Simulation of a Region Operating at 100% Renewable Energy

By
Mohamed Ahmed Taha Shalaby

A Thesis submitted to Faculty of Engineering at Cairo University and Kassel University in Partial Fulfillment of the Requirements for the Degree of Master of Science in Renewable Energy and Energy Efficiency

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Cairo University, Egypt
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March 27, 2013
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Declaration for the Master’s Thesis

I, Mohamed Shalaby, hereby affirm that the master thesis at hand is my own written work and that I have used no other sources and aids others than those indicated. Only the sources cited have been used. Those parts which are direct quotes or paraphrases are identified as such.

Kassel, Germany
March 27, 2013
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List of Acronyms

\(\alpha\) Thermal coefficient of short circuit
\(\alpha\) Exponent depends on the roughness of the surface
\(\eta_{xx}\%\) Efficiency of the inverter at \(xx\%\)
\(\rho\) Standard air density
\(A\) Area of the wind turbine
\(C_{InvBio}\) Investment costs for Bio
\(C_{InvPV}\) Investment costs for PV
\(C_{InvW}\) Investment costs for Wind
\(C_{O&M_{RE}}\) Operation & Maintenance cost for Renewable Energy technology
\(C_{sellBio}\) Selling price for Bio
\(C_{sellPV}\) Selling price for PV
\(C_{sellW}\) Selling price for wind
\(C_f\) Capacity factor
\(C_p\) Power coefficient of wind turbine
\(C_T\) Temperature coefficient of power
\(Cap\) Capacity of PV system
\(Cap_{NewBio}\) New Bio capacity
\(Cap_{NewPV}\) New PV capacity
\(Cap_{NewW}\) New Wind capacity
\(E_{CO2Bio}\) Emission due to operation of Bio generators
\(E_{CO2PV}\) Emission due to operation of PV
\(E_{CO2W}\) Emission due to operation of wind turbine
\(G\) Global irradiation
\(I\) Current produced by PV module
\(I_{MPP}\) Maximum power point current
\(I_{ph}\) Photocurrent
\(I_{SC}\) Short circuit current
\(I_D\) Diode current
\(I_o\) Diode saturation current
\(M\) Slope at open circuit voltage
\(N_{JobBio}\) Number of jobs created by Bio generators
\(N_{JobPV}\) Number of jobs created by PV
\(N_{JobW}\) Number of jobs created by wind
\(P_{ACp}\) AC power produced by PV
\(P_{ACW}\) AC power produced by Wind turbine
\(P_{NetPW}\) Power produced by PV and wind subtracted from load profile
\(P_{NetPW}\) Load Profile after subtraction of power produced by PV and wind turbine
\(P_{AC}\) AC power output
\(P_{Bio}\) Power produced by Bio generators
\(P_{DC}\) Output power from PV model
\(P_{Load}\) Load Profile
$P_{loss}$ Normalized power losses in inverter
$P_{MPP0}$ Photovoltaic module at specific solar irradiation and temperature
$P_{Net,H}$ $P_{Load} - P_{PV}$
$P_{out}$ Normalized output power to the nominal power
$P_{PV}$ Power by PV system
$P_{PV}$ Power produced by all PV systems
$P_{Self}$ Normalized self-consumption for the inverter
$P_{W}$ Power produced by all wind turbines
$PA_{RE}$ Public acceptance for the renewable energy technology
$r_{loss}$ Normalized ohmic losses in inverter
$R_{PV}$ Photovoltaic resistance
$R_{S}$ Series resistance
$RE\%$ Renewable Energy percent
$T_{amb}$ Ambient temperature
$T_{j}$ Temperature of Photovoltaic module
$V_{loss}$ Normalized voltage losses on diodes and transistors in inverter
$V_{MPP}$ Maximum power point voltage
$V_{OC}$ Open circuit voltage
$V_{PV}$ Photovoltaic module voltage
$V_{T}$ Thermal voltage
$ipv$ Institute for Photovoltaics
$AC$ Alternating current
$BMU$ Nature Conservation and Nuclear Safety
$CO_{2}$ Carbon dioxide
$DAAD$ German Academic Exchange Service
$DC$ Direct Current
$GWh$ Gigawatt hour
$IdE$ Institut dezentrale Energiotechnologien
$ISE$ Fraunhofer-Institute for Solar Energy Systems
$kV$ Kilo Volt
$kW$ Kilowatt
$kWh$ Kilowatt hour
$LED$ Light Emitting Diode
$MW$ Megawatt
$NOCT$ Nominal Operating Cell Temperature
$P_{L,Gross}$ Gross load profile
$P_{L,Net}$ Net load profile
$PV$ Photovoltaic
$SOC$ State Of Charge
$STC$ Standard Test Condition
$SWOT$ Strength, Weakness, Opportunities and Threats
$UBA$ Federal Environment Agency
Abstract

This master thesis presents PV, wind, bio generator models to model renewable energy generators. Those models were built on MATLAB platform. A new optimization tool is presented to calculate the optimum capacity needed to be installed in order to reach 100% renewable energy with in the region. This optimization tool takes into consideration autonomy, costs, CO$_2$ emission, job creation, operation & maintenance costs and public acceptance. The result of optimization tool is the optimum capacities from each renewable energy technology needed to be installed in the region to be operating at 100% renewable energy. The first region is Osnabrück, Germany, while the second region is Siwa, Egypt. The optimization tool proposed to increase the capacity of PV systems to 578 MW, wind capacity to 1842 MW and bio generators to 120 MW, so the county of Osnabrück could operate at 100% renewable energy. The result of optimization tool have been used to simulate hour-by-hour the county gross load profile and power generated by renewable energy within the county of Osnabrück. Energy efficiency in street lights in Siwa has been discussed from the technical and economical point of view, in order to facilitate the path for renewable energy to fulfill the load demand. Siwa region could operate at 100% renewable energy by installing 21 MW PV systems and construct transmission lines connecting Siwa grid with Libya grid.
Chapter 1

Introduction

The Institute of decentralized Energy technologies (IdE) is currently carrying out the "100% Renewable Energy Regions" project. This project identifies, monitors and networks regions and municipalities whose goals are to switch their energy supply in the long run to be supplied entirely on renewable energy. There are over one hundred and thirty districts, municipalities and regional networks in Germany pursuing this goal. The project "100% Renewable Energy Regions" is funded by the Federal Ministry for Environment, Nature Conservation and Nuclear Safety (BMU) and the Federal Environment Agency (UBA).

This Master Thesis presents a new optimization method to simulate a region operating at 100% renewable energy. Moreover it contains two cases studies simulations one for Osnabrück, Germany and the other for Siwa, Egypt.

1.1 Introduction to Renewable Energy

Renewable Energy is defined as energy that is produced by natural resources - such as sunlight, wind, rain, waves, tides and geothermal heat - that are naturally replenished within a time span of a few years [1].

1.2 Reasons to shift to Renewable Energy

Many countries such as Denmark, Ireland and Japan are setting goals to switch their energy supply to be working on 100% renewable energy [1, 2, 3, 4]. The main reasons that those countries took the decision of replacing fossil energy and nuclear energy by renewable energy are:

- **Energy Security**: As the prices of fossil fuel are increasing and fossil fuel reserves are depleting, countries dependent on importing oil may face risk of supply of energy [1].

- **Environment**: With the increase of the concentration of green house gases in the atmosphere, the temperature of earth increases, which have an effect on the human health and the environment [5].

- **Nuclear Energy problems**: Although Nuclear Energy could produce tremendous amount of energy, it has many disadvantages like waste treatment, accidents (Chernobyl 1986 and Fukushima 2011), safety and high investment costs.
1.3 Renewable Energy Analysis Programs

There exist a large number of different computer programs that analyses renewable energy systems. Those programs could be categorized into two main groups. The first group is based on aggregated annual calculations, while the second group is based on a detailed hour-by-hour simulation. In analyses of 100% renewable energy regions it is essential to use hour-by-hour simulation [1]. Table 1.1 shows different Renewable Energy analysis programs available in the market that are based on aggregated annual calculations and ones which are based on detailed hour-by-hour simulation.

Table 1.1: Energy system analysis programs.

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<th>Detailed Hour-by-Hour Simulations</th>
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<td>EnergyPLAN</td>
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<td>LEAP</td>
<td>LEAP</td>
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<tr>
<td>MARKAL</td>
<td>RAMSES</td>
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<td>PRIMES</td>
<td>BALMOREL</td>
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<td>ENPEP</td>
<td>SESAM</td>
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IdE would like to have a deep look on the grid problems and what needs to be changed in the infrastructure of the transmission grid for the regions which would operate on 100% renewable energy. IdE had to implement a tool like the ones presented in table 1.1 in two phases to determine the grid problems. The first phase is presented in this master thesis, which is modeling each renewable energy technology and combining it together to calculate the net electric energy produced by renewable energy and subtract it from the electric load profile to determine the imports and exports from and to the region. Moreover this tool has a new optimization method that takes into the consideration many aspects like autonomy, costs, CO₂ emission, job creation, operation & maintenance costs, public acceptance and etc. This program is based on hour-by-hour simulation and it could be easily modified to work with accuracy minute-by-minute, depending on the accuracy of the meteorological data. In the second phase, which is still under development, the tool would be able to predict problems that may occur to the transmission system to the regions operating at 100% renewable energy.

