Master thesis by Arne Kaas - Sustainable off-grid power for rural areas

Analysis of a hybrid power station for rural area’s, powered by wind, solar and diesel energy
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INTRODUCTION

Extension of energy grids is a costly business. Especially for rural area’s, the cost of a grid connection is often higher than the cost of a local energy system. The long connection lines are a large investment and cause large energy transportation losses. A local system run with diesel engines requires low investments and can often be cheaper than a grid connection. Though, the operational cost of system run with diesel generators can become vary costly with the rising diesel prices. Especially in remote area’s where fuel transportation cost are also increasing, this asks for a different solution.

A hybrid power system fed with wind, solar and diesel energy can be a cheaper and more sustainable option. This thesis focuses on the design and operation of a off grid hybrid power system. Because demand and supply of renewable energy do not match for 100% and because of seasonal variations, it is important to look at the most optimal design and operation of by analysing the system for a yearly cycle. This thesis will show the consequences of different sizing and operation approaches and the thereby corresponding conversion, storage and fuel losses. Secondly, it shows an analysis of three different power management strategies and their influence on losses and cost. Finally, it shows the operational cost and total cost of ownership for different locations and system configurations around the world. The focus of the simulations is on a off grid energy system installed in the Netherlands.

![Hybrid power system overview](image)

Figure 1.1 Hybrids power system overview.

Figure 1.1 shows the systems overview, where the black lines show the energy carrying cables. The top right icons show the system controlled and the blue lines show the control and communication cables. All subsystems displayed in the figure will be addressed in the following chapter.
2 TECHNOLOGY DESCRIPTION: A HYBRID POWER SYSTEM

This chapter describes the system topology and assumptions about the operation principles of all the sub systems. The power in the hybrid power system (HPS) is delivered by wind turbines, solar panels and diesel generators. Because the supply of this system is not always equal to the demand, energy needs to be stored. The multi hybrid inverter (MHI) takes care of the difference by storing excessive power in a battery and taking energy from the batteries when required. The MHI consist of DCDC converter and a bidirectional DCAC inverter. The next paragraph describes the system topology. All mentioned components and their important characteristics are described in the subsequent paragraphs.

2.1 Topology

Figure 2.1 shows the optimal system topology as was determined by Leake. The solar panels (PV) and batteries (BAT) operate on DC and are therefore connected to a DC-bus. This DC-bus has a voltage that is equal to the momentary battery voltage, which therefore changes with the state of charge (SOC) of the battery. The solar panels are connected via a maximum power point tracker (MPPT) to make sure that they operate on their optimum power point. The MPPT is displayed in the figure as a DCDC converter, because it operates the solar panels on the maximum power voltage and converters this dc voltage to the battery voltage. The wind turbines (WG), diesel generators (DG) and loads (LD) are connected to the AC-bus. A directional DCAC inverter connects the AC-bus and DC-bus.

Figure 2.1 Hybrids power system topology with solar, wind and diesel energy supply.

2.2 Inverter (MHI)

The multi hybrid inverter (MHI) exist of two stages as was explained in the previous paragraph. The first stage of the MHI converter is a DC/DC converter that converts the DC voltage from by the solar panel to the required DC-Bus (battery) voltage. The DC/DC converter makes sure that the solar panels are working on their maximum power point by means of MPPT algorithm. The second stage of the MHI converter is a DC/AC converter that makes sure that the frequency and voltage on the AC side are always as desired even if the diesel generators are switched off. This stage inserts or removes energy from the AC-bus as function of the required power on this side. The inverters in this system are modular and therefore it is possible to have multiple inverters that connect the DC-bus to the AC-bus.

2.2.1 Inverter efficiencies

The efficiencies of the inverter are taken as 98% for the DCDC stage and 94% for the DCAC and ACDC conversion. More information about the efficiencies at different power levels is given in chapter ***.

2.3 Solar panels (PV)

The solar panels in this system are connected in arrays such that the voltage of these strings is high enough to match the battery voltage. If more inverters are installed, each inverter has its own solar panel array. The solar panels can be of each type; in spite of this an average solar panel efficiency of 11% was used in this thesis.
2.4 Wind turbines (WG)

Wind turbines/generators (WG) are connected to the AC-bus. The WG will supply its energy directly to the households. The MHI will take care energy storage if the power supply of the WG is higher than the demand of the load. Is this way no energy is lost. More information on the wind turbines is given in Appendix: Wind speed to wind power.

2.5 Batteries

The batteries are connected to the DC-bus in between the DCDC (MPPT) and DCAC stage of the MHI. The batteries are assumed to be of the lead acid type. The reason for this type of batteries is that they are commercially available and have the lowest cost per kWh. The cycle life of the lead acid batteries is addressed in Appendix ***. It is assumed that the battery charge efficiency is 95% and the discharge efficiency is 90%, meaning that the round trip efficiency is 85.5%.

The battery cells are connected in strings, such that the string voltage range is favourable for the efficiency of conversion from DC to AC and back.

