrification rate in the country. However, this thesis work gives an additional breakdown on the costs and on the optimal use of the resources, presenting their respective shares in the electricity generation. An interesting outcome would be to combine the two software, OnSSET and OSeMOSYS, to generate a very powerful analysis and planning tool. Additionally, in this thesis work the demand for industry and commercial sector is considered, as well as a longer time-frame until 2050.

The Afghanistan Power Sector Master Plan (APSMP) is a study also based on optimization models [Fichtner GmbH & Co, 2013]. It provides the forecasts of possible projects that would allow meeting the forecasted demand growth. The work gives a general insight into the Afghan energy sector and its expansion opportunities, especially within the transmission network. The study was carried in 2013, thus most of the data need an update, as well as an extension of the time frame which was only up until 2032. What is more, most of the planned investments in the power sectors were finally delayed or postponed, thus this needs to be taken into account for future planning and provide even stronger consideration of uncertainties and risks. The paper does not consider the potential of renewables either.

Renewables potential is more developed by the Afghanistan Renewable Energy Development paper [The World Bank, 2018]. It assesses the potential of natural resources in Afghanistan. It also evaluates the viability of RE usage on the supply side to cover 10% of national demand by 2030. This goal is set by the Government of Afghanistan (GoA). At the same time, the study indicates possible obstacles to achieve this target. Such an approach is crucial while planning new power units. Nevertheless, apart from a theoretical assessment, it does not contain an optimization model itself.

# 3. METHODOLOGY

The following chapter presents an overview of the methodology used to build the energy system model of Afghanistan and its scenarios. Building a model that could give a satisfying representation of the country's actual situation, needs a detailed approach. The work has been divided into four steps. Firstly, a thorough data collection has been carried out; Afghanistan's socio-economic data, as well as fuels, technologies, and related costs have been collected, using the most reliable sources accessible online. Secondly, an electricity demand projection has been created to be used as an input for the optimisation model. Afterwards, several parameters and criteria have been set, using the MoMani interface, to build a complete energy model. Finally, a Multi-Criteria Analysis has been performed. The latter uses the outcomes of the optimisation software to calculate relevant indicators.

## *3.1 Demand Projection*

A crucial parameter to build an energy system model is the electricity demand. In order to build scenarios with a long time-frame, Afghanistan's demand was forecasted until 2050. Scarcity of data led to the decision to proceed with a mixed top-down and bottom-up approach.

One of the first variables that influences the electricity demand is the country's population. Therefore, past and forecast population data from 1950 until 2050 have been downloaded from the United Nations Statistic Division [United Nations, 2019]. A distinction between rural and urban areas has been considered to have a better depiction of the reality of the country. This was decided due to the profound energy access differences between the two areas and considering their historical different growth profiles.

Energy access is another key factor and it shows the economic, social, and technical development of a country. The measurement of energy access has historically been a matter of concern for governments and development agencies. The Energy Sector Management Assistance Program (ESMAP), under the Sustainable Energy for All (SE4ALL) initiative, has developed the Multi-tier Framework (MTF) to measure, track, and evaluate energy access by following a multidimensional approach. [ESMAP, 2019] MTF defines energy access in a multi-dimensional definition as "the ability to avail energy that is adequate, available when needed, reliable, of good quality, convenient, affordable, legal, healthy and safe for all required energy services" [ESMAP, 2019]. That is, having an electricity connection considers different factors, as affordability and reliability. Energy access is therefore measured in a tiered-spectrum, from Tier 0 (no access) to Tier 5 (the highest level of access). The MTF was used as one of the parameters to calculate the demand projection. For a more indicative representation of the electricity consumption per household considered for each tier, please see the Appendix.

For the purpose of this thesis, the created demand projection includes three sectors: the residential, industrial and commercial. The overall forecast was split, considering separately the residential sector from the industrial and commercial ones. The residential demand was projected using a bottom-up approach. This decision was taken due to the availability of more parameters, such as Tier levels, electrification rates, and population for urban and rural areas. Due to scarcity of data, the industrial and commercial demand was projected using a top-down approach. Moreover, two separate final energy demand forecasts were created, assuming two different scenarios, one of prosperous growth and the other one of slower development. The positive growth scenario and the negative growth scenario mainly differentiate from each other in terms of electrification. Electrification rates starting from 2019 were assumed to be 89% for the urban areas and 11% for the rural areas. [Korkovelos et al., 2017]

In the positive growth scenario, Afghanistan is assumed to be fully electrified by 2030 (i.e reaching 100% electrification in both urban and rural areas). Also, using assumptions of consumption taken from the study of Korkovelos [Korkovelos et al., 2017], it is further assumed that the urban population will reach Tier 5, while rural Tier 3, in 2030. Developing countries show a typical trend of growth in population over the years [The World Bank, 2021]. Because of this, it is deduced a consequential increase in consumption, which is connected to the rise of the Tier level for the rural area until Tier 4 in 2050. It is worth to remind that in Afghanistan 75% of the population currently lives in rural areas [The World Bank, 2021].

In the negative growth scenario, although starting from the same Tier levels as in the previous projection, the rate of growth in energy consumption is assumed to be much slower. Therefore, in this case, the urban and rural areas reach respectively Tier 5 and Tier 3 only in 2050.

The total energy consumption for each year for the residential sector is calculated considering the number of people per household, as well as its forecasted values for the future, the total urban and rural population, the level of electrification, and the Tier targets selected. Figure 3.1 below shows the final results for the residential sector.

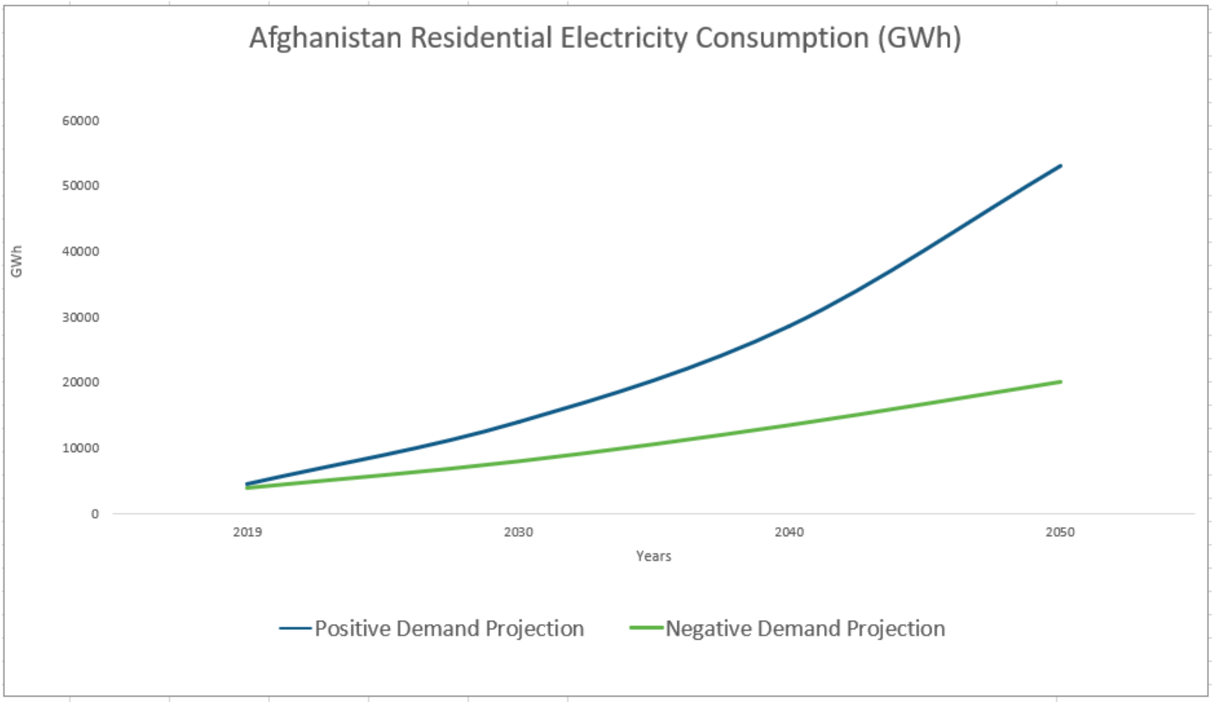


*Fig. 3.1:* Residential Electricity Consumption

It is worth mentioning that the APSMP [Fichtner GmbH & Co, 2013] predicts an electricity consumption of 4190 kWh per person by 2030 for urban areas and a consumption of 1301 kWh for rural areas. The total population is forecasted to reach 46,700,000 by 2030 [The World Bank, 2021]. At the moment, the global average is 3126 kWh, which means that even if Afghanistan will face a decade of energy development and progress, in ten years from now it will still be far behind the global average level of consumption, according to the forecasted levels.

In order to forecast the electricity consumption for the industrial and commercial sectors, a top-down approach has been followed by using a simple linear regression. Linear regression is commonly used as a quantitative method to determine an underlying trend between different variables. Data of GDP per capita and total electricity consumption, starting from 2000 until 2019, have been collected, defining the two variables under analysis. The correlation between GDP and electricity consumption has been assessed by considering electricity as the dependent variable and GDP as the independent variable. Thanks to the linear association between these two variables, it is possible to forecast their values until 2050. The Data Analysis tool of Excel has been used for this purpose and to extrapolate the needed coefficients.