Chapter 2 in this master thesis introduces the models used to build this tool, while chapter 3 presents the new optimization method. This optimization tool is going to be used to get the optimum capacity needed to be installed in Osnabrück, Germany, which is going to be the first case study in thesis, which is explained in more details in chapter 4. The second case study is in Siwa, Egypt which is presented in chapter 5.
Chapter 2

Modeling Renewable Energy Generators

This chapter is going to introduce models for representing Photovoltaic (PV) systems, wind turbine and bio generators. The power produced by PV systems, wind turbines and bio generators are summed up hourly and subtracted from the electric load to know the hourly exports/imports for electricity to/from region.

2.1 Photovoltaic system model

This section is going to present two different PV systems. The first PV system would be directly connected to the electric grid, while the second PV system is connected to the electric grid with battery bank to increase the self consumption of the building.

2.1.1 Photovoltaic system connected to grid

PV systems connected to the electric grid consists of PV modules connected in series and parallel to convert sun light to direct current (DC) and inverter that convert DC to alternating current (AC) for grid connection.

PV module consists of number of solar cells connected in series. The solar cell has the same physical structure as a diode. It consists of a p- and n- doped semiconductor, which could be represented by a diode. A current source in parallel with the diode represents the current produced by an ideal solar cell when light is applied on it. Figure 2.1 shows the equivalent circuit for an ideal solar cell.

![Equivalent circuit for an ideal solar cell](image)

Figure 2.1: Equivalent circuit for an ideal solar cell is a current source in parallel with diode.
Wagner presented the equivalent circuit for the effective solar cell characteristic by adding fictitious PV resistance $R_{PV}$. $R_{PV}$ is different than the series resistance $R_S$ in the single diode model [6, 7]. It is fictitious, as the value for it could be a negative or positive. As negative resistance doesn’t exist in reality, the component in the equivalent circuit diagram can’t be an ohmic resistance. Figure 2.2 shows the equivalent circuit diagram for the effective solar cell characteristic.

![Equivalent circuit diagram](image)

Figure 2.2: Equivalent circuit diagram for the effective solar cell characteristic with $R_{PV}$ connected in series

The value for the current $I$ produced by the PV module could be calculated by equation 2.1

$$I = I_{Ph} - I_o \left( \exp \left( \frac{V_{PV} + IR_{PV}}{V_T} \right) - 1 \right)$$  \hspace{1cm} (2.1)

Where $I_{Ph}$ is the photocurrent produced by current source, $I_o$ is the diode saturation current, $V_T$ is the thermal voltage and $I_D$ is the diode current. While the voltage across the PV module $V_{PV}$ is

$$V_{PV} = V_T \ln \left( \frac{I_{Ph} - I + I_o}{I_o} \right) - IR_{PV}$$  \hspace{1cm} (2.2)

The value for $R_{PV}$ is defined by equation 2.3

$$R_{PV} = -M \frac{I_{SC}}{I_{MPP}} + \frac{V_{MPP}}{I_{MPP}} \left( 1 - \frac{I_{SC}}{I_{MPP}} \right)$$  \hspace{1cm} (2.3)

Where $I_{SC}$ is short circuit current, $I_{MPP}$ is the maximum power point current, $V_{MPP}$ maximum power point voltage at standard test condition (STC) and $M$ is the slope at open circuit voltage $V_{OC}$ and it could be calculated by equation 2.4

$$M = \frac{V_{OC}}{I_{SC}} \left( K_1 \frac{I_{MPP} V_{MPP}}{I_{SC} V_{OC}} + K_2 \frac{V_{MPP}}{V_{OC}} + K_3 \frac{I_{MPP}}{I_{SC}} + K_4 \right)$$  \hspace{1cm} (2.4)

Where $K$ are constants defined in the following vector

$$K = \begin{pmatrix} -5.411 \\ 6.450 \\ 3.417 \\ -4.422 \end{pmatrix}$$  \hspace{1cm} (2.5)

The photocurrent $I_{Ph}$ produced by current source could be calculated by equation 2.6

$$I_{Ph} = \frac{I_{SC} G \left( 1 + \alpha (T_j - 25) \right)}{1000}$$  \hspace{1cm} (2.6)
where $G$ is the global irradiation in watt on 1 m$^2$, $\alpha$ is the thermal coefficient of short circuit and $T_j$ is the temperature of PV module. The thermal voltage $V_T$ is calculated by equation 2.7

$$V_T = -(M + R_{PV})I_{SC}$$  \hspace{1cm} (2.7)

The diode saturation current $I_o$ is calculated by equation 2.8

$$I_o = I_{SC} \exp \left( -\frac{V_{OC}}{V_T} \right)$$ \hspace{1cm} (2.8)

The temperature for the PV module $T_j$ is calculated by equation 2.9

$$T_j = T_{amb} + (NOCT - 25) \frac{G}{800}$$ \hspace{1cm} (2.9)

where $T_{amb}$ is the ambient temperature of the air and NOCT is nominal operating cell temperature.

The maximum power point $P_{MPP0}$ for PV module at specific solar irradiation and temperature is calculated based on Wagner model by equations 2.10, 2.11, 2.12 [7].

$$P_{MPP0} = V_{MPP0}I_{MPP0}$$ \hspace{1cm} (2.10)

$$V_{MPP0} = \frac{V_{MPP}}{1 + C_T(T_j - 25)} + V_T \frac{298}{T_j + 273} \ln \left( \frac{G}{1000} \right) - I_{MPP} R_{PV} \left( \frac{G}{1000} - 1 \right)$$ \hspace{1cm} (2.11)

$$I_{MPP0} = I_{MPP} \frac{G}{1000}$$ \hspace{1cm} (2.12)

where $C_T$ is temperature coefficient of power. Figure 2.3 shows the block diagram for the PV model which was implemented on MATLAB platform. The inputs for this PV model are $I_{MPP}, V_{MPP}, V_{OC}, I_{SC}, C_T, NOCT, G, T_{amb},$ Capacity of PV system ($Cap$), installation year and simulation year, while $P_{DC}$ is output from PV model. The year of installation of PV and year which the PV module is simulated are inputs for PV model in order to calculate the degradation of PV module.
Figure 2.3: Block diagram for the PV model with inputs $I_{MPP}$, $V_{MPP}$, $V_{OC}$, $I_{SC}$, $C_T$, $NOCT$, $G$, $T_{amb}$, $Cap$, installation year and simulation year, while $P_{DC}$ is output from PV model

Photovoltaic Inverter model

H. Schmidt and D. U. Sauer from Fraunhofer-Institute for Solar Energy Systems (ISE) presented a model for the efficiency curve of inverters [8]. This inverter model requires parameters which could be easily determined from the datasheet of the inverter. The efficiency for the inverter could be described by equation 2.13

$$\eta = \frac{1 + v_{loss}}{2r_{loss}P_{in}} + \sqrt{\frac{(1 + v_{loss})^2}{(2r_{loss}P_{in})^2} + \frac{P_{in} - P_{self}}{r_{loss}P_{in}^2}}$$  \hspace{1cm} (2.13)

Where $P_{Self}$ represents normalized self-consumption for the inverter, $v_{loss}$ represents normalized voltage losses on diodes and transistors and $r_{loss}$ normalized ohmic losses. The normalized power losses $P_{loss}$ is described by equations 2.14, 2.15.

$$P_{loss} = P_{in} - P_{out}$$  \hspace{1cm} (2.14)

$$P_{loss} = P_{self} + v_{loss}P_{out} + r_{loss}P_{out}^2$$  \hspace{1cm} (2.15)

$P_{out}$ represents the normalized output power to the nominal power. Equation 2.15 shows that the losses increase with the square of the power output. By substituting with the above two equation, $P_{out}$ could be calculated by solving the following quadratic equation 2.16.

$$r_{loss}P_{out}^2 + P_{out}(v_{loss} + 1) - P_{in} + P_{self} = 0$$  \hspace{1cm} (2.16)

The parameters $v_{loss}$, $P_{self}$ and $r_{loss}$ could be easily calculated from the power curve from the datasheet of the inverter by knowing the efficiencies of the inverter at 10%, 50% and 100% of the nominal power.
\( v_{\text{loss}} \) is calculated by equation 2.17.

\[
v_{\text{loss}} = -\frac{4}{3} \frac{1}{\eta_{100\%}} + \frac{33}{12} \frac{1}{\eta_{50\%}} - \frac{5}{12} \frac{1}{\eta_{10\%}}
\]  
(2.17)

\( P_{\text{self}} \) is calculated by equation 2.18.

\[
P_{\text{self}} = -\frac{1}{99} \frac{1}{\eta_{100\%}} + \frac{10}{99} \frac{1}{\eta_{10\%}} - \frac{1}{11}
\]  
(2.18)

\( r_{\text{loss}} \) is calculated by equation 2.19.

\[
r_{\text{loss}} = \frac{100}{99} \frac{1}{\eta_{100\%}} - \frac{10}{99} \frac{1}{\eta_{10\%}} - \frac{10}{11}
\]  
(2.19)

Figure 2.4 shows a block diagram for the inverter model. The inputs for the inverter model are efficiency of the inverter at 10%, 50% and 100% of the nominal power and the input DC power \( P_{DC} \). While the outputs for the inverter model are AC power \( P_{AC} \) and efficiency of the inverter \( \eta_{xx\%} \).