2.6 Diesel generators (DG)

The diesel generators (DG) are connected to the AC-bus. The DG's can be disconnected from the system when they are not required in a period when there is a lot of renewable energy. They might be off for weeks if enough renewable power is installed in the system.

The DG's power is controlled because the fuel consumption per generated kWh is higher when DG's are running on low power levels. Chapter 6 explains in which way the DG can be controlled and analyses the three power management strategies.

2.7 The Load

The maximum load of the system is determined by the sum of all DG's and MHI's powers. It should be noted that the MHI's can not continues supply the maximum powers, because the batteries should charged occasionally. This should not be a problem because the average load of a common load profile is normally below 50% of the maximum load.
3 ANALYSIS OF SUPPLY AND DEMAND PROFILES

This chapter starts with an analysis of available wind and solar energy, the supply. Secondly, it contains an analysis of the demand. The analysis is done for daily and seasonal cycles. All data\textsuperscript{1} used in the analysis is typically applicable for locations in the Netherlands and has a data point every 10-15 minutes. The next chapter will explain why the data analysis and the described variations in supply and demand are so important for load balancing.

3.1 Irradiance

The figure below shows the monthly average irradiance in the Netherlands for 2001 to 2010, calculated from data with a measurement frequency of 10 minutes. It can clearly be seen that the seasonal variance is almost the same every year. It should be noted that the energy peaks location varies a bit in the summer. Missing irradiance data for 2007 causes the dip in the figure.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{irradiance.png}
\caption{Irradiance data from Cabauw, Netherlands for the years 2001-2010, source: KNMI}
\end{figure}

The lowest average irradiance occurs in the winter and is about 25 W/m\textsuperscript{2}, compared to about 250 W/m\textsuperscript{2} in the summer. This means that the energy supply from solar panels will be about 10 times more in the summer than in the winter. This will cause a yearly misbalance with the demand as will be shown at the end of this chapter.

3.1.1 Solar power

Because solar irradiance in the dataset linearly corresponds to the solar power, no corrections to the data where applied. The irradiance data was divided by the maximum irradiance that occurred, to obtain the per unit solar power.

\textsuperscript{1} Irradiance and wind speeds data from Cabauw, Netherlands for the year 2001-2010 where used, source: KNMI

Energy demand profiles for the year 2007 (and 2008) where used, source: Ecofys
3.1.2 Yearly variations in solar power

The figure below shows the pu solar power of 2010 in red. The blue line shows the change of power. It can directly be seen that the pu power changes of solar power are much larger in the summer. The main reason for this is that the average power is much higher. This means that a larger power fluctuation will need to be supplied by the batteries or diesel generators to match the load. It can be seen that there are some periods (in the summer) where the load changes is very small during a couple of days. The small power changes only occur when no clouds are present or when there are a lot of clouds present. These dips in the blue lines can be seen everywhere in the year.

![Figure 3.2 Profile analyses of irradiance data from Cabauw, Netherlands for the year 2010, source: KNMI](image)

3.1.3 Daily variations in solar power

Solar power increases from sunrise until midday, after which it decreases to zero at sunset. The figures below show two typical daily profiles with and with variation. The left figure shows the solar power of a clear sky day in the summer. The right figure shows a day where a lot of variations occur, due to clouds passing by.

![Figure 3.3 Profile analyses of irradiance data from Cabauw, 2 days of the year 2010, source: KNMI](image)

It can be seen in the blue line that the power fluctuation are considerable higher on cloudy days. This means more energy fluctuations need to be supplied by the batteries or diesel generators, as will be show in the next chapter.
Even though the irradiance can change frequently during the day, the monthly 24 averages show a clear trend as can be seen in the figure below. It clearly visible that the daylight period is much longer during the summer and that the maximum irradiance almost always occurs on round 12 o’ clock.

3.2 Wind speeds

The figure below shows the monthly average wind speeds in the Netherlands for 2001 to 2010, calculated from data with a measurement frequency of 10 minutes. Even though it can be seen that the variation between years is large, there is some correlation between the seasonal variations. The months November till January are occasionally months wind long periods with high wind speeds. The months in the summer show clearly that there is less wind in the summer.
3.2.1 **Wind power**

Because wind turbines are more efficient at higher wind speeds, significantly more wind power is available at higher wind speeds. It can be seen in the figure below that the monthly average per unit power produced by wind turbines is much high is the months where the wind speeds where higher. See appendix 'Wind speed to wind power' for calculation details.

![Smoothed yearly wind power for the period 2001-2010](image1)

**Figure 3.6** Calculated wind power for Cabauw, Netherlands for the years 2001-2010 (smoothed curves!)

3.2.2 **Yearly variations in wind power**

The figure below shows the pu wind power and its fluctuations during the year 2010 in red. The blue line shows the change of power. It can be seen in the red line that there are some periods where almost no wind power is delivered for about a week. It can already be seen that the wind fluctuations are rather large and non cyclic. Though, the average wind power capacity factor is also most twice as high as the one of solar power.