Top-down approaches are known to usually overestimate forecasting outcomes. Indeed, the results obtained for Afghanistan from the regression looked too promising to be realistic. As a consequence, the value of the industrial and commercial sectors' combined share were limited to 44.6% of the forecasted total electricity consumption. The industrial sector was assumed to cover 36% of the total electricity consumption, while the commercial sector only 8.6% [energypedia.info, 2020]. Due to lack of data for Afghanistan, these numbers were chosen by retrieving the shares of industrial and commercial sectors in the neighboring Turkmenistan [Danish et al., 2017]. Since the residential demand projection was supported by more accurate data, no adjustments were needed. Its share in the total demand (accounting for 55.4%) was maintained fixed during the analysed time period. All these values are considered cumulatively throughout the whole time horizon.

Analysing both positive and negative demand projections was useful to understand the possible different outcomes for the future of the country. However, since the purpose of this work is to explore future pathways of energy development, it was decided to use the positive demand forecast. In this way, the model could have less limitations and more opportunities of investments. The final positive demand forecast for the three analysed sectors is shown in Figure 3.2 below, whereas the negative demand forecast can be found in the Appendix.

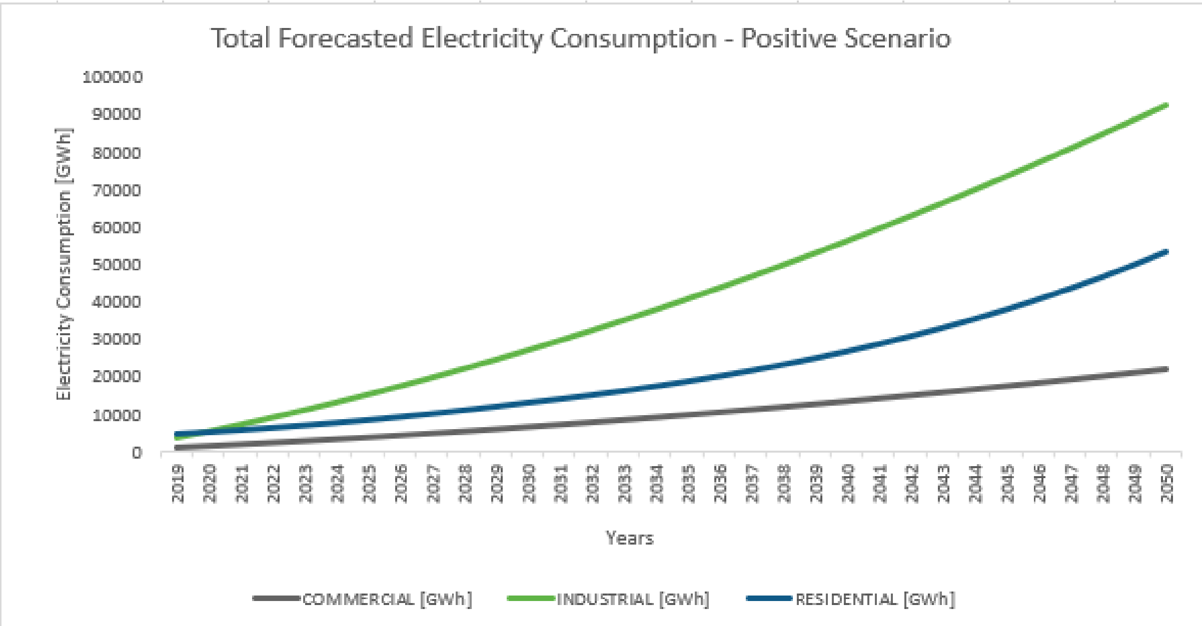


*Fig. 3.2:* Positive Demand Projection

## 3.2 OSeMOSYS Model

OSeMOSYS (Open Source Energy Modeling System) is an optimisation model for long-term energy planning. [Almulla et al., 2019] The software enables energy system optimisation through linear programming. This means that, for each scenario, an optimal solution is found by minimising the total costs, while covering the specified demand with a suitable energy mix. As an input, the user sets several parameters that act as constraints for the model.

MoManI (Model Management Infrastructure) is a browser-based interface that allows the user to insert data, build scenarios, and visualise the final results.

### *Reference Energy System*

When developing a model in an optimisation software such as OSeMOSYS, the energy system needs to be mapped. This is necessary to identify all the relevant technologies that will be involved and to simplify the modeling process. In addition, it can ease its comprehension to external parties. Figure 3.3 represents the Reference Energy System (RES) of the Afghanistan model. This diagram helps visualising the energy system that needs to be built. On the left of the figure, the primary energy resources are listed. The arrows represent the energy flows. Moving from the left to the right, the energy carriers are transformed through different technologies to ultimately meet the final energy demand for different end sectors. The latter are presented by the technologies at the very right-hand side of Figure 3.3.

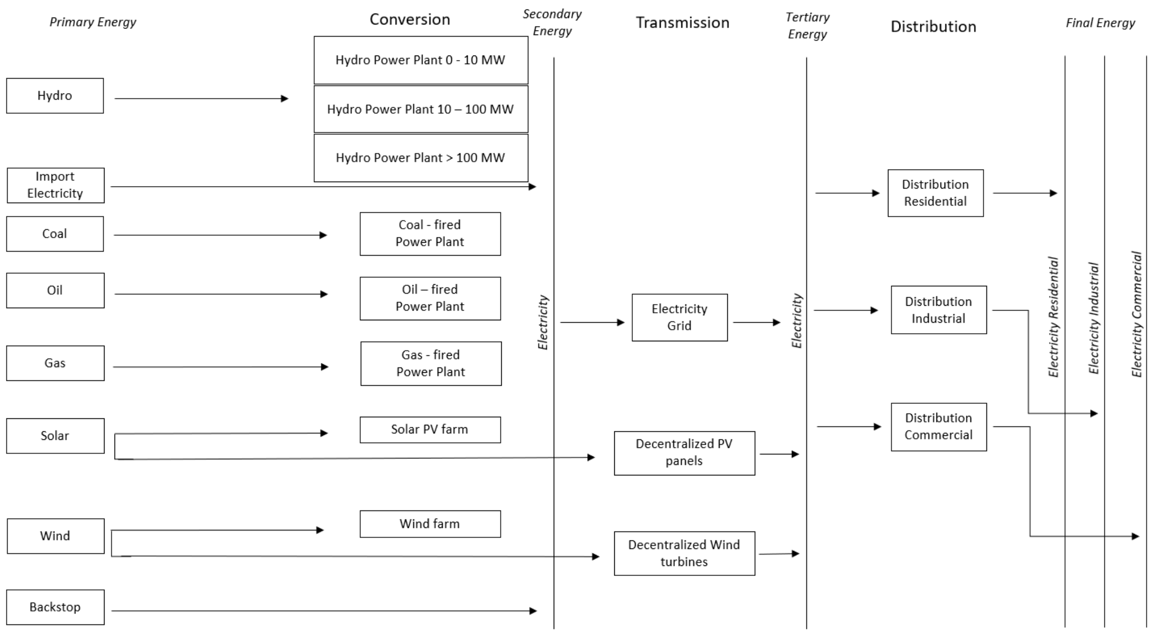


*Fig. 3.3:* Reference Energy System

## 3.3 Structure of the Model

The sets are the initial base of the model and the main independent values. Below are presented the main sets used in this model.


*Fig. 3.4:* Set Data in OSeMOSYS

Fuels and technologies represent any element of the energy system that takes part in the process of electricity generation for the country.

The primary sources of generations used in Afghanistan are hydro-power and import electricity from neighboring countries. Other sources of generation such as gas, oil, coal, solar, and wind are present in the region. For more detail on the data used in the model, please see the Appendix, under Model Assumptions and Power Plants Data. In the aforementioned sections, it is possible to find all the data that were used as an input in the model, both in terms of the type and total capacity of Afghanistan's power plants, as well as the costs and assumptions associated to them.

A key parameter in energy models is also the time frame of the model itself. When defining the time frame it is also critical to understand that energy, in particular electricity, is used at different times. As a general assumption, 2/3 of the electricity is used during the day, whereas only 1/3 is used during the night. In OSeMOSYS, it is possible to define the fraction of the different times of the year through the parameter year split. The parameter Specified Demand Profile allows to allocate the different shares of energy consumption to the defined year splits.

The parameters are numerical inputs to the model set by the user. These values are not fixed throughout the entire modeling period, but vary according to a particular scenario and assumptions considered. OSeMOSYS works by relating all the inputs and outputs of a technology, i.e. every activity needs to be related to the capacity of each technology. The parameters that make this correlation possible are included in Figure 3.5 below.