![Block diagram for the inverter model](image)

Test Photovoltaic model

PV model have been tested by comparing \( P_{AC} \) output from the PV model with real PV system installed on top of the university building in Stuttgart. Figure 2.5 shows a figure for the different PV systems installed on the roof of Stuttgart University. Schubert and Wurster from Institute for Photovoltaics (ipv), Stuttgart University provided us with data for global radiation \( (G) \), temperature of PV module and AC power from PV system \( (P_{AC}) \) for one of the PV systems for one week. This PV system consists of 5 modules of Suntechnics (STM200FM) connected in series. The PV module array is connected with SMA (Sunny Boy 1100) inverter.
Figure 2.5: Different PV systems installed on the roof of Stuttgart University

Figure 2.6 shows a graph for the simulated $P_{AC}$ by Wagner model and real $P_{AC}$ by $ipv$ for one week. The error in energy between the real and simulated $P_{AC}$ is around 10%. This error could be due to the tolerance of the PV module and error within real $P_{AC}$ measurements and calculations, as real $P_{AC}$ provided by $ipv$ is calculated from the energy counter and not measured by power meter.

Figure 2.6: Test for PV model shows the simulated $P_{AC}$ by Wagner model and real $P_{AC}$ for one week
2.1.2 Photovoltaic system with Batteries

The prices of installation of PV modules have been decreasing dramatically in the last few years, in addition to that the prices for feed in tariff is decreasing too [9]. Grid parity has been reached in Germany, therefore people have become more interested in self-consumption of their own energy generated from PV systems. As PV systems produce power only during day time, while the home/company consumes power during the entire day, so batteries are needed to cover the evening demand.

This section is presenting PV system with batteries as a backup. Figure 2.7 shows a block diagram for the PV system with batteries. The PV system with batteries uses the PV model presented in the previous section. The load profile for home/company $P_{\text{Load}}$ is fed into the model, so that the load profile $P_{\text{Load}}$ is subtracted from $P_{\text{AC}}$ produced by PV model. The result from the subtraction is named $P_{\text{NetH}}$. Based on the value of $P_{\text{NetH}}$ the algorithm would take a decision.

If $P_{\text{NetH}}$ is positive it means that there is enough power to supply the load at that time and the extra power should be used either to charge the batteries or to feed in the extra power into the electric grid based on the state of charge (SOC) of the batteries.

In case $P_{\text{NetH}}$ is negative it means that there is not enough power to supply the load, so power has to be discharged from the batteries or taken from the electric grid, depending on SOC of the batteries.

The inputs for the PV model with batteries are load profile $P_{\text{Load}}$, capacity of batteries and the same inputs for the PV model, while the outputs are self-consumption-percent, $P_{\text{NetH}}$, and SOC. The maximum allowed SOC is 100%, while the minimum allowed SOC is 50%, to protect the life cycle of the batteries.

![Figure 2.7: Block diagram for the PV system with Batteries, explains the algorithm for PV system with Batteries](image)
2.2 Wind turbine model

This section presents a model for 3-bladed horizontal axis wind turbine. The inputs parameters for this model are wind speeds $v(h_o)$, height of measuring equipment ($h_o$), hub height of wind turbine ($h$), roughness of the surface ($\alpha$), swept area of the wind turbine ($A$) and the power coefficient of wind turbine ($C_p$).

2.2.1 Vertical Wind Profile

The wind turbines are installed at high hub heights, while wind measurement equipment are installed at 10~50 meter high. The wind speed at the hub height of the wind turbine could be estimated by the vertical wind profile equation 2.20 [10]. Table 2.1 shows the variation of $\alpha$ with terrain.

$$v(h) = v(h_o) \left( \frac{h}{h_o} \right)^\alpha$$

(2.20)

Table 2.1: Variation of $\alpha$ with terrain.

<table>
<thead>
<tr>
<th>Type of terrain</th>
<th>$\alpha$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Calm open sea</td>
<td>0.104</td>
</tr>
<tr>
<td>Snow</td>
<td>0.1</td>
</tr>
<tr>
<td>Rough pasture</td>
<td>0.112</td>
</tr>
<tr>
<td>Crops</td>
<td>0.131</td>
</tr>
<tr>
<td>Scattered trees</td>
<td>0.188</td>
</tr>
<tr>
<td>Forest</td>
<td>0.213</td>
</tr>
<tr>
<td>Suburbs</td>
<td>0.257</td>
</tr>
<tr>
<td>City centers</td>
<td>0.289</td>
</tr>
</tbody>
</table>

Figure 2.8 shows a block diagram for wind model, explaining the algorithm of the wind turbine model. If $v(h)$ is higher than cut-out wind speed, that means that the wind turbine, should be switched off to protect it and $P_{AC}$ is zero, while if $v(h)$ is lower than the cut-in speed that means there isn’t enough power in the wind to rotate the wind turbine and $P_{AC}$ is zero.

If $v(h)$ is between cut-in and cut-out wind speed that means that wind turbine is producing and $P_{AC}$ produced by the wind turbine could be calculated by equation 2.21 [11].

$$P_{AC} = \frac{1}{2} \rho (v(h))^3 C_p A$$

(2.21)

Where $\rho$ is the standard air density 1.225 $kg/m^3$. $C_p$ and $A$ are available in the datasheet of the wind turbine manufacture.
2.2.2 Test wind turbine model

Figure 2.9 shows 2 curves for $P_{AC}$ by ENERCON E-126 wind turbine. The dashed black curve is power curve that is given by the datasheet of the manufacturer. The second curve in red is $P_{AC}$ simulated by wind model.

![Wind Turbine Power Curves](image)

Figure 2.9: Test for wind model shows the simulated $P_{AC}$ and power curve from datasheet
2.3 Bio Generator Model

This section presents the bio generator model and an algorithm for it. The input parameters for the bio generator model are load profile after subtracting the power produced by PV and wind ($P_{NetPW}$) and the bio capacities which are going to be simulated, while the output for the bio generator model are load profile after subtraction of power produced by PV, wind and power produced by the bio generator model.

2.3.1 Algorithm for the Bio Generator Model

The gross load profile ($P_{Load}$) and power produced by the simulated PV systems with in the region ($P_{AC,P}$) for one year are loaded and subtracted from each other. The result of this subtraction is called $P_{Net,P}$. The power produced by wind turbines in the region ($P_{AC,W}$) is subtracted from $P_{Net,P}$ and the result is named $P_{NetPW}$.

The bio generator model operates each bio generator 15 hours within 30 hours. It would check the highest peaks within 30 hours. Then it would check if there is any Bio generator that could fulfill the load demand by itself, if yes then this generator would go into operation, if not then the Bio model would operate more than one generator to fulfill the load demand (Priority to bigger generators as they are more efficient). After the load has been covered by the one or more Bio generators, the Bio model would check the next highest peak, until it reaches with it to minimum for 30 hours. Then it would go to check the next 30 hours until the year is done.

The outputs for the Bio model are $P_{NetPW}$, which is load profile minus power produced by PV, wind and Bio generators and $P_{AC,Bio}$ which is the power produced by the Bio generators.

Figure 2.10: Block diagram for bio model, explaining the algorithm for bio model
Chapter 3

Optimization Method

3.1 Motivation for Optimization Method

100% renewable energy projects presented in [1, 3, 4, 12] are propose four to six scenarios with different combination of technology and comparing between those different scenarios on the basis of economic factors, carbon dioxide (CO\textsubscript{2}) emission, imports/exports of energy etc. On the other hand, there could be infinite combination of different renewable energy technologies with which a region could reach 100% renewable energy. This chapter is going to introduce a new optimization tool that scans the space of different renewable energy technologies starting from current installed capacity to the maximum potential that could be installed in the region, until it reaches 100% renewable energy and presents an optimal result for each of the following factors: autonomy, costs, CO\textsubscript{2} emission, job creation, operation & maintenance costs and public acceptance. The MATLAB platform was used for developing the optimization method. This optimization tool finds the optimum technology combination based on weighted sum matrices.

3.2 Introduction to the Optimization tool

Figure 3.1 shows the block diagram of the algorithm for the optimization tool. The tool consists of the PV, Wind and Bio models presented in chapter 2. It starts by the current installed capacity in the region and calculates the hourly power produced by each technology and subtracts it from the load profile. The energy produced by renewable energy is calculated as a percentage from the total electric load demand. If the percentage of renewable energy is less than 100%, then the tool would recalculate with higher capacity installed for PV, Wind and Bio until 100% renewable energy is achieved in the region.
3.3 Algorithm for optimization tool

First the algorithm calculates the hourly power produced by PV systems ($P_{PV}$) within the region, based on the current installed capacity. Then, it calculates the hourly power produced by wind turbines ($P_W$) within the region based on the current installed capacity and sums it with the power produced by PV systems. The summed power from $P_{PV}$ and $P_W$ are subtracted from the hourly growth load profile for the region and the result of this subtraction named $P_{NetPW}$. $P_{NetPW}$ is one of the inputs for the Bio model. The Bio model chooses the load peaks, when there isn’t enough power from PV and wind to supply the load demand and operates the Bio generators. The outputs from the Bio generator model are hourly power produced by Bio generators ($P_{Bio}$) in the region and load profile after subtracting power generated by PV, wind and Bio generators. The energy for each renewable energy technology is calculated by summing the hourly power generated for the whole year.