![Potential wind power (pu) for Cabauw, Netherlands for the years 2010. Data points every 10min.](image2)

**Figure 3.7** Potential wind power (pu) for Cabauw, Netherlands for the years 2010. Data points every 10min.

It can be seen in the figure below that the average capacity factor for wind power is about 0.30, which means that a 1kW wind turbine will produce about 300W on average. The figure
also shows that the average capacity factor in the summer varies between 0.15 and 0.30 and the capacity factor in the winter varies from 0.30 to 0.50 in some years. It should be noted though that this figure shows 4 months average values, meaning that the plotted pu power on January 1st actually represents the average of the period from 1 November to the 1st of March.

![Smoothed yearly wind power for the period 2001-2010](image)

**Figure 3.8** Average potential wind power for Cabauw, Netherlands for the years 2010. (smoothed curves!)

3.2.3 **Daily variations in wind power**

Wind speeds and wind power have very large fluctuations during the year as could already be seen in the previous paragraph. These variations also occur during the day, as can be seen in the figures below. The left figure shows a typical day with varying wind power. The average wind power during this day was about 0.5 pu. The right figure shows a day where the wind speed was so high that wind power was constant during the day. It can be seen that the wind power reduces during the night.

![Load analyses, largest load change at 3.5% of the max load](image)

**Figure 3.9** Profile analyses of wind power data for Cabauw, 2 days of the year 2010.
Even though the figures above show that the wind power is highly variable, a clear daily 24 hour profile can be seen in the figure below. The figure below show the average wind power profiles for 24 hours for 2 month periods in the year 2006. It can clearly be seen in each line that the wind power increases during the day and that the most wind power is generated around 13 o’clock.

Figure 3.10 2 Months average 24-hour profiles of potential wind power for Cabauw, for 2006.

The wind power has significantly larger daily fluctuations in the spring and summer months, which is caused by local thermal winds. These thermal winds are cause by irradiance and therefore reduces during the night.

The wind power in the autumn and winter months also have peaks around the afternoon, though these peaks are much smaller compared to there daily average. The average wind power in these months is therefore not only higher, but also has smaller daily variations.

It should be noted though that the real wind power during a day is highly variable and therefore almost never the same as the 2 month average profile. These profiles are therefore only used to get a better understanding of the variations is wind power during the year.
3.3 **Demand**

3.3.1 **Yearly variations in demand**

The figure below shows the pu demand for about 100 households (max 230V current: 3x80A) and its fluctuations during the year 2007 in red. It can be seen that the demand fluctuations are higher cyclic and that the average per unit demand is 0.43. The blue line shows the change of demand, which is always below 3% of the maximum demand that occurred.

![Diagaram showing yearly variations in demand](figure3_11.png)

**Figure 3.11** Demand analysis for Dutch households for the years 2007. Data point every 15 min.

It can be seen in the black line that there is a decrease of energy demand during the summer. This decrease of average demand is about 25%, while the decrease of the daily peak is about 50%, which can be seen in the red line. It can also be seen in the green (and red) line that there is a base load of 0.18 pu power which does not change during the year. It can thus be concluded that there is a base load and a variable load. The variable load doubles in the winter.
3.3.2 Daily variations in demand
The figure below shows the average daily demand profiles for 6 periods on 2 months for the year 2007. The load profiles show the same base load as mentioned in the previous paragraph. It can be seen for all periods that the demand increase in the morning and that there is a peak at night. The overall demand profile, but especially the night peak is larger in the winter months.

![Smoothed daily average demand profiles for 2007](image)

**Figure 3.12** 2 Month average 24-hour demand profiles for the year 2007.

3.4 Capacity factor (fluctuation)
The figure below shows the capacity factor for each source for each year. It can be seen that the wind power has almost twice as much variation during the years as solar power. The legend shows the normalized standard deviation over the years, which is about 10% for wind power and 6% for solar power.

![Capacity factors for solar and wind from 2001 to 2010](image)

**Figure 3.13** Capacity factors of the solar and wind data sets calculated for each year.

In the following chapters, the capacity factor for each year is used to normalize the average power from each source. This means that the results of the simulations are only valid for that specific year and that when multiple years are compared to each other, it should be kept in mind that the capacity factor vary a little.
4 DESCRIPTION OF MODEL

The model analyses:
• losses due to:
  o shortage in bat capacity
  o conversion and storage losses
    ▪ by daily cycles
  o influence of modularity
• effect of 3 PMS on
  o fuel consumption
  o losses
  o DG runhours

4.1 Fixed efficiencies

4.2 Variable efficiencies
5 ANALYSES OF ENERGY BALANCE

Supply and demand have daily, seasonally and yearly cycles as was explained in the previous chapter. The supply and demand power cycles (power profiles) do not match during these cycles. This means renewable energy storage (or energy dumping) is required. In days when there is no renewable energy, diesel energy must be used. This chapter will show three sizing approach for the hybrid power system and the consequence of the unbalance between supply and demand. Conclusions are drawn on a way to minimize the unbalance in supply and demand by selecting the optimal energy mix.