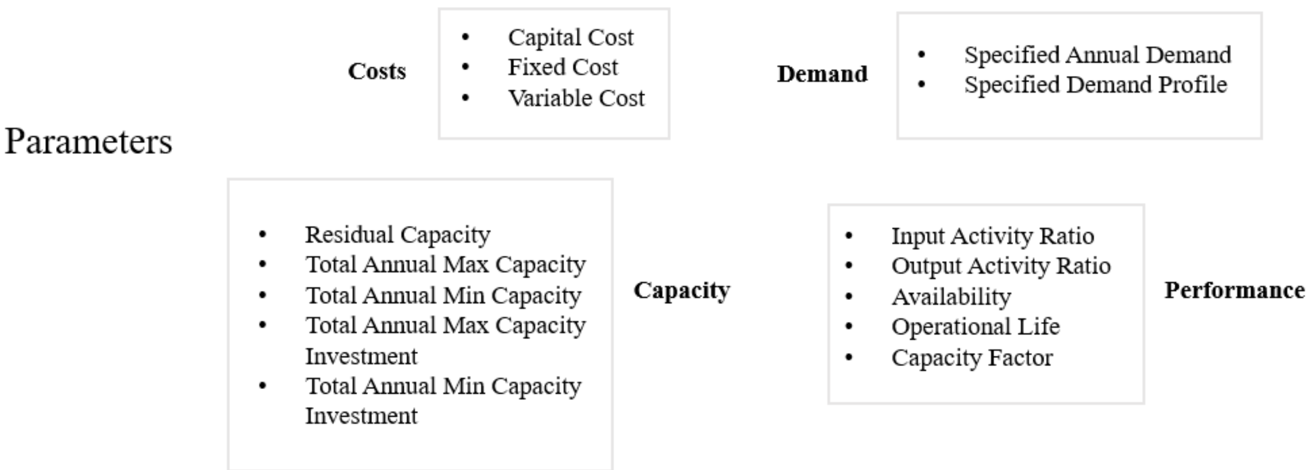


*Fig. 3.5:* Parameters in OSeMOSYS

## 3.4 Model Scenarios

### *Reference Scenario*

The core part of the country's energy model is the Business As Usual Scenario (BAU). This represents the base from which additional scenarios, with different constraints, can be derived.
In the base scenario, almost no constraints were set for investments, thus the model can freely invest in all technologies.

One of the limitations present in the model, was to gradually restrict import electricity from 80% to 60% by 2050. Globally, the energy demand is expected to increase, especially in developing countries such as Afghanistan [Danish et al., 2017]. It was therefore assumed that neighboring countries will not have the same freedom to export their generation to Afghanistan in the future [Afghanistan Analysts Network, 2015].
Correlated with the previous assumption, the model also increases the cost of import electricity of 10% every year. This gives a closer representation of the real costs that the country might face with a continuous import from neighboring country over the years. Moreover, the current import electricity costs are extremely low (accounting for \$0.06–\$0.10 per kWh on average). Such a high rate of increase was assumed in order to give the model more opportunities to invest in other technologies aside import electricity.

*Limit Import Scenario*

This scenario was considered an interesting case study to evaluate the changes in the energy mix if the imports were strongly limited across the modeling time frame. The import limit started already in 2019 at 70% and gradually increased throughout the time horizon until reaching 40% of maximum allowed import electricity use in 2050.

*Renewable Scenario*

This scenario had its focus on increased penetration of Renewable Energy Technologies. These have been part of the energy mix of developed countries for quite a few years already. However, for countries with poor regulatory frameworks and physical infrastructure, like Afghanistan, it will indeed be much harder to see a greater deployment in the future. This scenario showed the implementation of RE with fixed targets to analyse the impact on the energy system. For instance, the following lower constraints were used in the model, in terms of minimum RE penetration:
-20% by 2020
-30% by 2030
-40% by 2040

*National Policies Scenario*

National plans, such as the Power Sector Master Plan (APSMP) [Fichtner GmbH & Co, 2013], were used to assess the impact of the commissioned power plants on the energy mix. In OSeMOSYS, this was implemented by defining both a minimum and a maximum capacity of these planned power plants in each year. According to the Power Sector Master Plan study, more than 3000 MW were planned to be added to the national system only by 2025.

# 4. RESULTS AND DISCUSSION

This chapter presents the final results of the different scenarios. Moreover, some considerations are elaborated regarding the most promising scenario for the country. OSeMOSYS returns the least-cost mix (i.e. the most economical investment solution) and its total needed investment. In the reality, the future energy investment budget is unknown, but constrained. This must be considered as a limitation of the model itself. It is then policy and decision-makers that are responsible for the selection of the best strategies to achieve the national targets.

## *4.1 Modeling Results*

*Reference Scenario*

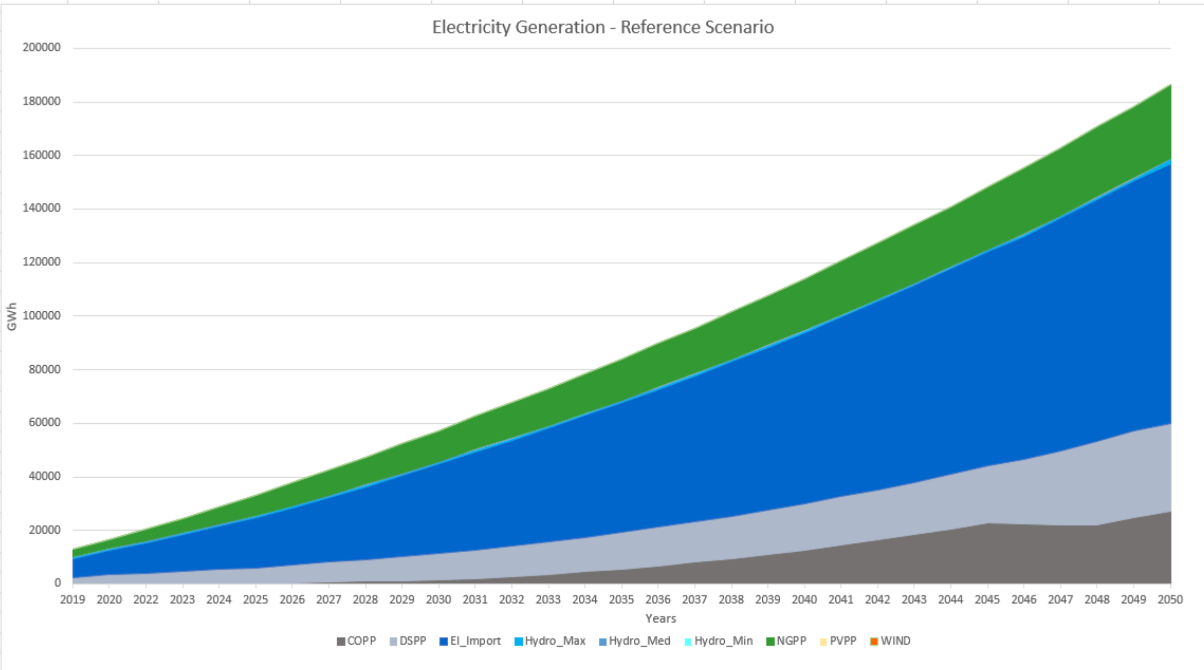


*Fig. 4.1:* Electricity Generation - Reference Scenario

While running the simulations of the Reference Scenario, it became clear that if the import electricity was limited to only 80% across the modeling period, renewable sources did not contribute in the supply mix. RE presented a slightly bigger share in the mix only if the import was capped to 60%. Since in the scenario, imports were gradually limited from 80% in 2019 to 60% by 2050, RE started to play a more relevant role only close to 2050. However, during the first years (2020-2025) of the modeling period, the model invested almost 6% on hydro. This can be justified by the historical supply data used as an input in the model, as well as the lower demand.

Excluding these first years, across the whole study period, hydro contributed only around 1%. Only closer to 2050 its share grew to around 2%. This can be seen in Figure 4.1, where hydro generation is represented in light blue. PV and wind generation presented such a small share (less than 1%) that it is barely visible on the graph.
Overall, the results showed that the current least-cost energy mix would include electricity import and a baseload generation of coal, diesel, and NG. Fossil fuels would then optimally supply most of the power consumption. Their contribution started in 2020 around 25% and reached almost 39% in 2050, increasing together with the constraint on imports. NG and diesel generation were responsible for most of the fossil fuel generation, with coal constituting 2% in 2020 to 10% in 2050.
In the reality, the current data of the energy mix in Afghanistan show a contribution of 20% of hydro-power plants, which is not reflected by this model [The World Bank, 2018]. Since an optimisation software was used and it was free to invest in different technologies, it picked the cheapest of the mix, which at the prices considered in this work, were fossil fuels-based.