When 100% renewable energy is reached, the tool would calculate the autonomy, CO$_2$ emission, investment costs, number of jobs created, operation & maintenance costs and income for the region.
3.3.1 Percentage of Renewable Energy

The tool calculates the percentage of renewable energy $RE\%$ for this region by equation 3.1, which is the sum of energy produced by PV systems, wind turbines and Bio generators, divided by the total energy demand for this region, multiplied by 100 to present it as a percentage.

$$RE\% = \frac{\sum_{i=1}^{8760} P_{PV} + \sum_{i=1}^{8760} P_{W} + \sum_{i=1}^{8760} P_{Bio}}{\sum_{i=1}^{8760} P_{Load}} \times 100$$ (3.1)

The tool presents the percentage of renewable energy in a 4D plot. Figure 3.2 shows the 4D plot for the percentage of renewable energy. The x-, y-, z-axes represent the capacities installed for PV, Wind and Bio respectively. While the color of the surface represents the fourth dimension, which is the percentage of renewable energy for the given input combination. The surface in figure 3.2 represents the 100% renewable energy surface and higher\(^1\), which means that any point below this surface denotes a scenario less than 100% renewable energy, while any point above this surface means it is more than 100% renewable energy. The color column on the right hand side represents the color code for the percentage of renewable energy.

![4D plot for Renewable Energy Percent](image)

Figure 3.2: 4D plot for the percentage of Renewable Energy

3.3.2 Autonomy percentage

The autonomy could be defined as the percentage of energy that is produced and consumed locally without exports and imports. The inputs for the autonomy block are $P_{Load}$ and $P_{Net_{PW}}$. The autonomy block calculates the percentage of demand which hasn’t

\(^1\)The reason that there are more than 100% renewable energy on the surface, is the big steps taken by renewable energy capacities, decreasing the steps would lead to increase the computation time for 4D plot
been directly supplied by renewable energy produced within the region and subtracts it from 100, to calculate the percentage of energy that has been produced and consumed locally without exports and imports.

Figure 3.3 shows a 100% renewable energy surface. The color of the surface represents the percentage of autonomy for each combination. The color column on the right hand side represents the color code for the percentage of autonomy. It can be noticed from the plot that there is a direct correlation between the capacity of Bio generators and the autonomy, as Bio generators are flexible renewable energy sources which operate based on the demand, while PV and wind energy production is dependent on meteorological conditions.

![4D plot for Autonomy](image)

Figure 3.3: 4D plot for the percentage of autonomy

### 3.3.3 Carbon dioxide emission

The carbon dioxide emission is one of the key elements that make the regions take the decision of shifting to renewable energy. The carbon dioxide (CO₂) emission block calculates the amount of carbon dioxide emission based on the amount of energy produced by each renewable energy technology. The carbon dioxide emission for PV is 94 g/kWh\text{el} (\(E_{CO2_{PV}}\)), wind is 32 g/kWh\text{el} (\(E_{CO2_{W}}\)) and Bio generators 640 g/kWh\text{el} (\(E_{CO2_{Bio}}\)) [13].

\[
E_{CO2_{Total}} = \left( E_{CO2_{PV}} \sum_{1}^{8760} P_{PV} \right) + \left( E_{CO2_{W}} \sum_{1}^{8760} P_{W} \right) + \left( E_{CO2_{Bio}} \sum_{1}^{8760} P_{Bio} \right) \tag{3.2}
\]

Figure 3.4 shows the plot with the 100% renewable energy surface. The color of the surface represents the carbon dioxide emission reduction for each combination. The color column on the right hand side represents the color code for carbon dioxide emission reduction. It can be noticed that the more the Bio generators installed the higher the emission, while the more PV and wind are installed the less the CO₂ emission.
3.3.4 Annual income to the region

One of the advantages of a 100% renewable energy project to the region is the value created by the income from selling renewable energy electricity to the region and the regions around it. The selling price for PV ($C_{sell_{PV}}$) is set at 0.18 €/kWh$_{ele}$, wind ($C_{sell_{W}}$) 0.07 €/kWh$_{ele}$ and Bio ($C_{sell_{Bio}}$) 0.05 €/kWh$_{ele}$ [14]. The income block would calculate the annual income to the region by equation 3.3.

\[
Income = \left( C_{sell_{PV}} \sum_1^{8760} P_{PV} \right) + \left( C_{sell_{W}} \sum_1^{8760} P_{W} \right) + \left( C_{sell_{Bio}} \sum_1^{8760} P_{Bio} \right)
\]  

(3.3)

Figure 3.5 shows plot for 100% renewable energy surface, while the color of the surface represents the annual income to the region, due to selling electricity into the region and the regions around it. It is noticed from the figure 3.5 that the higher the installed wind capacity the higher the annual income to the region.
3.3.5 Investment costs

The region has to invest money to install new renewable energy in order to reach 100% renewable energy. The prices for the investment costs for PV \( C_{Inv_{PV}} \) 1400 €/kW, wind \( C_{Inv_{W}} \) 1294 €/kW [14] and Bio \( C_{Inv_{Bio}} \) 3889\(^2\) €/kW. The Bio investment cost have been calculated by IdE. The total investment cost is calculated by equation 3.4. Figure 3.6 shows plot for 100% renewable energy surface, while the color of the surface represents the investment cost to reach 100% renewable energy in the region.

\[
\text{Invest} = (C_{Inv_{PV}} \cdot \text{Cap}_{New_{PV}}) + (C_{Inv_{W}} \cdot \text{Cap}_{New_{W}}) + (C_{Inv_{Bio}} \cdot \text{Cap}_{New_{Bio}}) \tag{3.4}
\]

\(^2\)This price is for Bio combined heat and power generators (CHP)
3.3.6 Job creation

The number of jobs created in the region is one of the key elements for the value creation within the region. The number of jobs created for installing PV ($N_{\text{Job}_{\text{PV}}}$) is 30 $\text{Job}/\text{MW}$, wind ($N_{\text{Job}_{\text{W}}}$) is 22 $\text{Job}/\text{MW}$ and Bio ($N_{\text{Job}_{\text{Bio}}}$) is 15 $\text{Job}/\text{MW}$ [15]. The total number of jobs created is calculated by equation 3.5. Figure 3.7 shows plot for 100% renewable energy surface, while the color of the surface represents the number of jobs created.

$$N_{\text{Job}_{\text{Total}}} = (N_{\text{Job}_{\text{PV}}} \cdot \text{Cap}_{\text{New}_{\text{PV}}}) + (N_{\text{Job}_{\text{W}}} \cdot \text{Cap}_{\text{New}_{\text{W}}}) + (N_{\text{Job}_{\text{Bio}}} \cdot \text{Cap}_{\text{New}_{\text{Bio}}})$$  (3.5)
Figure 3.7: 4D plot shows the number of jobs created within the region.

### 3.3.7 Annual Operation & Maintenance costs

The annual operation & maintenance costs ($C_{O&M_{Total}}$) are calculated for PV and wind based on the capacity installed. The annual cost for operation & maintenance for PV ($C_{O&M_{PV}}$) is 34.75 €/MW and wind ($C_{O&M_{W}}$) is 47.32 €/MW, while the annual operation & maintenance costs for Bio is based on the annual generated energy, as operation & maintenance costs for Bio generators depends more on operation hours for the generator. The annual cost for operation & maintenance for Bio ($C_{O&M_{Bio}}$) is 2.74 €/MWh [14]. The total annual operation & maintenance costs are calculated by equation 3.6.

$$C_{O&M_{Total}} = (C_{O&M_{PV}} Cap_{PV}) + (C_{O&M_{W}} Cap_{W}) + \left(C_{O&M_{Bio}} \sum_{1}^{8760} P_{Bio}\right) \quad (3.6)$$
3.3.8 Public acceptance

The public acceptance ($PA$) is defined by grading system (from 0 to 5) for each renewable energy technology. Zero means that this technology isn’t accepted within the region, on the other hand five means that this technology is highly accepted within the region. Based on this grading system the new installed capacity from each technology in kW would be multiplied by its grade. Then all the results of multiplicities grades would be summed up to give a figure for the public acceptance within the region. The matrix for public acceptance is normalized by dividing by highest element in the matrix. It has been assumed that the public acceptance for PV ($PA_{PV}$) is 3, wind ($PA_{W}$) is 3 and Bio ($PA_{Bio}$) is 5. Equation 3.7 shows how the elements of the matrix for public acceptance is calculated. Figure 3.9 shows a 4D plot for the public acceptance within the region. The color code for public acceptance is form 0 to 1. Zero means it isn’t accepted, while one means that it is highly accepted.

$$PA = (PA_{PV} Cap_{New_{PV}}) + (PA_{W} Cap_{New_{W}}) + (PA_{Bio} Cap_{New_{Bio}})$$  (3.7)
3.4 The optimum scenario

The question when choosing the capacity that needed to be installed to reach 100% renewable energy, which is the technology is the most optimum and from which point of view? Is it the investment costs, CO$_2$ emission · · · etc?