The three approaches for system sizing are:
- sizing for (average) potential balance between demand and renewable sources
- sizing for maximum energy fraction from renewable energy
- sizing for minimal losses of energy with max renewable energy

The first, sizing for potentially 100% renewable energy, means that the expected output of renewable energy sources is equal to the demand. The second, sizing for 100% renewable energy, meaning overcapacity of renewable energy sources is installed to account for the part of energy that could not be stored. The third, sizing for max renewable energy without energy losses due to limited storage capacity, meaning the system is sized such that is can never supply 100% of demand by renewable energy. Though, almost no renewable energy is lost because of limited storage capacity.

*** MORE DETAILED EXPLANATION OF MODEL AND SIMULATION APPROACH ***

5.1 Analyses of a systems with potentially 100% renewable energy

The following paragraphs show three analyses of systems sized with; 100% solar energy, 100% wind energy and 60% wind + 40% solar energy. The percentage gives an indication of the expected power output of the source compared to the demand. 100% solar energy means that the solar panels are sized such that the average power output of solar is exactly equal to the average demand.

The battery capacity in the three analyses is equal to 1 day of average demand power, meaning it has a capacity to supply the average demand for 1 day. In the analyses it is assumed that when too much energy is produced by the renewable energy sources, this energy cannot be stored and is therefore lost. It is assumed that diesel generators can supply the seasonal energy shortage, while a battery (if charged) supplies the daily energy shortage. This means that the renewable energy is almost never enough to supply all the demand, because some energy (~5-10%) is lost in the storage cycle. This loss is not taken into account. The aim was to have a system where 100% of the demand was supplied by renewable energy, but because of the imbalance, diesel energy is still required in all cases as will be shown in the following paragraphs.
5.1.1 **High fraction of solar energy (100%)**

The supply side of the system described in this paragraph consists of solar panels, which are sized such that the average power output is equal to the average demand. This means that if all energy produced by the solar panels was stored at a 100% efficiency, the system would be in balance during one year.

The figure below shows the yearly energy balance of 2009. The orange bars in the top figure represent the result of the daily energy balance, which gives an indication of how much extra energy was produced each day or how much energy was not there. It can be seen that there are a lot of days in the summer where more than 2 days of extra energy was produced. This energy could of course not be stored in the batteries. The bottom figure shows the amount of energy that is lost in this way in the orange bars, which was 36% in total. The negative orange bars in the top figure represent the energy shortage that occurred during some winter days, the diesel generators supplied this energy. The amount of energy that was produced by the diesel generators can be seen in the red bars in the bottom figure. Because the system was sized such that the generated solar energy matches the demand exactly, the losses in the second figure are exactly the same as the used diesel energy (36%).

The top figure also shows the amount of energy (in energy days) that is stored in the battery in green and the amount of energy taken from the battery in blue. The losses for the battery cycles where not taken into account. In this design this would not lead to much extra losses, because most of the time there was more than enough energy to supply these extra losses. The legend shows the mean charge and discharge percentages. For this analysis it can be seen that on average 26% of the energy went into the battery before it was used. A mean (dis)charge of 26% on the battery means that effectively 95 days (0.26 x 365) of energy have flown through the battery. It can also be seen that the battery is almost not used in the winter, meaning that the average energy that went through the battery in the summer is about 50%.

![Energy analysis for a system where potentially 100% solar energy is installed](image)

**Figure 5.1:** Energy analysis for a system where potentially 100% solar energy is installed
5.1.2 High fraction of wind energy (100%)

The supply side of the system described in this paragraph consists of a wind turbine, which are sized such that the average power output is equal to the average demand. This means that if all energy produced by the wind turbine was stored at a 100% efficiency, the system would be in balance during one year. This is of course not the case, because energy is lost when it is stored and energy is lost when the battery is full.

The figure below shows the yearly energy balance of 2009. The orange bars in the top figure represent the result of the daily energy balance, which gives an indication of how much extra energy was produced each day or how much energy was not there. It can be seen that there are some days where more than 2 days of extra energy was produced by the wind turbines. This energy could of course not be stored in the batteries. The bottom figure shows the amount of energy that is lost in this way in the orange bars, which was 27% in total.

The negative orange bars in the top figure represent the energy shortage that occurred during some days, the diesel generators supplied this energy. The amount of energy that was produced by the diesel generators can be seen in the red bars in the bottom figure. Because the system was sized such that the generated wind energy matches the demand exactly, the losses in the second figure are exactly the same as the used diesel energy.

The top figure also shows the amount of energy (in energy days) that is stored in the battery in green and the amount of energy taken from the battery in blue. The losses for the battery cycles where not taken into account. The legend shows the mean charge and discharge percentages. For this analysis it can be seen that on average 21% of the energy went into the battery before it was used. A mean (dis)charge of 21% on the battery means that effectively 77 days (0.21 x 365) of energy have flown through the battery. With a battery round trip efficiency of 75%, this would cause a total loss of about 5% (19 days of energy).