*Limit Import Scenario*

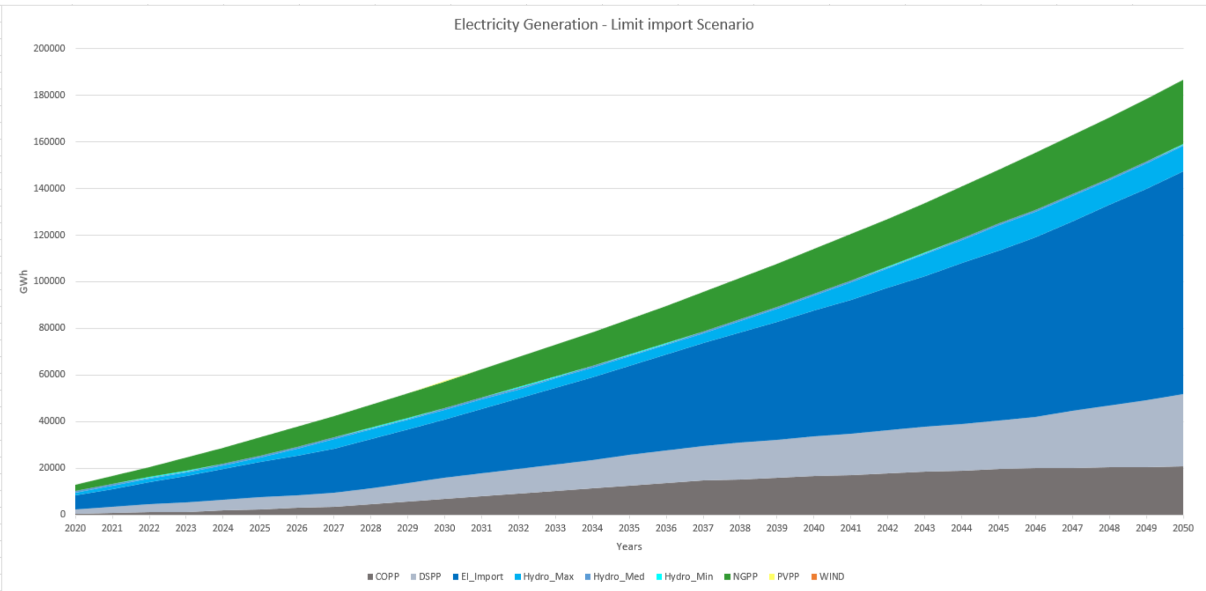


*Fig. 4.2:* Electricity Generation - Limit Import Scenario

This scenario's purpose was to assess the impact of a limited import on the electricity mix. This limitation allowed the model to invest in the next cheapest technology after imports and fossil fuels, i.e. hydro. In fact, in this scenario, hydro power plants contributed between 10% to 15% of the total demand. The presence of hydro-power grew towards the end of the time frame, in parallel with the increase in constraints of the electricity import. Fossil fuels' share raised compared to the Reference scenario, again as a consequence of the limitations on imports. The fossil fuels' total share was around 40-45% across the whole time frame, with NG and diesel power plants still being the main contributors. This can be seen in Figure 4.2. Similarly to the BAU, the model still considered PV and wind technologies not economically suitable to be present in the energy mix.

*Renewable Scenario*

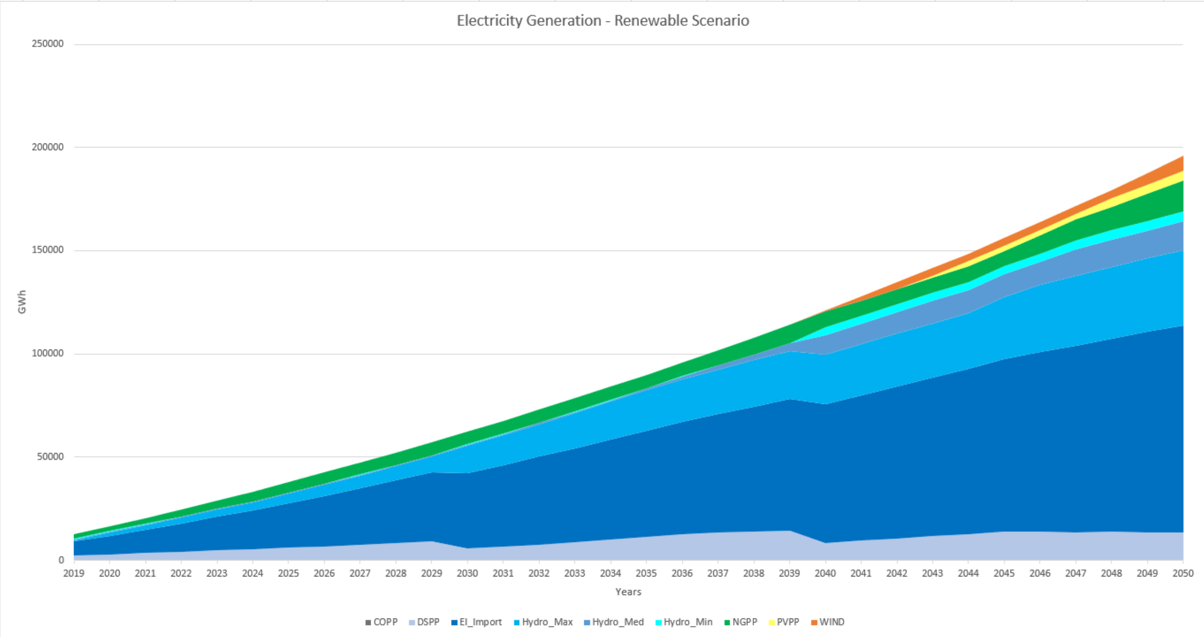


*Fig. 4.3:* Electricity Generation - Renewable Scenario

The results obtained in this scenario (see Figure 4.3), indicated that only if strong green targets were applied RE would be a relevant part of the mix. The model did not have constraints on the amount of capacity it could invest for clean energy. However, it did not introduce solar and wind to a great extent, but still considered hydro as the most cost-optimal strategy. Hydro covered from 15% up to 30% of the total demand across the whole time frame. On the contrary, PV and wind started contributing more only from 2040 onward, when their share increased until 10% by 2050. This is due to the 40% RE target applied, which forced the model to increase investments in solar and wind capacity, parallel to hydro. Another interesting aspect was a greater penetration of medium (10-100MW) and small (below 10MW) hydro power plants. This is in contrast with the previous scenarios, where these technologies were hardly visible in the final graphs (less than 1% of the total supply mix) and only bigger hydro power plants (above 100MW) were included. Here medium and small hydro power plants contributed up to 10% by 2050.
The applied RE targets, even if sustainable, would mean a great challenge for the country. First of all, an extreme expansion of the national grid would be necessary in order to allow the penetration of renewables. Energy security could also potentially be an issue, due to the high variability and intermittency of wind and solar. Furthermore, a baseload and fast response generation would be needed at all times, such as diesel power generation. This would ensure a homogeneous development of both urban and rural areas, without interruptions in the supply of electricity.
In all scenarios, the electricity imports were capped to 60%. Because of the higher number of constraints in this scenario, imports oscillated between 55-50% across the modeling period. Due to the RE targets, fossil fuels also presented a more limited share, compared to the previous scenarios. This varied between 30% in 2020 to 10% in 2050. Moreover, it is possible to notice in Figure 4.3 that the coal generation was excluded from the energy mix. The total share of the fossil fuel was almost equally

split between NG and diesel generation. Additionally, in Figure 4.3, every decade shows an abrupt change, which can be explained by a decrease of both fossil fuels generation and electricity import, caused by the entering RE targets.

*National Policies Scenario*

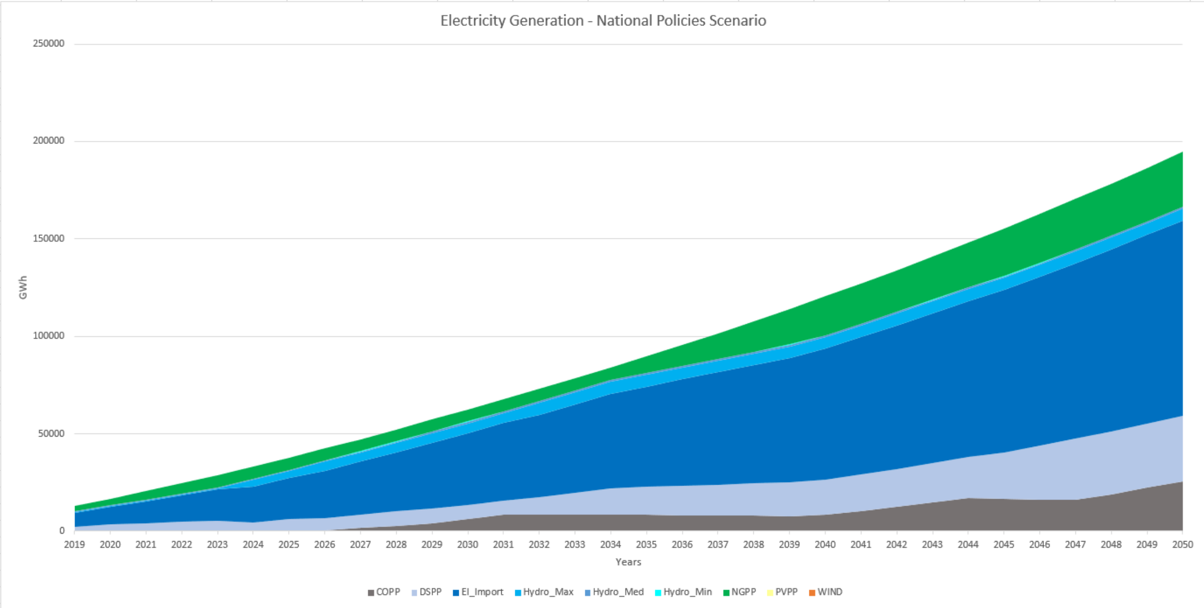


*Fig. 4.4:* Electricity Generation - National Policies Scenario

The National Policies scenario looked like the most optimal scenario for the future of Afghanistan. The National Plans have certainly considered the issues and limitations of the country. This was portrayed in the model by a more moderate capacity investment, as well as a higher investment in cheaper technology. These are represented by fossil fuel technologies, which would provide a constant supply of electricity at a reasonable cost. In fact, NG, diesel and coal generation increased together from 30% in 2020 to 42% in 2050. Import electricity, being again capped at 60%, oscillated between 55% and reached a minimum level of 50% in the last decade. The National Plans have committed to the introduction of new hydro power capacity and this was reflected very well in the model. In fact, even without RE targets applied, the outcomes of the optimisation indicated that hydro would cover around 8% to 10% of the total demand across the study period. In reality, we could expect this share to be even higher, as in Afghanistan the current contribution of hydro generation is already 20%. It could be asserted that this scenario might overall represent the safest approach for the government and institutions, if the support from foreign countries was not available. They would be able to avoid dealing with the creation of a new regulatory system for renewables, but especially, they could mitigate the costs of developing the energy infrastracture.