The product of each of the 4D plots in section 3.3 is a matrix, the elements of the matrix could be normalized, by dividing it by the maximum element within the matrix, so that all the elements of the matrix is between 0 and 1. The optimum matrix is calculated by the below equation, where $C$ represents the coefficients of the matrices and it is a scalar value. The coefficients are graded from 0 to 5 based on how important this parameter to the region, for example if this region suffers from high carbon dioxide emission, then this region would give $C_{CO_2}$, 5, while on the other hand if this region have low unemployment, then $C_{Job}$ could be set to 0 or 1. Equation 3.8 shows how the optimum matrix is calculated. The optimum matrix is normalized by dividing all the elements of the matrix by the maximum element in the matrix. The color code for optimum is form 0 to 1. One means that it is the optimum scenario.

Figure 3.9: 4D plot shows the public acceptance within the region.
Figure 3.10 shows a 4D plot for optimum with assumed coefficient for autonomy \((C_{Auto})\) 3, coefficient for \(CO_2\) emission \((C_{CO_2})\) 3, coefficient for income \((C_{Income})\) 5, coefficient for job creation \((C_{Job})\) 5, coefficient for investment \((C_{Invest})\) 1, coefficient for operation and maintenance \((C_{O&M})\) 1 and coefficient of public acceptance \((C_{Public})\) 3.

\[
\begin{pmatrix}
X_{11} & \cdots & X_{i1} \\
\vdots & \ddots & \vdots \\
X_{1j} & \cdots & X_{ij}
\end{pmatrix}_{Optimum} = C_{Auto.} \begin{pmatrix}
A_{11} & \cdots & A_{i1} \\
\vdots & \ddots & \vdots \\
A_{1j} & \cdots & A_{ij}
\end{pmatrix}_{Auto} - C_{CO_2} \begin{pmatrix}
E_{CO2_{11}} & \cdots & E_{CO2_{i1}} \\
\vdots & \ddots & \vdots \\
E_{CO2_{1j}} & \cdots & E_{CO2_{ij}}
\end{pmatrix}_{CO_2}
\]

\[+C_{Income} \begin{pmatrix}
Inc_{11} & \cdots & Inc_{i1} \\
\vdots & \ddots & \vdots \\
Inc_{1j} & \cdots & Inc_{ij}
\end{pmatrix}_{Income} + C_{Job} \begin{pmatrix}
N_{job_{11}} & \cdots & N_{job_{i1}} \\
\vdots & \ddots & \vdots \\
N_{job_{1j}} & \cdots & N_{job_{ij}}
\end{pmatrix}_{Job}
\]

\[-C_{Invest} \begin{pmatrix}
Inv_{11} & \cdots & Inv_{i1} \\
\vdots & \ddots & \vdots \\
Inv_{1j} & \cdots & Inv_{ij}
\end{pmatrix}_{Invest} - C_{O&M} \begin{pmatrix}
O&M_{11} & \cdots & O&M_{i1} \\
\vdots & \ddots & \vdots \\
O&M_{1j} & \cdots & O&M_{ij}
\end{pmatrix}_{O&M}
\]

\[+C_{Public} \begin{pmatrix}
PA_{11} & \cdots & PA_{i1} \\
\vdots & \ddots & \vdots \\
PA_{1j} & \cdots & PA_{ij}
\end{pmatrix}_{Public}
\]

Figure 3.10: 4D plot shows the optimum case at 100% renewable energy.

### 3.5 Results

The optimum tool proposes to increase the capacity of PV systems to 578 MW, wind capacity to 1842 MW and bio generators to 120 MW in order to reach 100% renewable energy.
energy based on the grading scale proposed in section 3.4. That means that the region have to invest in 473 MW in PV systems, 1535 in wind and 40 MW in Bio technology.

The optimum point is sensitive many parameters such as the coefficient of grading system, public acceptance, operation & maintenance, number of jobs created, investment costs, annual income and carbon dioxide emission for each renewable energy technology.
Chapter 4

Case study#1: Osnabrück, Germany

The first case study of a region, aiming to reach 100% renewable energy presented in this master thesis is Osnabrück, Germany. Osnabrück is located in southwestern Lower Saxony on the border with Nordrhein-Westfalen. The area of the region is 2121 km² with 360,000 inhabitants. Currently the share of renewable energy in the region is around 40%. The county of Osnabrück consists of 34 municipalities including 8 cities and 4 joint communities ranging in size from 7,000 to more than 45,000 inhabitants [16].

4.1 Overview about Renewable Energy in Osnabrück

In 2008, the Osnabrück region produced 500 GWh from renewable sources. The total installed renewable energy capacity in Osnabrück is around 492 MW, Figure 4.1 shows the capacity installed in Osnabrück. Wind represents 63% of the installed renewable energy capacity with 307 MW, PV 21% with 105 MW, Bio 16% with 80 MW, while hydro power represents less than 1% of the installed renewable energy capacity with 309 kW [16].

![Renewable Energy installed in Osnabrück](image)

Figure 4.1: Renewable Energy installed in Osnabrück

Figure 4.2 shows the installed capacity in each community in Osnabrück. Bippen has the highest installed wind capacity with 30.1 MW, while Melle has the highest installed PV capacity with 13.8 MW; also Melle has the highest installed Bio capacity with 8.3 MW. Figure 4.3 shows a map for Osnabrück with the installed renewable energy capacity in each community.
Figure 4.2: Installed renewable energy capacity for each community in Osnabrück

Figure 4.3: Map with Renewable energy installed in each community in Osnabrück
4.2 Renewable Energy Potential in Osnabrück

4.2.1 Photovoltaic

The capacity factor ($C_f$) for the energy produced by PV systems is defined by equation 4.1. It is the total energy produced by PV systems through the year divided by the energy that would be generated if the PV system operates all the year without a stop. Hourly solar meteorological data have been used from Meteonorm 7 for Osnabrück to calculate the capacity factor for PV systems. The capacity factor is 14% for PV systems oriented south with angle of inclination of 30°.

$$C_f = \frac{\sum_{1}^{8760} P_{PV}}{C_{ap_{PV}} \times 8760}$$  (4.1)

Photovoltaic on roof top systems

The annual solar radiation is 950 kWh/m² on the horizontal surface in Osnabrück and area available to PV plants is approximately 9.8 million feet square. The average efficiency of a PV system on a building is around 12%. These areas can approximately produce 1100 GWh of electricity per year [16].

Photovoltaic ground mounted systems

Osnabrück has a total installed capacity of 8 MW in ground mounted systems. The calculated potential for ground mounted PV plants is 294 MW. Assuming full utilization of the available area the potential capacity for ground mounted systems can be approximately 250 GWh of electric energy per year [16].

4.2.2 Hydropower

The hydrological conditions in the district of Osnabrück translate to a total potential of 880 MWh of electricity per year. The total electric energy production from Hydropower was approximately 535 MWh in 2008 [16].

4.2.3 Biogas

Biogas plants in Osnabrück can generate about 400 GWh of electricity and about 420 GWh of thermal energy per year [16].

4.2.4 Wind

At the end of 2008, in Osnabrück there were 125 wind turbines of size classes 50 to 2300 kW with a total capacity of 188 MW. All the plants together produce an average about 340 GWh of renewable electricity. The operation hours for wind turbines in this area is around 1800 hour/year [16].

With a complete repowering of the plants (3 MW, rotor diameter of 100 m and 120 m hub height), the number of turbines could decrease to 63 turbines and the total installed capacity of the renewed facilities increases to 189 MW. The benefits in terms of
the achievable energy yield per plant in the same space is enormous. With each larger meter hub height the energy yield increases by approximately 1% moreover this increases the average permissible full load operation hours after repowering to approximately 2500 hour/year [16].

4.3 Electric demand for Osnabrück

In 2008, the electric consumption for county Osnabrück was 1782 GWh. The household consumed 557 GWh, while the commercial and industrial sectors consumed 1225 GWh. The current share for the households is relatively constant in all communities at an average 1425 kWh/capita. The share of the industrial and commercial sectors is subject to the local commercial structure [16]. Figure 4.4 shows the annual expected electric energy consumption and energy generated by renewable energy from 2010 until 2050 in the county of Osnabrück. It is expected that the energy generated from renewable sources would be able to fulfill the load demand in 2030, without including electric mobility and by 2050, with electric mobility.