Figure 5.2: Energy analysis for a system where potentially 100% wind energy is installed
5.1.3 **Mix with solar and wind energy**

The supply side of the system described in this paragraph consists of solar panels (40%) and wind turbines (60%), which are sized such that the average power output is equal to the average demand. This means that if all produced energy was stored at a 100% efficiency, the system would be in balance during the year.

The figure below shows the yearly energy balance of 2009. It can directly be seen that the yearly energy balance is better than the previously analysed systems. The main reason for this better balance is that the wind blows more in the winter and the sun shines more in the summer. Meaning that an energy system with a mix of both has better match with the yearly demand cycle. The orange bars in the top figure show that the amount energy produced on one day is never more then 2 times to much as was often the case for the 100% wind system. The orange bars in the bottom figure show that the amount of energy lost in the summer is much smaller as was the case for the 100% solar system. The total losses for this system are 17%, which is ~10% less than the 100% wind system and almost ~20% less than the 100% solar system.

![Energy balance for a system with 365 with wind-60% solar-40% diesel-0 - Battery capacity: 1 day(s)](image1)

![Energy lost, Energy from diesel and SOC in energy days](image2)

**Figure 5.3:** Energy analysis for a system where potentially 60% wind and 40% solar energy is installed

It can also be seen in the bottom figure that the SOC during the year is more variable, meaning that better use was made of the battery. The amount of energy that went through the battery is still only 25-26%, which was also the case for the 100% solar system. The cycle profile for the battery is much better, because the battery receives a trickle charge more often.
5.1.4 **Conclusions on a potentially 100% renewable energy system**

The amount of lost energy is a function of the solar-wind-diesel energy mix. There is an optimum point between the amount of solar and wind energy as was already show in the previous paragraph where less energy was lost for the 60% wind and 40% solar energy approach then for the other approaches.

The figure below shows that the optimal energy mix is not only dependent on the renewable energy mix (solar-wind mix on the horizontal axis), but also of the amount of installed renewable energy compared to the amount of demand (represented by green lines). All the lines in the figure below show the amount of energy that is lost during the year 2009 for each energy mix. The top line shows the mix where no diesel was meant to be used, meaning the wind and solar sources where sized such that they could deliver just as much energy as the demand, which was the sizing approach in the previous paragraphs. The blue point represents the 100% wind system, the orange point the 100% solar system and the green point the 60% wind + 40% solar system. It can clearly be seen that for each amount of installed renewable energy, there is an optimum point in the renewable energy mix.

![Figure 5.4: Yearly lost renewable energy due to imbalance in supply and demand for different energy mixes.](image-url)
5.2 Analysis of a system with optimal fraction of renewable energy

The top line in the figure represents the potentially 100% renewable energy system, which was discussed in paragraph 5.1.4. The second green line in the figure represents and energy mix with 90% renewable energy, meaning the solar and wind sources where sized such that they would supply 90% of the demand in the ideal case. This means that for the second line the most left point on the line represents a 90% wind system and the most right point a 90% solar system. Thus, the lower the line, the lower the installed renewable energy and thus the lower the losses due to misbalance. The horizontal axis shows the renewable energy fraction. It can be seen in the red point that for a 90% renewable energy system the minimum losses are 12% for a system with a renewable energy fraction of about 60% wind and 40% solar, meaning 54% wind, 36% solar and 10% diesel + 12% losses which are also supplied by diesel energy.

It can clearly be seen in the figure that the total amount of losses has a minimum around the 50-50 renewable energy mix for systems with a low renewable energy fraction (<70%). The point with minimum losses moves more to the left, when more renewable energy is installed. This means that the optimum renewable energy mix has more wind energy than solar energy. Because the capacity factor of wind is bit higher then the one of solar, this can mean that there is still more solar power installed. The figure above only gives an indication of the energy mix, which is not equal to the power mix.
5.2.1 **Optimal energy mix where no renewable energy is lost**

If system is installed with about 40% wind 30% solar and therefore 30% diesel, almost no energy losses will be occur during the year. This can clearly be seen in the figure in the previous paragraph (green dot), where the line for 70% renewable energy fraction almost crosses the horizontal axis.

The figures below show the analyses of 4 year for a system with 40% wind 30% solar.

![Energy balance for each year](image1)

![Energy balance for each year](image2)

![Energy balance for each year](image3)

![Energy balance for each year](image4)

**Figure 5.6:** Yearly energy analyses for a system with 40% wind 30% solar (optimum point for loss reduction).

It can be seen that for each year the losses are around 1-2% and that the losses occur during the year. It can be seen that most energy shortage occurs in the winter, and most losses in the summer. Therefore it seems that still too much solar power is installed, which produces most energy in the summer. This is actually not the case, because more installed wind power will also cause losses, only they are more spread over the year and are therefore not as clearly visible as the solar losses.
5.3 Analysis of a system with almost 100 % renewable energy

When more renewable energy is installed, this will cause more losses due imbalance between supply and demand. Though, when more renewable energy sources are installed, there is a decrease in required diesel energy because some of the extra renewable energy can be used. This means that there is a point where enough renewable energy is installed, such that no diesel is required. The following analysis shows the point where almost no diesel energy is required.