## 4.2 *Cost of Electricity Supply*

The price of electricity in Afghanistan was registered to be 0.049 $/kWh in June 2020 [Afghanistan Electricity Prices, 2020]. Using the results from OSeMOSYS, it was possible to make a comparison of the cost of electricity supply obtained across the scenarios. As already studied in the APSMP [Fichtner GmbH & Co, 2013], transmission and distribution would need a capital-intensive expansion. These costs are depicted by the increasing cost of power supply presented in all the scenarios. The reference scenario was the only one where the energy system infrastructure did not require as much level of development as in the other scenarios. In the BAU, the cost of supply most likely increased proportionally with the investments required to cover the greater demand. The Renewable and Limit on Import scenarios resulted in a overall higher penetration of renewables, correlated with a much higher cost of supply, as can be seen in Figure 4.5. This was mainly due to the higher costs of investments of RE compared to the fossil fuel based technologies. This phenomenon was highlighted especially in the Renewable scenario. In fact, the model was forced to cover 30% of the energy demand with RE by 2030 and 40% by 2040. These constraints resulted in two rises of the cost of supply. The first jump can be seen close to 2030, marked with the yellow line. The second is a steep rise starting from 2040 (see Figure 4.5). This cost went above 1.6 $/kWh after 2040, representing more than 300% increase in cost, compared to 2020. The National Policies scenario and the BAU hit a maximum cost of supply of around 0.6 $/kWh, which could portray a more realistic option for the future of Afghanistan. Moreover, this cost was reached only close to 2050, whereas the Limit on Import scenario got to the same price level already in 2040.

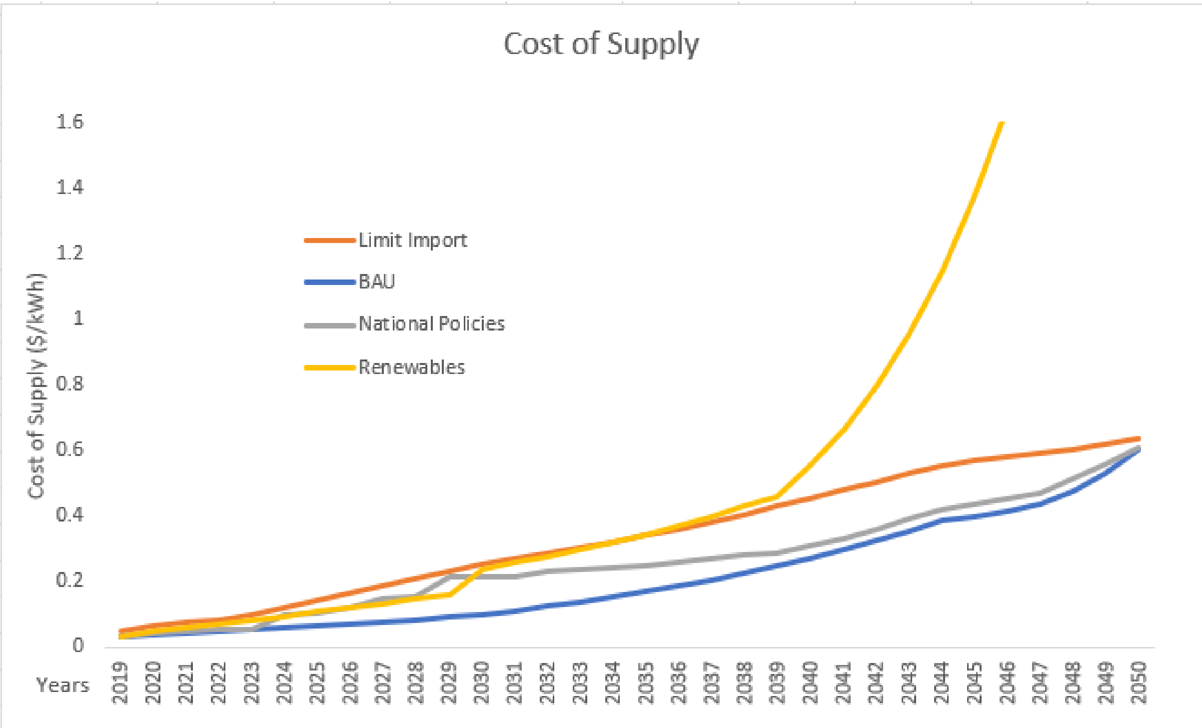


*Fig. 4.5:* Cost of Supply

## 4.3 Self Sufficiency

The Self Sufficiency rate showed the capacity of the country to cover its energy demand using domestic resources. In this case, the Total Primary Energy Supply (TPES) was made up of indigenous production plus imports. In fact, there were no

exports or stock changes. Indigenous Production was calculated as the production of primary energy, i.e. hard coal, diesel, natural gas, hydro, solar and wind.
The indicator of Self Sufficiency was formulated as Indigenous Production divided by the TPES and finally converted into a percentage. The heavy dependence on imports from neighboring countries is explicit when looking at Figure 4.6. In fact, all the scenarios maintained a Self Sufficiency rate at the level of 9-11%. The main concern for the GoA should be considering a scenario where imports would be severely reduced. This would be needed in order to assess the consequences on the energy system and on the energy security of the country. Due to the imports being predominant, none of the scenarios developed in this study actually influenced the Self Sufficiency ratio significantly. In fact, even in the scenario that had the strictest constraints on import, the country was still relying at 40% on the neighboring countries' electricity in 2050. Optimally, Afghanistan development should not be based on the least-cost solution, but overall should focus on ensuring a stable energy supply, by establishing a robust energy system based on domestic resources.

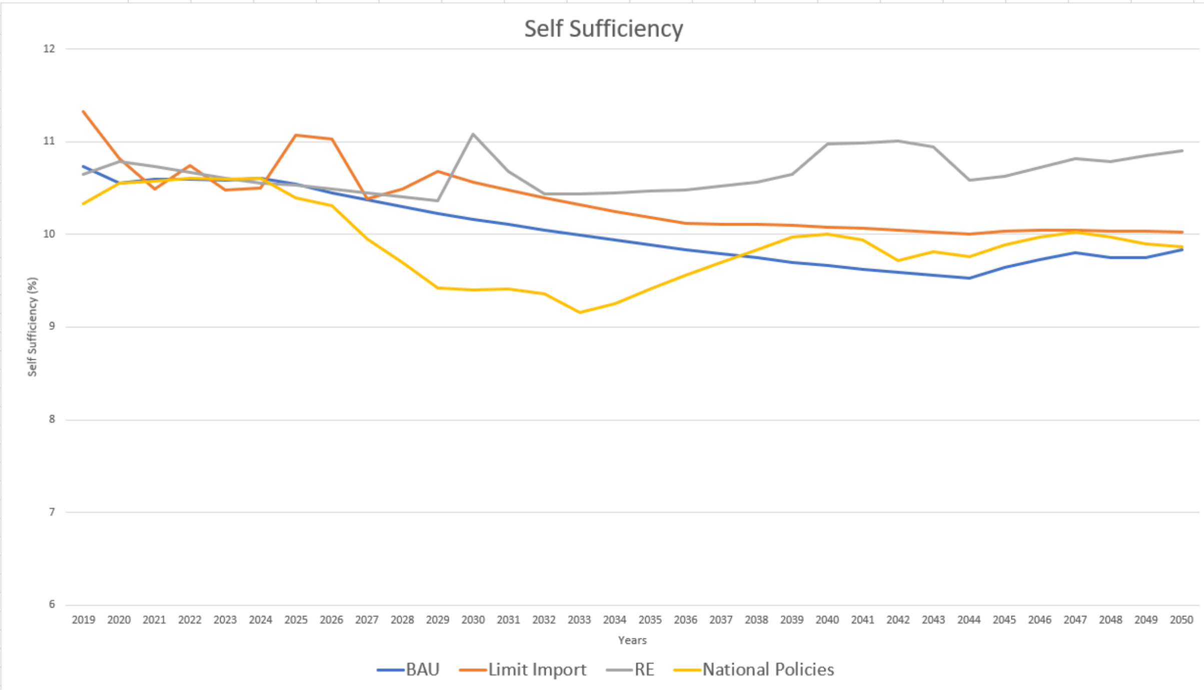


*Fig. 4.6:* Self Sufficiency

## 4.4 Geopolitical Issues and Considerations

This study has modeled different scenarios which could help identifying different pathways for the development of the social-economic sector of the country. However, while steps have already been taken to develop National plans, it is important to consider the challenges and limitations present in the country. Financing and commercial risks are the first obstacles for the further deployment of current technologies, as well as for the investments in new and more sustainable resources. [Afghanistan Analysts Network, 2015] This also accounts for the proportional correlation between pace of decarbonisation and level of societal change. Decarbonisation in Western Countries is influenced and driven by greater levels of consumer engagement. Unfortunately, in Afghanistan, the energy services need to be improved first, whereas consumer engagement will be addressed further in the future. As a matter of fact, more attention should be given to energy security, trying to ensure at least basic levels of energy supply with minimum disruptions.

Electricity tariffs have been historically fixed by Government of Afghanistan, vesting these responsibilities as an independent electricity regulatory body. [Gencer et al., 2018] This is opposed to the situation in Western Countries that allows competition in the energy market. In competitive markets, customers are entitled to choose which energy supplier will provide their energy and at what tariff. This approach could potentially stimulate the energy development of a country such as Afghanistan, which currently finds itself in a stagnant situation.