![Graph showing electric demand for Osnabrück](image-url)

Figure 4.4: The annual expected electric energy consumption and energy generated from renewable sources from 2010 until 2050 in the county of Osnabrück

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1The industrial sector doesn’t include steel plants. The steel plants in the county consumes around 500 GWh. [16]
4.4 Load profile for Osnabrück

The hourly load profile for the county of Osnabrück wasn’t provided to us, so the load profile has been generated for the county from the hourly load profile provided by the stadtwerke-osnabrück [17]. The load profile for 2030 for the county of Osnabrück has been generated by multiplying the stadtwerke-osnabrück load profile by a factor which is the ratio between the expected energy consumed in the county in 2030 and the energy consumption for the region supplied by stadtwerke-osnabrück. Equation 4.2 shows how the load profile for 2030 for the county of Osnabrück. Figure 4.5 shows hourly load profile for the county of Osnabrück in 2030. The minimum expected load is 105 MW, while the maximum expected load is 495 MW in 2030.

\[
\begin{pmatrix}
P_{Load_{1}} \\
\vdots \\
P_{Load_{8760}}
\end{pmatrix}_{2030(county)} =
\begin{pmatrix}
P_{Load_{1}} \\
\vdots \\
P_{Load_{8760}}
\end{pmatrix}_{2011(Sstadtwerke)} \times \frac{\sum_{1}^{8760} P_{Load2030}}{\sum_{1}^{8760} P_{Load2011}}
\] (4.2)

Figure 4.5: The expected hourly load profile for the county Osnabrück in 2030
4.5 Simulation load profile with renewable energy

As has been mentioned in section 3.5 the county needs to increase the capacity of PV systems to 578 MW, wind to 1842 MW and Bio generators to are 120 MW to reach its goal of 100% renewable energy.

It has been assumed that 378 MW from the PV systems are from panels that south oriented with angle of inclination 30°, 100 MW south east oriented with angle of inclination 25° and the last 100 MW are south west oriented with angle of inclination 25°.

The wind turbines needed to be installed in the county of Osnabrück have been divided into three categories. The first category is 82 wind turbines of ENERCON E-126 with a rated power 7.5 MW, while the second and third categories are 409 wind turbines of ENERCON E-101 and ENERCON E-82 with a rated power 3 MW.

The county of Osnabrück needs to install 40 MW of Bio generators. It has been assumed that this new capacity is divided between 226 Bio generators.

4.6 Results

Figure 4.6 shows the gross, net load profile and power generated by renewable energy for 48 hours. The y-axis of this graph represents the power in MW, while the x-axis represents the time in hours. The solid black line represents the gross load profile for the county of Osnabrück for 48 hours, while the dashed black line represents the net load profile, which is the gross load profile subtracted from it the power generated by renewable energy in the county of Osnabrück. The solid orange line represents the total power produced by all PV installed in the county. The solid blue line represents the total power produced by all the wind turbines installed in the county. The solid green line represents the power produced by all Bio generators in the county. The net load profile is the result of subtraction of the sum of all the renewable energy technologies from the gross load profile.

Positive net load means that the county imports power from outside the county to fulfill the electric load demand, as the power produced by renewable energy technologies in the county is not enough to fulfill the electric load demand. Negative net load means that the county produces electric power higher than the electric load demand in the county and this extra power is exported outside the county.
Figure 4.6: Hourly load profile for the county of Osnabrück for 48 hours and the generated power from renewable energy sources in the region
Chapter 5

Case study#2: Siwa, Egypt

The second case study of a region aiming to reach 100% renewable energy presented in this master thesis is Siwa, Egypt. Siwa is located between the Qattara Depression and the Egyptian Sand Sea, nearly 300 km south of Mersa Matruh, Egypt, 50 km east of the Libyan border and 700 km from Cairo, Egypt. The Siwa oasis is located in a deep depression that extends below sea level. This depression, an area lower than the surrounding region, reaches to about -19 m. Agriculture is the main activity of the Siwi, particularly the cultivation of dates and olives. Siwa consists of 11 Tribes, with around 30,000 inhabitants. The information provided in this chapter about the Siwa grid, is based on an interview with Eng. Ali Abdelnaby, head of the Siwa Engineering sector, El-Behera distribution company from 30th of December 2012 to 2nd of January 2013.

5.1 Overview about Siwa electric grid

5.1.1 Grid history

Electricity entered Siwa during the end of 1960s. Due to increase in the electric demand the government had to install 4 generators each of 680 kVA (2 generators were working during day and the other 2 during evening). The transmission network during this period was on 3.3 kV. Due to the start of the olive oil and water packaging industry in Siwa, the electric demand increased and the government had to install between 1991 and 1996, 3 electric generators, each generator with a capacity of 2.5 MW. Those generators operate on diesel fuel and consumed 1 liter of diesel to produce 3.2 kWh.

Until now, Siwa is not connected to the Egyptian national grid. It is 100 km away from the Libyan grid and 300 km from Egyptian national grid through Mersa Matruh. Siwa is divided into 6 communities which are Siwa city, Agorny, Abo-Shrof, Al-Maraky, Baha-El-Din and Om-El-Sager. Siwa city, Agorny, Al-Marak and Baha-El-Din are connected with the Siwa grid. While Om-El-Sager and part of Abo-Shrof (Ayn-Zahra district) are operating on PV systems. Each house, mosque and light pole in Om-El-Sager and Ayn-Zahra are operating as an island system, with PV modules on the roof, batteries and inverters.

5.1.2 Electric Energy

Figure 5.1 shows the monthly electric energy consumption for Siwa for 2011 and 2012. It is noticed from figure 5.1 that there is increase in the electric demand from one year to
another, with an average increase of 22%. There are five companies working in the water packaging industry in Siwa, during summer there is a high demand for water bottles in the Egyptian market, so those companies have to work 24/7 in order to fulfill the market demand. Moreover the water packaging companies are installing new production lines to increase their production. The mean outage time for electricity for households in Siwa is 24 hours per year.

Figure 5.1: The monthly electric consumption for Siwa, Egypt for 2011 and 2012.

Siwi used to live in houses made of karshif, which is a traditional building material made out of mud, sand and sun-dried salt harvested from Siwa’s salt lakes [18]. Karshif acts as a natural insulator, moreover the walls of houses were made thick to keep indoor air temperature mild in both hot and cold seasons. The temperature could reach higher than 40 °C during summer and in winter it could reach below 5 °C. From 1990s, modern developments in Siwa began and people started to replace karshif in building their houses with lime, red bricks and concrete, which results in new houses being less energy efficient and people have started to install air conditioning in their houses in the last few years. The maximum peak for Siwa local grid was 6 MW in August 2012.

5.1.3 Load Profile

Figure 5.2 shows a four day hourly electric load profile. It is noticed that there isn’t a big difference between the load profile during the weekdays and weekend as factories operate during the weekend too. Moreover the electric load is higher during summer due the usage of air conditioning. The electric load is nearly constant during morning and increases during evening due to lighting load.
5.1.4 Electric Energy Expectation

Figure 5.3 shows the expected electric energy consumption for Siwa from 2013 until 2020. This scenario is based on annual increase in the electric energy consumption by 10%. It is expected by 2020 that the total electric energy demand reaches 54 GWh. The electric energy consumption in 2011 was 21 GWh, while in 2012 it was 25\textsuperscript{1} GWh.

\textsuperscript{1}The electric energy for December 2012 has been assumed, as the data was collected before the end of December 2012.
5.2 Energy Efficiency Potential

Before analyzing the Siwa region and how this region could reach 100% renewable energy, there should be an energy efficient auditing done to the region to reduce the electric energy consumption, to facilitate the path to 100% renewable energy. There are 3000 street light poles in Siwa. The power for each street light pole is 280 W, thus the total electric load for streets light poles is 840 kW, which represents more than 10% of the electric load during evening. Two scenarios have been proposed to reduce the electric load for street light poles:

1. To replace the current street light poles with new ones operating with PV modules with batteries as a storage. The new street light poles would be working as an island system and won’t be connected with electric grid.

2. To keep the same street light poles and replace the lamps operating on 280 W with new Light Emitting diode (LED) ones operating on 60 W, while keeping the street light poles connected to the grid as it is.

In both scenarios the street light poles are going anyway to operate on renewable energy. The second scenario has been chosen because:

- The investment costs for the second scenario is less.
- In the first scenario the grid won’t benefit from the battery storage by the street light poles.
- The available light pole is quite new and reinvestment in new street light leaving the grid connection for street light poles is considered wastage of public money.

Figure 5.4 shows the old and new winter load profile after replacing the old street lamps by new LED lamps. It has been assumed that the street lights operate from 6 PM until 7 AM in January. The energy consumed by old load profile is 74 MWh, while the new load profile consumes 64 MWh, which means that replacing the lamps could reduce the energy consumption by more than 12%.
5.3 Pre-Feasibility study for replacing current street lamps by LED lamps

5.3.1 Introduction

This section is going to study from the economic point of view replacing current lamps by LED lamps. The power of the current installed street lamps is 280 W, while the power of the new LED lamps is 60 W. The life span of the new LED lamps is 50,000 hours, with a beam angle 360 degree and 5900 lm. The input voltage range for the LED lamps is 85-277 VAC.

5.3.2 Investment costs

The investment cost for 1 LED is 242 EGP that includes the purchase costs, shipping and installation [19]. The total investment costs to replace all the street light poles in Siwa, (which are 3000 light street pole) is 727 thousand EGP.