A system where twice as much renewable energy is installed as is used by the demand is called a 200% RE energy system. The figure below shows an analysis of a 200% system, with 100% solar and 100% wind. It can be seen in the top figure that there are almost no days where an energy shortage occurs, except for the 2\textsuperscript{nd} and last 2 months of the year. Of the 200\% generated renewable energy, 106\% is lost, which means that 6\% of energy needs to be supplied by diesel energy. The bottom figure indicates the only 5\% comes from diesel energy. This is because the simulation starts with a full battery, which reduces the diesel consumption of the first day.

If more renewable energy was installed this would reduce the diesel load even further, though a lot more renewable energy would be required as will be shown in the next paragraph.
5.3.1 Influence of more installed renewable energy

For each extra installed renewable energy source, more energy is lost as fraction of the produced energy. This means that for the extra installed renewable energy source only a tiny fraction of the produced energy can be used. The figure below shows the amount of energy that is lost as a fraction of produced renewable energy for each renewable energy mix. It can be seen that for systems with more than potentially 60% renewable energy losses start to increases. A system with 100% solar and 100% wind is indicated with the green dot. It can be seen that the amount of lost energy is about 53%, which correspond to the lost energy in the previous paragraph (106% of the 200% produced).

![Figure 5.8: Yearly lost renewable energy due to imbalance in supply and demand for different energy mixes.](image)

It can be seen in the figure that the average loss percentage increase when more renewable energy is installed, meaning that the extra installed renewable energy sources do not add much extra except more overall losses.

The figure below shows the required amount of diesel energy a function of the energy mix. It can be seen in the bottom of the figure that the amount of diesel reduces when more renewable energy is installed. Though for each 10% extra installed renewable energy above 200% only less then one percent of diesel energy reduction is achieved. Meaning that of the 10% extra energy, less than one tenth is really used.

![Figure 5.9: Yearly required diesel energy due to imbalance in supply and demand for different energy mixes.](image)

It can also be seen that the amount of diesel energy does not reduces to zero, not even for a system where potentially 300% of renewable energy is installed.
5.4 Loss dependence on battery capacity

Energy supplied by the renewable energy source cannot be stored when the battery is full. This means that this energy is lost as is show in the figures below. A larger battery is able to store more energy and therefore causes fewer losses. Though, the energy gain due to a bigger battery is rather small. The left figure shows the amount of energy than is lost for each energy mix when a battery is used with a size equal to one average day of energy demand. The right figure shows the losses in the system for a battery with a storage capacity of 4 average demand days.

Figure 5.10: Yearly lost renewable energy due to imbalance in supply and demand for different battery capacities.

It can be seen that for a 100% wind system, the losses are considerably lower when a larger battery is installed. The blue dots in the figures show a reduction from about 26% to about 13%. Though, for a 100% solar system the losses are almost the same. The orange dots show a reduction from 36% to 35% only. The reason for this is that wind energy is more variable, meaning that more low renewable energy periods occur during the year where the extra stored energy can be used. This is not the case for solar energy, which occurs more regular. This can very clearly be seen in black lines that represent the state of charge (SOC) in the bottom figures of paragraphs 5.1.1 and 5.1.2.
5.5 Percentage of energy that flows via the battery

The amount of energy that is stored during a day is determined by the amount of renewable energy sources that are installed, but also by the shape of the (average) 24-hour renewable energy power profile. The more the 24-hour demand and supply power profiles match, the less energy needs to be stored during the day. This paragraph will show that the average amount of energy that flows through the battery is also dependent on the renewable energy mix (wind-solar).

5.5.1 Comparison of 24 hour demand and supply profiles

The figures below show yearly average 24-hour profiles for wind and solar energy compared to the average 24-hour demand profile. The left figure shows the average power from wind. It can be seen that the wind profile matches the demand profile quite well. The results of the corresponding battery profile (green) show that only 15% of the total energy needs to be stored. The right figure shows the average power from the sun. It can be seen that the solar profile matches the demand less. The amount of energy that needs to be stored during a day is about 47%, which is three times a high as for the wind profile.

It should be noted though that the wind is more variable during the year and day cycles, therefore the average profile gives an incorrect positive image form the wind power profile. The actual amount of wind energy that is stored during the year for a 100% wind system is much higher as was shown in the previous paragraph. The actual percentage of energy that needs to be stored for a 100% solar system is actually lower as was also shown in the next paragraph.
5.5.2 **Real battery storage percentage for each energy mix**

The figures below show the average amount of energy that flows through the battery before it used. It can be seen that for systems where more solar energy is installed, the more energy needs to be stored. The main reason for this is that the 24-hour profile of solar does not correspond so well to the demand profile.