The challenge of increasing the share of renewables is to encourage investors. Tax deductions, long term Power Purchase Agreements (PPAs), subsidies and attractive tariffs are some of the potential incentives. What is more, pilot projects could be a solution to assess risks and potential of new energy plans. Additionally, if RE were to penetrate the energy market to a greater extent, it would be necessary to create a regulatory and institutional framework for renewable energy development.

Finally, climate change needs to be considered as an out of control risk for the country. One of the main concerns could be the availability of water resources. Scarcity of water would affect hydro power generation, being one of the largest contributors into the energy mix of the country.

# 5. CONCLUSIONS

This work presented different options of the least-cost energy mix for Afghanistan through different scenarios. The ample use of assumptions limited the validity of the results. Also, the employed tool OSeMOSYS delivered a general view of the energy system with a limited dataset. The use of a more sophisticated software, combined with a more accurate database, would probably provide a better depiction of the reality and more reliable forecasts. Anyhow, this study could give a base of further analyses for the policy makers to formulate strategic development plans.

Among the key findings, the work highlighted that RE investments costs were indeed decreasing over time, but they were still too high to compete with conventional generation. In the results, hydro power was the main contributor amidst the renewable technologies. At the same time, fossil fuels played a fundamental role in the energy supply in all the scenarios. The strong dependency on neighboring countries' import is both a risk and a limitation. It is a risk because the electricity imports might not be available as much in the short term. It is a limitation because it prevents from an Afghan energy system transition towards more reliable and sustainable energy technologies. Based on the simulations of this work, it could be advised that Afghanistan should slowly increase its self sufficiency to at least 50% of the energy supply. As seen in section 4.1, by limiting the import, domestic generation can be enhanced. The improvement of the whole energy system in Afghanistan represents a crucial requirement to satisfy a growing electricity demand.

Finally, it could be suggested as a further work to integrate a study on carbon emissions. Greenhouse Gas (GHG) emissions will eventually become a point of interest for the country. As a matter of fact, the results of this study showed that Afghan's future might rely mostly on fossil fuels. In this case, it would be necessary to investigate the impact of these technologies on the environment and on the current trends of sustainable development.

# BIBLIOGRAPHY

[Afghanistan Analysts Network, 2015] Afghanistan Analysts Network (2015). Power to the People: How to extend Afghans' access to electricity. Available at: https://www.afghanistan-analysts.org/power-to-the-people-how-to-extend-afghans-access-to-electricity/. Last accessed: 2019-05-27.

[Afghanistan Electricity Prices, 2020] Afghanistan Electricity Prices (2020). Available at:https://www.globalpetrolprices.com/Afghanistan/electricity_prices/. Last accessed: 2020-10-16.

[Almulla et al., 2019] Almulla, Y., Broad, O., Shivakumar, A., Gardumi, F., Ramos, E., Avgerinopoulos, G., and Howells, M. (2019). MoManI User Manual.

[Aminjonov, 2016] Aminjonov, F. (2016). Afghanistan's energy security.

[Asian Development Bank, 2012] Asian Development Bank (2012). Sector Assessment - (Summary) : Energy.

[Asian Development Bank, 2014] Asian Development Bank (2014). Regional Power Transmission Interconnection Project.

[Central Statistics Organization, 2016] Central Statistics Organization (2016). Afghanistan living conditions survey,central statistics organization. Available at: http://cso.gov.af/en/page/1500/1494/nrav-report. Last accessed: 2019-06-05.

[Danish et al., 2017] Danish, M. S. S., Sabory, N. R., Senjyu, T., Ludin, G. A., Noorzad, A. S., and Yona, A. (2017). Electricity Sector Development Trends in an After-war Country: Afghanistan Aspiration for an Independent Energy Country. *Journal of Energy and Power Engineering*, 11.

[energypedia.info, 2020] energypedia.info (2020). Turkmenistan Energy Situation. Available at: https://energypedia.info/wiki/Turkmenistan_Energy_Situation. Last accessed: 2020-04-13.

[Ershad, 2014] Ershad, A. M. (2014). Potential of solar photovoltaic and wind power plants in meeting electricity demand in afghanistan.

[ESMAP, 2019] ESMAP (2019). Multi-Tier Framework for Measuring Energy Access. Available at: https://www.esmap.org/node/55526. Last accessed: 2019-09-08.

[Fichtner GmbH & Co, 2013] Fichtner GmbH & Co (2013). Asian Development Bank - Islamic Republic of Afghanistan: Power Sector Master Plan.

[Gencer et al., 2018] Gencer, D., Irving, J., Meier, P., Spencer, R., and Wnuk, C. (2018). Energy Security Trade-Offs under High Uncertainty.

Resolving Afghanistan's Power Sector Development Dilemma. Available at: https://energypedia.info/wiki/File:%E2%80%A2_Energy_Security_Trade-offs_under_High_Uncertainty._Resolving_Afghanistan%E2%80%99s_Power_Sector_Development_Dilemma.pdf. Last accessed: 2019-1-03.

[GENI, 2017] GENI (2017). Afghanistan Map - Existing and Planned Power Plants. Available at: http://www.geni.org/globalenergy/library/national_energy_grid/afghanistan/afghanistannationalelectricitygrid.shtml. Last accessed: 2020-12-04.

[Goepner, 2018] Goepner, E. W. (2018). Why Afghanistan Remains Stuck in Conflict. page 32.

[GreenTech Construction Engineering, 2018] GreenTech Construction Engineering (2018). Environmental and Social Impact Assessment of 15MW On-Grid Power Project - Kandahar Solar Power Project.

[IEA, 2010] IEA (2010). Hydropower. Available at: https://iea-etsap.org/E-TechDS/PDF/E06-hydropower-GS-gct_ADfina_gs.pdf. Last accessed: 2020-03-16.

[IRENA, 2012a] IRENA (2012a). Renewable Energy Technologies: Cost Analysis Series. Hydropower. Available at:https://www.irena.org/documentdownloads/publications/re_technologies_cost_analysis-hydropower.pdf. Last accessed: 2019-11-01.

[IRENA, 2012b] IRENA (2012b). Renewable Energy Technologies: Cost Analysis Series. Wind Power. Available at:https://www.irena.org/DocumentDownloads/Publications/RE_Technologies_Cost_Analysis-WIND_POWER.pdf. Last accessed: 2019-20-01.

[Irving and Meier, 2012] Irving, J. and Meier, P. (2012). Afghanistan resource corridor development: Power sector analysis. Technical report, The World Bank.

[Korkovelos et al., 2017] Korkovelos, A., Bazilian, M., Mentis, D., and Howells, M. (2017). A Gis Approach to Planning Electrification in Afghanistan.

[LeighFisher Ltd, 2016] LeighFisher Ltd (2016). Electricity Generation Costs and Hurdle Rates. Available at:https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/566803/Leigh_Fisher_Non-renewable_Generation_Cost.pdf. Last accessed: 2019-11-06.

[Renewables.ninja, 2020] Renewables.ninja (2020). Web tool. Available at: https://www.renewables.ninja. Last accessed: 2020-04-12.

[Rostami et al., 2017] Rostami, R., Khoshnava, M. S., Lamit, H., Streimikiene, D., and Mardani, A. (2017). An overview of afghanistan's trends toward renewable and sustainable energies. Available at: https://www.sciencedirect.com/science/article/pii/S1364032116309261. Last accessed: 2019-05-05.

[Schröder et al., 2013] Schröder, A., Kunz, F., Meiss, J., Mendelevitch, R., and von Hirschhausen, C. (2013). Current and prospective costs of electricity generation until 2050. Technical report, DIW Berlin.

[The Asia Foundation, 2016] The Asia Foundation (2016). A survey of the Afghan People. Available at:https://asiafoundation.org/wp-content/uploads/2016/12/2016_Survey-of-the-Afghan-People_full-survey.Jan2017.pdf. Last accessed: 2019-11-01.

[The World Bank, 2018] The World Bank (2018). Afghanistan renewable energy development issues and options. Technical report, The World Bank.

[The World Bank, 2021] The World Bank (2021). Rural population. Available at: https://data.worldbank.org/indicator/SP.RUR.TOTL.ZS. Last accessed: 2019-06-04.

[United Nations, 2019] United Nations (2019). United Nations Statistics Division - Energy Statistics. Available at: https://unstats.un.org/unsd/demographic-social/products/dyb/dybcensusdata.cshtml. Last accessed: 2019-05-22.

[Ventura, 2019] Ventura, L. (2019). Global Finance Magazine - The World's Richest and Poorest Countries. Available at: https://www.gfmag.com/global-data/economic-data/worlds-richest-and-poorest-countries. Last accessed: 2019-06-04.

# APPENDIX

# Appendix A: Assumptions and Data

Data scarcity and incongruousness have lead to use several assumptions during the project work.

## Demand Projection Assumptions

Urban and rural energy consumption's level for 2030 were based from the Power Sector Master Plan estimates [Danish et al., 2017]. The average electricity consumption in Afghanistan was projected to reach approximately 1500 kWh/household/year by 2030. Using this estimate, Tier 5, with a consumption of 4190 kWh/household/year and Tier 3 with a consumption of 1301 kWh/household/year, were selected as electricity targets for urban and rural households for 2030 in the positive scenario. In the negative scenario, these targets were shifted until 2050. The rate of increase of electricity consumption in urban and rural areas was assumed to be 5% per year.