5.3.3 Running costs

It has been assumed that Egypt imports diesel fuel at a price 1 $/l of diesel, which is equivalent to 6.73 EGP. As it have been mentioned previously in section 5.1.1 that 1 liter of diesel produces 3.2 kWh for diesel generators in Siwa. That means that the cost for 1 kWh is 2.1 EGP in Siwa. Figure 5.5 compares the monthly electric energy consumed by LED lamps and old lamps, while figure 5.6 compares the monthly costs for LED lamps and old lamps.

Figure 5.4: Old and new electric load profile after replacing the old street lamps by new LED lamps.
The old street lighting lamps consume annually 3252 MWh, while LED street lighting lamps will consume 697 MWh. That means that just replacing the old lamps with new LED lamps saves 2555 MWh, which saves around 5 Million EGP. The payback period is
5.3.5 Sensitivity Analysis

Figure 5.7 shows the sensitivity analysis for the payback period. The x-axis represents the increase and decrease of the prices of diesel fuel in percentage, while the y-axis represents the payback period in months. The diesel price changes while fixing the price for LED lamps. It is noticed that with decreasing the price of diesel with 80%, which is near the subsidized price of diesel fuel, the payback period would increase to around 9 months. The payback period decreases with increasing the prices of diesel fuel.

Figure 5.7: Sensitivity analysis for the payback period for the project by changing the price of diesel at constant investment cost.

Figure 5.8 shows the sensitivity analysis for the payback period. The x-axis represents the price development for LED lamps in percentage at constant diesel fuel price, while the y-axis represents the payback period in months. It is noticed that even with increasing the prices of LED lamps by 200%, the payback period is around 5 months. There is direct correlation between the price of LED lamps and the payback period of the project.

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2The payback period doesn’t take into consideration the payment from carbon dioxide credits.
Figure 5.8: Sensitivity analysis for payback period for project by changing the price of LED lamps at constant diesel price.

5.3.6 Strengths, Weaknesses, Opportunities and Threats (SWOT analysis)

Strengths
- Reduction of the power demand on the grid
- Increase the stability of the Siwa electric grid
- Reduction of CO₂ emission and other pollutants NOₓ and SO₂
- Facilitate the path for renewable energy to fulfill the load demand
- Short payback period
- Low investment costs

Weaknesses
- LED lamps are not manufactured locally
- Less load shifting as the LED lamps represent less amount of the electric load

Opportunities
- Encourages people, companies and government’s interest to replace old lamps by new LED lamps
- Positive economic impacts through saving money and diesel fuel to the country
Threats

- Awareness of energy efficiency does not reach all potentially interested parties

## 5.4 Potential of Renewable Energy in Siwa

This section is going to present the potential of renewable energies in Siwa. Moreover this section is going to calculate the capacity factor for the energy produced by PV systems and wind turbines. The capacity factor could be defined by the equation 5.1 as the total energy produced by a renewable energy technology through year divided by the energy that would be generated if this renewable energy technology is operating all year round without stop.

\[
C_f = \frac{\sum_1^{8760} P_{RE} \times 8760}{Cap_{RE}}
\]  

(5.1)

### 5.4.1 Wind Energy

The average wind speed in Siwa at 10 m above the ground level is 2.4 m/sec [20]. Nordex (N43) which is installed in Zafarana, Egypt has been simulated under Siwa weather condition. The capacity factor was 1.8%, which doesn’t make the region particularly interesting to install wind turbines. Figure 5.9 shows the wind atlas for Egypt, it shows that Siwa is in region class 1 [21], with low wind speeds. Moreover H. Abu ElEizz, M. Al-Motawakel and Z. Abu El-Eizz showed in their paper on "Wind characteristic and energy potentialities of some selected sites in the Yemen Arab Republic and the Republic of Egypt” that the accumulated annual wind energy for Siwa is around 33 kWh/m² and they proposed wind turbines with the following characteristics for Siwa with cut in wind speed 2 m/sec, rated wind speed 4 m/sec and cut out speed 10 m/sec [22].

![Figure 5.9: Wind regime map for Egypt (Wind atlas for Egypt).](image)

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5.4.2 Bio Energy

This thesis was focusing on the Bio energy generation in Siwa from garbage, animal excrement and wood from olive trees. Every family have a number of chickens, those chicken is feed by the remaining food from family. About the plastic garbage, all the plastic is collected in Siwa and recycled in Siwa and sold outside the region, so producing Bio energy from garbage doesn’t have high potential in Siwa. It is difficult to produce Bio energy from the animal excrement residues, as some families grow one or two sheeps or cows at the backyard of the house, but there isn’t any animal farms in Siwa, so collecting the animals excrement from large distributed area is difficult. Using wood from olive trees means the reduction of number of olives trees. Olives trees represents for Siwi as their income, so it is very hard to get red off olive tree.

5.4.3 Solar Energy

Siwa has high potential for solar energy and sky is clear all over the year. Figure 5.10 shows solar atlas for Egypt, the solar radiation intensity over Siwa is around 2500 kWh/m²/year [21]. The capacity factor for installed PV system in Siwa is around 29%. Moreover, it have been noticed that dust contamination in Siwa is very low, which reduce the need to clean the PV modules.

Figure 5.10: Solar radiation intensity Map for Egypt (Solar atlas for Egypt).
5.5 Pre-Feasibility study for 100% Renewable Energy for Siwa

5.5.1 Introduction

This section is going to study the possibility of reaching 100% renewable energy in Siwa at 2020 from the economic point of view. Figure 5.3 shows the expected energy consumption for Siwa region until 2020, it is expected before energy efficiency in streets light that the annual energy consumption is 54 GWh/year for 2020. On the other hand it is expected that energy efficiency in street lights would reduce the annual energy consumption by around 2.5 GWh/year. The annual consumption after energy efficiency in street lights is around 51.5 GWh/year.

5.5.2 Key Assumptions

| Period of Analysis: | 20 years |
| Timing of Payments: | At the end of each year |
| Interest rate: | 5% |
| Currency: | EGP |
| Exchange rate: | 1 $ = 6.73 EGP |
| | 1 € = 8.99 EGP |

5.5.3 Renewable Energy Scenarios for Siwa

After analyzing different renewable energy technologies in Siwa: wind energy, bio energy and solar energy, it has been notice that the best renewable energy technology for Siwa is solar energy. Siwa hasn’t been analyzed by the optimization method presented in chapter 3 as potential for wind energy and bio energy is very weak.

As solar energy could only supply the load only during morning, while there have to be another solution to supply load at evening. Three scenarios have been proposed to supply the load during all the day:

- PV system are used to supply the load during morning and charge the battery banks to supply the load during evening
- PV system are used to supply the load during morning, extra power generated by PV systems would be exported through a transmission line to Libya and during evening Siwa region will import power from Libya through transmission line
- PV system are used to supply the load during morning, extra power generated would be exported through a transmission line to Mersa Matruh to national grid and during evening Siwa region will import power from Mersa Matruh from national grid through transmission line

The three scenarios would be analyzed from the investment cost point of view and the one which have the least investment cost would be further analyzed. Siwa region needs to install 21 MW PV systems, in order to generate annual energy 53 GWh, which is higher than the electric energy demand by 2020 in case it is connected to Libya grid or national
grid through Mersa Matruh. On the other hand, Siwa needs to install 45 MW PV systems, in case it is not connected to other grid and battery banks with capacity 200 MWh, in order to fulfill the evening demand.

5.5.4 Investment cost

Table 5.1 shows the investment cost for each scenarios. The investment cost for PV modules with inverter is 1400 € per kW [14], for transmission line 400,000 $/km [23] and for battery 175 € per kWh [24]. It is noticed from table 5.1 that the highest investment cost is scenario PV system with grid connection to Mersa Matruh, while the lowest investment cost is scenario PV system with grid connection to Libya. The scenario with PV system with grid connection to Libya, will be further investigated from the economic point of view.

Table 5.1: Investment cost of different renewable energy scenarios for Siwa.