The top line indicated in the figures show that there is a maximum percentage of energy that needs to be stored during the year for each energy mix. This maximum does not increase much if more renewable energy is installed (it actually decreases). The reason for the limit is that not more energy flows through the battery, because there is simply not enough capacity to store it. The percentage is therefore dependent on the battery capacity as can be seen if the two figures are compared. The left is show the results for a simulation with one day battery capacity and the right show the results for a system with 3 days of battery capacity. Especially systems with more wind are more sensitive to a bigger battery capacity, this is again because the wind is more variable.
6  POWER MANAGEMENT STRATEGIES

The hybrid power system has diesel generators to make sure that it can always deliver the required power. By switching on the generators at the right time, the batteries will never discharge below a certain level and the load will always be supplied. Diesel generators run at lower efficiencies at lower powers, therefore it is not smart to switch on a generator when a low power are required.

This chapter will discuss three power management strategies (PMS) that will limit inefficient generator loading during a day. The first paragraph shows why the DG power should always be above a certain pu power. The second paragraph shows how to determine the pu power where the DG should switched on to obtain a daily energy balance. The third paragraph shows how to predict the required diesel energy by looking at the SOC and the expected RE energy.

6.1  Diesel generators only on at high power level

Because generators operate more efficient when they are loaded is higher powers, the generator should be switched on at times where the demand per generator is highest. The main strategy of all power management strategies is therefore to prevent this low power operation as much as possible. When not so much renewable energy is present during a day, this means that the generator needs to supply a large part of the demanded energy and therefore it should also operate when a low power demand is present. The point where a diesel generator should switch on this therefore determined by the pu power in which it would be loaded. For example, if the pu power where the generator switches on is 0.5, this causes a generator of 50kW to switch on when the demand is above 25kW. If 2 generators of 50kW would be present, the second would be switched on when the demand is above 50kW, which causes both generators to operate at 25kW. At what actual power the generators operate above this point differs between the three strategies.

6.1.1  Generator fuel efficiency compared to battery storage efficiency

Because a generator has lower pu fuel efficiency at a lower pu power, it can be smart to operate the generator at its optimum power point. In this thesis it is assumed that generators have a base load fuel consumption of 10 to 15% of the maximum fuel consumption. It is also assumed that the fuel consumption increases linear with the generators power output. This means that the pu fuel efficiency of the generator is increasing with power, as can be seen in the red line in Figure 6.1. A more detailed explanation of the pu generator efficiency is given in Appendix: Diesel generator per unit fuel efficiency.
Figure 6.1: Per unit fuel consumption efficiency of the DG at different power compared to battery storage.

At pu power levels below 0.5, the efficiency of the generators drops dramatically, meaning that energy produced at this power level requires a lot more fuel per kWh. If the generator is load in the point with optimum fuel efficiency (pu power = 1) even if the required power pu is lower than 1, an excess of power is available which can be stored in the batteries. If for example the required pu power is 0.5 and the generator is operated at 1 pu power, this means 50% of the power needs to be stored. The round trip efficiency of the battery including conversion losses is 75%. The real efficiency for 0.50 pu power where the remaining excess power is stored in the battery is thus 0.5 x 100% + 0.5 x 75% = 87.5%. This is already higher than the DG fuel efficiency at 0.5 pu power as is show in Figure 6.1. The blue line in the figure represents the combined efficiency if the DG is operated at a pu power of 1, where the remaining energy is stored in the battery. The red dashed line represents the point where operation with storage of the remaining energy is equal to the operation without storage. The diesel generator should therefore not operate at powers below this cross point, because operation at full power with energy storage is more efficient.

6.2 Daily energy balance obtained by increasing pu power where DGs are on

In the analyses of power management strategies, the pu power is increase in a loop for each day, until an exact energy balance occurs. This means that the pu power point was not predicted, but determined by looking at the daily cycle at the end of the day. This is of course not possible in a real system and therefore a prediction of the required pu level should be made. The prediction will be discusses in the following chapter.

6.2.1 Balance example

The figure below shows pu fuel consumption for a system with 3 generators and PMS1 in orange. It can be seen that the light orange area above the load (red line) is extra fuel consumption because the generators are loaded at a lower efficiency.
The green line shows the power of generators for PMS 2, it can be seen that the dashed green line (average fc) is lower then the dashed orange line, meaning the total fuel consumption of PMS 2 is lower. The reason will be explained in the following paragraphs.

6.3 Prediction strategy

During a day there must be enough diesel energy to make sure that the battery doesn’t run low. Because diesel generators operate best at higher power level, it is smart to only operate the diesel generators above a predetermined pu power. By looking at the energy balance of previous days and at the SOC, it is possible to predict the required pu power point where the generators should be switched on.