Target values for the development of the country were adapted from a previous study [Korkovelos et al., 2017] and are reported in the following table A.1.

| Access level | Tier 1 | Tier 2 | Tier 3 | Tier 4 | Tier 5 |
|---|---|---|---|---|---|
| Indicative power appliances | Task lighting - phone - radio | Lighting + fan + television | Tier 2 + medium power appliances (e.g. refrigeration) | Tier 3 + medium power or continuous appliances (e.g. water heating, ironing, microwave) | Tier 4 + high-power and continuous appliances (e.g. air conditioning) |
| Consumption per urban household and year [kWh] | 54 | 307 | 1124 | 2964 | 4190 |
| Consumption per rural household and year [kWh] | 62 | 355 | 1301 | 3430 | 4849 |

*Tab. A.1:* Indicative Services and Annual Consumption per Tier

## Negative Demand Projection

Below, it is presented the results of the negative demand projection:

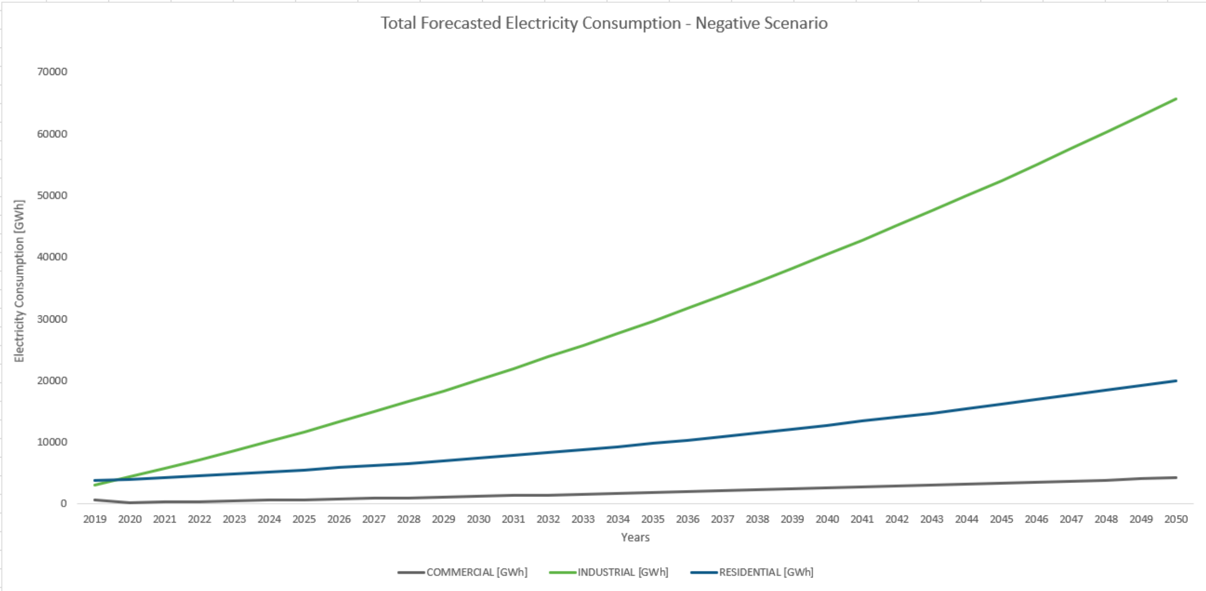


*Fig. A.1:* Negative Demand Projection

*Model Assumptions*

At the moment, in Afghanistan, transmission and distribution losses are very high, reaching a level of 24%. [Asian Development Bank, 2014]
In the model, these were assumed to decrease over the years, reaching a world average value of 10% by 2050. A variable cost was associated to transmission and distribution which was estimated thanks to the Regional Power Transmission Interconnection Project [Asian Development Bank, 2014].

Economic values, such as variable costs, were assigned different rates of growth or decline during the period of time considered. These assumptions were taken considering the past and present dynamism of the prices, as well as considering socio-political factors. In fact, fossil fuel prices were growing of 10% every year in the model. This rise represented a pure assumption, since in reality, fossil fuel prices are very fluctuating and it was not scope of this study to model the future evolution of these prices. The increase considered in the fossil fuel prices were including a possible increase due to carbon taxes. [LeighFisher Ltd, 2016]
Capital costs for solar and wind have been assumed to decrease over the years. See tables A.11 and A.13.
Electricity import cost was assumed to increase already in the BAU scenario of 10% every year.

*Power Plants Data*

The following tables show the main data and parameters used to set up the model in OSeMOSYS. Many data were taken from reliable sources such as the Deutsches Institut für Wirtschaftsforschung [Schröder et al., 2013] and IRENA [IRENA, 2012a] and [IRENA, 2012b], as well as other organisations [GENI, 2017].

| Plant | Capacity [MW] | Status |
|---|---|---|
| Baghdara | 240 | PLN |
| Sarobi 2 | 128.6 | PLN |
| Naghlu (4 units 25 MW each) | 100 | OPR |
| Mahipar (3 units 22 MW each ) | 66 | OPR |
| Khanabad (2 units each 20MW) | 40 | PLN |
| Kajaki 1-3 (2 units 16.5 MW each) | 33 | OPR |
| Kajaki 2 | 16.5 | DEL |
| Salma Dam (3 units 14 MW each) | 42 | DEL |
| Sarobi 1 (2 units 13 MW each) | 26 | OPR |
| Shoraba | 5 | PLN |
| Darunta (2 units 3.8 MW each) | 7.6 | OPR |
| Pol-E-Khomri (3 units 1.6 MW each) | 4.8 | OPR |
| Pol-E-Khomri (1 unit of 3 MW) | 3 | OPR |
| Chaki-Vardack (2 units 1.1 MW each) | 2.2 | OPR |
| Charikar (3 units 0.88 MW each) | 2.64 | OPR |
| Panwar (3 units 0.8 MW each) | 2.4 | OPR |
| Jabul-E-Seraj 3 | 0.77 | OPR |
| Baharak | 0.5 | PLN |
| Jabul-E-Seraj 1 | 0.5 | OPR |
| Tagab | 0.5 | PLN |
| Assadabad | 0.35 | OPR |
| Baba-Wali | 0.25 | OPR |
| Jurm 1 | 0.23 | OPR |
| Chamkani (2 units 0.2 MW each) | 0.4 | DEL |
| Istalif | 0.2 | OPR |
| Jurm 2 | 0.2 | OPR |
| Sheeshan (2 units 0.2 MW each) | 0.4 | OPR |
| Shah Delir | 0.14 | OPR |
| Yangan | 0.14 | OPR |
| Chatta | 0.125 | OPR |
| Jurm 3 | 0.125 | OPR |
| Sangab | 0.125 | OPR |
| Ghorban (4 units 0.1 MW each) | 0.4 | DEL |
| Tira Koh (2 units 0.07 MW each) | 0.14 | OPR |
| Bamyan | 0.05 | DEL |
| Sameda | 0.048 | OPR |
| Konar (2 units 0.045 MW each) | 0.09 | UNK |
| Olang | 0.043 | OPR |
| Jalalabad Surkhrod | 0.025 | OPR |
| Rayn | 0.025 | OPR |
| Warduj | 0.025 | OPR |
| Borghaso | 0.013 | OPR |
| Daud | 0.007 | UNK |

*Tab. A.2:* Hydro Power Plants

| Data | 2019 | 2020 | 2030 | 2040 |
|---|---|---|---|---|
| Lifetime [years] | 100 | - | - | - |
| Construction time [years] | 4-6 | - | - | - |
| Efficiency [%] | 95 | - | - | - |
| O & M Costs [$/kW] | | | | |
| Max | 55 | 55 | 55 | 55 |
| Med | 62.5 | 62.5 | 62.5 | 62.5 |
| Min | 70 | 70 | 70 | 70 |
| Capital Costs [$/kW] | | | | |
| Max | 2150 | 2150 | 2200 | 2200 |
| Med | 2775 | 2775 | 2800 | 2825 |
| Min | 3400 | 3400 | 3400 | 3450 |
| Capacity Factor [%] | 46 | - | - | - |