<table>
<thead>
<tr>
<th></th>
<th>PV - Grid to Libya [Million EGP]</th>
<th>PV - Grid to Mersa Matruh [Million EGP]</th>
<th>PV - Battery [Million EGP]</th>
</tr>
</thead>
<tbody>
<tr>
<td>PV cost</td>
<td>264.3</td>
<td>264.3</td>
<td>566.4</td>
</tr>
<tr>
<td>Transmission line costs</td>
<td>269.2</td>
<td>807.6</td>
<td>0</td>
</tr>
<tr>
<td>Battery costs</td>
<td>0</td>
<td>0</td>
<td>314.7</td>
</tr>
<tr>
<td>Total investment cost</td>
<td>533.5</td>
<td>1,071.9</td>
<td>881</td>
</tr>
</tbody>
</table>

5.5.5 Cash Flow Analysis

Figure 5.11 shows the net cash flow for 100% renewable energy project in Siwa. The total investment of this project to install PV systems and construct transmission line connecting Siwa with Libya is 533.5 million EGP. The income to this project is from the electricity sold to the Siwa region and Libya. The cost per kWh is assumed to be 2.1 EGP, as it has been calculated in section 5.3.3. This thesis assumes that the annual energy consumption will remain constant at 51.5 MWh starting from 2020 until 2040. The annual operation & maintenance cost for first year for PV system ($OM_{PV}$) is 6,560 EGP. It is assumed that the operation & maintenance cost increases every year by 1%. The interest rate has been assumed to be 5%. The Net Present Value (NPV) for the project is 268.6 million EGP, while the Internal Rate of Return (IRR) is 11%.
5.5.6 Savings and Payback Period

Figure 5.12 shows cumulative net cash flow for 100% renewable energy project in Siwa. It is noticed from figure 5.12 that the payback period for the project is 9 years. This project would save around annually around 16 million liter of diesel.
5.5.7 Sensitivity Analysis

It is noted that the dominating factors in the investment cost are the investment in PV system and the transmission line connecting Libya grid with Siwa. This section will present the effect of changing the prices of the PV system, transmission line and interest rate on NPV and IRR. Figure 5.13 shows the effect of the price development of PV system on the NPV of the project, while the price for transmission lines and interest rate are constant. The x-axis represents the development price in percentage for the PV system, while the y-axis represents NPV. NPV decreases with increasing the price of the PV system. NPV starts to be negative when the PV system cost increases by more than 40%.

![Figure 5.13: Effect of price development for PV system on NPV, at constant transmission lines cost and constant interest rate.](image)

Figure 5.13: Effect of price development for PV system on NPV, at constant transmission lines cost and constant interest rate.

Figure 5.14 shows the effect of the price development of the transmission lines on the NPV of the project, while the price of the PV systems and interest rate are constant. The x-axis represents the development price in percentage for the transmission line, while the y-axis represents NPV. NPV decreases with increasing the price of transmission lines. NPV becomes negative when the price of transmission lines increases by more than 40%.
Figure 5.14: Effect of price development for transmission lines on NPV, at constant PV system cost and constant interest rate.

Figure 5.15 shows the effect of interest rate development on NPV, at constant PV system and constant transmission line cost. NPV decreases with increasing the interest rate. NPV becomes negative when the price of interest rate increases by 60%.

Figure 5.15: Effect of interest rate development on NPV, at constant PV system and constant transmission line cost.

Figure 5.16 shows the effect of price development for PV systems on IRR, at con-
constant transmission lines cost and constant interest rate. The x-axis represents the price development in percentage for the PV system costs, while the y-axis represents IRR. IRR decreases with increasing the PV system costs. IRR becomes less than the interest rate when the price of PV system costs increases by more than 40%.

Figure 5.16: Effect of price development for PV systems on IRR, at constant transmission lines cost and constant interest rate.

Figure 5.17 shows the effect of price development for transmission lines on IRR, at constant PV system and constant interest rate. The x-axis represents the price development in percentage for the transmission lines, while the y-axis represents IRR. IRR decreases with increasing the transmission lines costs. IRR becomes less than the interest rate when the price of PV system costs increases by more than 40%.
Figure 5.17: Effect of price development for transmission lines on IRR, at constant PV system cost and constant interest rate.

Figure 5.18 shows the effect of development of interest rate on IRR, at constant PV system and transmission line cost. The x-axis represents the effect of development of interest rate in percentage, at constant PV system and transmission line cost, while y-axis represents IRR in percentage.

Figure 5.18: Effect of interest rate development on IRR, at constant PV system and transmission lines cost.
5.5.8 Strengths, Weaknesses, Opportunities and Threats (SWOT analysis)

Strengths

• Siwa grid would be operating at 100% renewable energy
• Increase the stability of the Siwa electric grid
• Increase the trade between Egypt and Libya
• Save annually 16 million liter of diesel to the country

Weaknesses

• High investment costs
• Long payback period for the project
• Increase of the prices of the investment costs or interest rate could lead that the project is invisible
• Siwa may face black out in case of problem with transmission lines

Opportunities

• Encourages people, companies and government's interest to start 100% renewable energy projects in other oasis
• Positive economic impacts through saving money and diesel fuel to the country

Threats

• Siwa region would be affected by any problem happens to Libyan grid.

5.6 Simulation

5.6.1 Monthly Energy Profile 2020

This master thesis is going to simulate the Siwa region at 2020 operating at 100% renewable energy. It is assumed that the monthly consumption in 2020 is with the same ratio as 2012. Figure 5.19 shows the monthly electric energy profile for Siwa in 2020. The maximum load expected in 2020 is 9.6 MW, while the minimum load expected is 4.2 MW.
5.6.2 Simulation load profile with renewable energy

Siwa region needs to install 21 MW PV system, in order to reach 100% renewable energy. There is around 30,000 inhabitant, if it is assumed that each family house have 6 persons, that means there is around 5000 house in Siwa. It have been assumed that each house would install PV system with capacity 2.1 kW_p. That means that the total installed capacity on the roof of the houses in Siwa is around 10.5 MW_p. There are around 16 factory in Siwa, so if each factory could install between 20 and 100 kW_p, so that the total installed capacity on the roof of factories in Siwa is 750 kW_p. There would be four PV power plants each power plant is with capacity 2.5 MW_p. The total PV capacity installed in Siwa is 21.25 MW_p. All PV system installed in Siwa is facing south with angle of inclination 30°. This PV capacity would generate annually 54.3 GWh. The hourly meteorological data for Siwa for 2020, have been predicted by Meteonorm version 7.

The gross load profile (P_{L_Gross}) is defined as the hourly electric load profile for the region, while the net load profile (P_{L_Net}) could be defined as the gross load profile subtracted from it the power generated by renewable energy within the region. Each month in 2020 have been weighted the same ratio as the weight for 2012. The gross load profile is generated from the new day hourly load profile after applying energy efficiency to the street lighting in Siwa. There is two daily load profiles one for summer and the second one for winter. The summer load profile have been applied for gross load profiles for April, May, June, July, August and September, while the winter load profile have been applied for gross load profiles January, February, March, October, November and December.

5.6.3 Results

Hourly net profile have been calculated by the method presented in subsection 5.6.2. The imported and exported electric energy have been calculated and presented in figure 5.20.
The electric energy imports/exports between Siwa grid and Libya is between 2045 and 3567 MWh monthly. It is noticed that the imports increases during summer due to air conditions. While exports increases during winter as the generated energy by PV system is higher than the energy demand.

Figure 5.20: The monthly imports/exports from and to Siwa region.
Chapter 6

Conclusion, Recommendations and Future Work

6.1 Conclusion

PV, wind, bio generator models have been presented in chapter 2. Those models have been used to represent renewable energy generators in the region. Chapter 3 presented a new methodology to get the optimum capacity needed to be installed in order to reach 100% renewable energy within the region. This optimization tool was implemented using MATLAB platform. The optimization tool takes into consideration autonomy, costs, CO₂ emission, job creation, operation & maintenance costs and public acceptance.

The county of Osnabrück could reach to 100% renewable energy by increasing the installed capacity of PV systems to 578 MW, wind to 1842 MW and Bio generators to 120 MW. Hourly simulation have been presented with the new renewable energy capacities in chapter 4.

Applying energy efficiency in street lighting systems would save annually 6 million EGP. Siwa region could reach to 100% renewable energy, by installing 21 MW PV systems and build transmission lines connecting Siwa region with Libya grid. Payback period expected for 100% renewable energy project in Siwa is 9 years.

6.2 Recommendations

In chapter 3, the coefficients for the optimization method have been assumed, it is recommended in the future that those coefficients are done by survey for the people living in the county and decision makers.

Tracking PV system is much more recommended for the four PV power plants that would be installed in Siwa, as it would produce much more energy, moreover the power produced by the tracking system is over longer period of day, which reduces exporting energy from Libya.

It is recommended to apply energy efficiency in houses in Siwa, as new houses built with bad energy efficiency in building, need to install air conditions, which consumes a lot of energy, so applying energy efficiency into houses would reduce the load demand during summer.

There is more than hot springs in Siwa oasis, so it is recommended to study the potential of producing electric energy from geothermal energy in Siwa.
PV systems in Om-El-Sager and Abo-Shrof regions, are operating as island system for each house. That means that each house have his own modules, battery and inverter. The problem with this system that new houses built won't have electricity and on the other hand people living there could afford to buy this PV system. So it is recommended in the future to make an internal grid for the region and make central battery bank, so that new houses built could have electricity.

This master focus on reaching with region to 100% renewable energy, which requires from Siwa region to build transmission lines or install battery bank, which increases the investment costs. On the other hand Siwa region could start to install PV systems to supply the morning demand, while during night it could operate the diesel generators to supply the night demand. Although this scenario won’t reach with Siwa region to 100% renewable energy, it would reduce the CO\textsubscript{2} emission for the region and diesel consumption.

### 6.3 Future Work

The algorithm for optimization tool needs to be further improved to reduce the computation time. Moreover the optimization tool needs to add a new optimization tool, such as the number of bio generators that needed to be installed.

The simulation tool for renewable energy needs to be modified to present the grid problems and what needed to be changed in the infrastructure of the grid to be operating at 100% renewable energy.
Bibliography