Prediction strategy needs to be checked/tested!
6.4 **PMS 1 – DG at battery power or required power**

The first power management strategy makes sure that the diesel generators run at the demanded power. The generator is switch on when the power is above a certain pu level, such that they generators only operate at the highest possible power windows during the day. The current SOC and the required diesel energy during previous days determine the pu point where the generator is switched on as was explained in the previous paragraph.

The power at which the generators run in PMS1 is equal to the remaining demand, causing the battery loading to go to zero. The remaining demand is the demand minus the available renewable energy power. This power management strategy therefore causes that the battery charging is limited as much as possible, though the demand on the generators can become very low to obtain the daily energy balance. The advantage is therefore that this strategy reduces the battery round trip and conversion losses. The disadvantage is that this strategy increases the fuel consumption, because the generators are loaded at a low power level.

6.4.1 **PMS1 power example**

The figure below shows the ideal point where the generator should switch on, such that the total supplied diesel energy is equal to the required energy in red. This means that the SOC at the start of the day is equal to the SOC at the end of the day. It can be seen in the black lines that the diesel generator operates in the evening and during the morning, when the demand on the battery is the highest. The blue line represents the real battery loading, when the diesel power is subtracted. It can be seen that the battery loading is zero when the diesel generator is supplying power. The dashed black line shows the pu fuel consumption. It can be seen that the fuel consumption is relatively higher at lower power level. This is because the generator is less efficient at lower power levels.
The green line shows the pu power of the generator and the dashed green line show the pu power where the generator efficiency is higher than the generator at full power, where the remaining energy is stored. This point was explained in paragraph 6.1.1.
6.5 **PMS 2 – DG at max power if $P > \text{min}_p\text{PU}$**

The second power management strategy makes sure that the diesel generators always run at their optimum power. The remaining energy is stored in the batteries. The generator is switch on when the power is above a certain pu level, such that they generators only operate at the highest possible power windows during the day.

The power at which the generators run in PMS2 is equal to their optimum (maximum) power, where the fuel consumption of the generators is ideal. Therefore the fuel losses do not exist. Because the generators run only at high power, they produce more energy during this time and thus need to run shorter then normal. Though a part of the energy needs to be stored which cause extra conversion and storage losses. The advantage is therefore that this strategy decreases the fuel consumption, because the generators are loaded at a high power level. The disadvantage is that this strategy increases the battery loading and conversion losses.

6.5.1 **PMS2 power example**

The figure below shows the ideal point where the generator should switch on, such that the total supplied diesel energy is equal to the required energy in red. This means that the SOC at the start of the day is equal to the SOC at the end of the day. It can be seen in the black lines that the diesel generator operates mostly in the evening, when the remaining demand is the highest. The blue line represents the real battery loading, when the diesel power is subtracted. It can be seen that the battery charging can become quite high when the diesel generator is supplying power. It can be seen there are some extra storage losses, though the generator losses are zero.
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6.6 PMS 3 – DG at max power only if $N_{DG} < N_{viaBat}$

The third power management strategy makes sure that the diesel generators run at their optimum power when the pu demand is low and that they run at the remaining power when the demand is high. The generator is switch on when the power is above a certain pu level, such that they generators only operate at the highest possible power windows during the day.

The power at which the generators run in PMS3 is equal to their optimum (maximum) power, when the pu demand is lower then the pu point where the battery round trip losses become lower than the losses due to inefficient loading of the generators. In this operation mode the remaining power is stored in the batteries just as in PMS2. The generators run at the remaining power at times where the generators run above the pu point where the battery round trip efficiency is higher, just as in PMS1. Therefore the fuel losses are limited and the battery loading is limited. Because the generators run at high power, they produce more energy during this time and thus need to run shorter then normal compared to PMS1. Though they need to run longer compared to PMS3. Because less energy needs to be stored compared to PMS2, the storage losses are lower. The advantage is therefore that this strategy decreases the fuel consumption, because the generators are loaded at a high power level. The disadvantage is that this strategy increases the battery loading and conversion losses.

6.6.1 PMS3 power example

The figure below shows the ideal point where the generator should switch on, such that the total supplied diesel energy is equal to the required energy in red. This means that the SOC at the start of the day is equal to the SOC at the end of the day. It can be seen in the black lines that the diesel generator operates mostly in the evening, when the remaining demand is the highest. The blue line represents the real battery loading, when the diesel power is subtracted. It can be seen that the battery charging has some high peaks when the diesel generator is running at is maximum power. It can also be seen that the battery power is zero when the generators are running at the remaining power.
6.7 Comparison of PMS

- **PMS1**
  - Business as usual, DG on at bat power until balance is reached
    - Fuel losses at low efficiencies

- **PMS2**
  - DG power only in full load
    - Removing inefficient dg loading
    - Efficiency via battery sometimes lower than DG efficiency

- **PMS3**
  - DG power at bat power when $n_{DG}$ is higher then $n_{via\_BAT}$
    - Some fuel losses due to inefficient loading.
  - DG power at full power when $n_{DG}$ is lower than $n_{via\_BAT}$
    - Some battery losses