*Tab. A.3:* Hydro Power Plants Data

| Plant | Capacity [MW] | Status |
|---|---|---|
| Aynak Copper IC (10 units 6.2 MW each) | 62 | PLN |
| Baghdis | 0.53 | RET |
| Baghdis New IC 1 | 0.4 | OPR |
| Baghdis New IC 2-3 | 0.824 | OPR |
| Bagram AFB GT 1-4 (4 units 10 MW each) | 40 | OPR |
| Bagram AFB GT 5 | 6 | OPR |
| Bagram AFB IC 1-10 | 14 | OPR |
| Bamyan BREP IC 1-3 (3 units 0.25 MW each) | 0.75 | OPR |
| Bamyan New IC 1 | 0.572 | OPR |
| Chakhchran New IC 1 | 0.856 | OPR |
| Farah IC 1-3 | 1.124 | UNK |
| Gardez IC 1-2 | 1.424 | OPR |
| Ghazni New IC 1-4 | 1.172 | OPR |
| Kabul IC 1-20 | 10 | OPR |
| Kabul Northwest GT 1 | 21.8 | OPR |
| Kabul Northwest GT 2 | 23.2 | OPR |
| Kabul Northwest SC 1 | 28.6 | DEL |
| Kabul Unicef IC 1-2 (2 units 0.44 MW each) | 0.88 | OPR |
| Kabul Uniced IC 3 | 0.22 | OPR |
| Kabul WHO IC 1-2 (2 units 0.22 MW each) | 0.44 | OPR |
| Kandahar Airfield IC 1-4 (4 units 3.5 MW each) | 14 | OPR |
| Kandahar EXT IC 1-14 | 11.9 | OPR |
| Khost IC | 0.9 | OPR |
| Khulm IC | 0.5 | OPR |
| KMTC Central Plant IC 1-3 (3 units 0.495 MW each) | 1.485 | OPR |
| Lashkar-Gah IC 1-3 (3 units 1 MW each) | 3 | OPR |
| Maimana IC 1-2 (2 units 0.5 MW each) | 1 | OPR |
| Musa Qala IC 1 | 0.85 | OPR |
| National Security Union IC 1-2 (2 units 1.35 MW each) | 2.7 | OPR |
| Paktia IC 1-4 | 0.6 | OPR |
| Paktia Urgon IC 1-3 | 0.3 | UNK |
| Pol-E'Alam NEW IC 1 | 0.368 | OPR |
| Pol-E-Charki BASE IC | 10 | CON |
| Qalat IC 1-2 (2 units 0.85 MW each) | 1.7 | OPR |
| Samanghan IC 1-3 | 1.68 | OPR |
| Sheeshan IC 1 | 0.5 | OPR |
| Takakhil (3 groups of 6 IC of 6 MW each) | 108 | OPR |
| Taloqan IC 1-4 | 1.608 | OPR |
| Trinkot New IC 1 | 0.4 | OPR |
| Zabol IC 1-10 | 1.13 | OPR |
| Zarank New IC 1 | 0.4 | OPR |

*Tab. A.4:* Oil Power Plants

| Data | |
|---|---|
| Lifetime [years] | 40 |
| Construction time [years] | 3 |
| Efficiency [%] | 39 |
| O & M Costs [$/kW] | 7.8 |
| Capital Costs [$/kW] | 650 |
| Variable Costs [$/MWh] | 17-20 |
| Capacity Factor [%] | 94.3 |
| Availability [%] | 90 |

*Tab. A.5:* Oil Power Plants Data

| Plant | Capacity [MW] | Status |
|---|---|---|
| Jarqodoq (6 units 2.5 MW each) | 15 | OPR |
| Khoja Gogirdak Field GT (2 units 2 MW each) | 4 | OPR |
| Kode Barq (4 units 12 MW each) | 48 | OPR |
| Sheberghan | 105 | PLN |

*Tab. A.6:* Gas Power Plants

| Data | 2019 | 2020 | 2030 | 2040 |
|---|---|---|---|---|
| Lifetime [years] | 40 | - | - | - |
| Construction time [years] | 3 | - | - | - |
| Efficiency [%] | 38 | 38 | 39 | 41 |
| O & M Costs [$/kW] | 25 | 25 | 25 | 25 |
| Capital Costs [$/kW] | 450 | 450 | 450 | 450 |
| Variable Costs [$/MWh] | 1.7 | | | |
| Capacity Factor [%] | 95 | - | - | - |
| Availability [%] | 90 | | | |

*Tab. A.7:* Gas Power Plants Data

| Plant | Capacity [MW] | Status |
|---|---|---|
| Bamyan Coal | 400 | PLN |
| Bamyan Coal 2 | 800 | PLN |

*Tab. A.8:* Coal Power Plants

| Data | 2019 | 2020 | 2030 | 2040 |
|---|---|---|---|---|
| Lifetime [years] | 40 | - | - | - |
| Construction time [years] | 4 | - | - | - |
| Efficiency [%] | 41 | 41 | 41 | 41 |
| O & M Costs [$/kW] | 65 | 65 | 65 | 65 |
| Capital Costs [$/kW] | 1600 | 1600 | 1600 | 1600 |
| Variable Costs [$/MWh] | 7.1 | | | |
| Capacity Factor [%] | 95 | - | - | - |
| Availability [%] | 90 | | | |

*Tab. A.9:* Coal Power Plants Data

| Plant | Capacity [MW] | Status |
|---|---|---|
| Bamyan | 1 | OPR |
| Sayed Karam PV | 0.1 | OPR |
| Herat | 1.7 | OPR |
| Khost | 10 | CON |
| Khandahar | 15 | CON |

*Tab. A.10:* Solar Power Plants

| Data | 2019 | 2020 | 2030 | 2040 |
|---|---|---|---|---|
| Lifetime [years] | 20 | - | - | - |
| Construction time [years] | 1 | - | - | - |
| O & M Costs [$/kW] | 24 | 22 | 20 | 20 |
| Capital Costs [$/kW] | 2360 | 1640 | 1260 | 1100 |

*Tab. A.11:* Solar Power Plants Data

| Plant | Capacity [MW] | Status |
|---|---|---|
| Panjshir | 0.075 | OPR |
| West Herat | 0.3 | OPR |

*Tab. A.12:* Wind Power Plants

| Data | 2019 | 2020 | 2030 | 2040 |
|---|---|---|---|---|
| Lifetime [years] | 20 | - | - | - |
| Construction time [years] | 1 | - | - | - |
| O & M Costs [$/kW] | 50 | 48 | 48 | 46 |
| Capital Costs [$/kW] | 2020 | 1920 | 1840 | 1800 |

*Tab. A.13:* Wind Power Plants Data

The construction time presented in the tables above is used in order to estimate in which year a planned power plant would be operational.

*Capacity Factor*

In order to take into account the variability and intermittency of renewable energy generation, OSeMOSYS allows to use a different capacity factor according to the season and part of the day when energy is generated. Capacity factor is the ratio between the actual energy output versus the maximum possible output of a unit over a given period of time. This is an important value to consider for renewable technologies due to their non-constant availability. The capacity factors used in this study have been calculated with the help of renewables.ninja [Renewables.ninja, 2020], a geospatial tool which allows to run simulations of the hourly power output from wind and solar. The areas chosen to make these estimations were Bamyan, Balkh and Herat. [Ershad, 2014] These provinces all have a huge potential for both solar and wind energy. Balkh and Herat have the highest annual average wind speed among the monitored sites and represent also an excellent solar resource. [GreenTech Construction Engineering, 2018] Other factors that make these provinces very attractive to renewable energy development are their relatively high electricity demand, well developed power systems, heavy reliance on imported power and proximity to the western and northern borders. After downloading the data from the simulation, the capacity factor was calculated taking into account a nominal capacity for both wind and solar. The results for each month were used to estimate a value for each season, finally using an average among the three provinces to get a final figure to consider for the whole country.

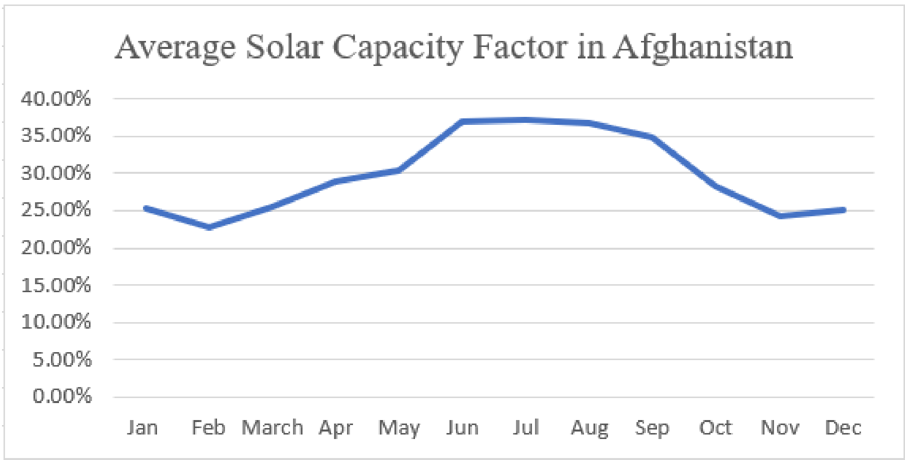


*Fig. A.2:* Capacity Factor Solar

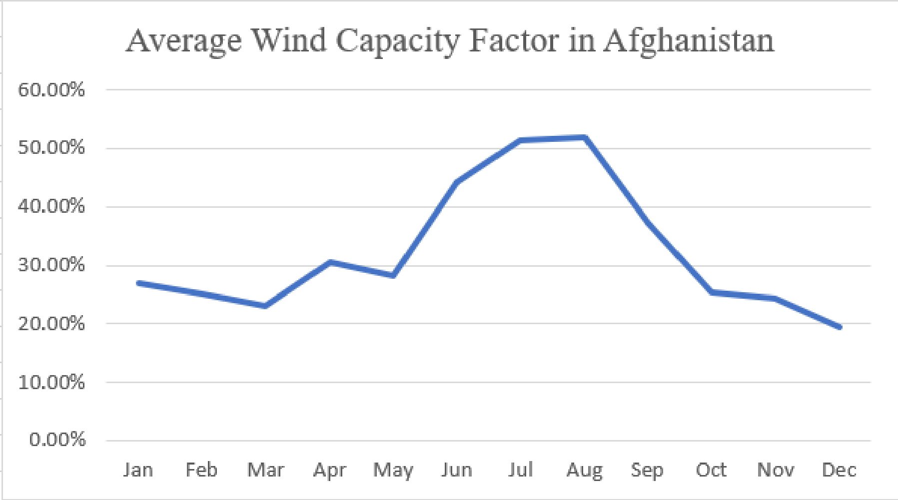


*Fig. A.3:* Capacity Factor Wind

The capacity factor for hydro-power was estimated using latest data from IEA [IEA, 2010], assuming a constant value of 46% throughout the year.