Master´s thesis

Feasibility analysis of power supply by small-scale wind turbines in urban, semi-urban and rural districts of Zimbabwe

Machbarkeitsstudie zur Energieversorgung durch Kleinwindanlagen in urbanen, semi-urbanen und ruralen Gebieten Simbabwes

written by

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submitted to

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Abstract

The thesis analyzes the feasibility of power supply by small-scale wind turbines in urban, semi-urban and rural districts of Zimbabwe in order to understand if there is a potential existing for this technology.

Therefore, the wind potential is analyzed. To gain the required data regarding the wind speeds, a low-cost wind measurement station was developed and installed at three sites in Zimbabwe. Additionally to the measured data, wind data from local experts as well as GIS data is used to assess the local wind potential, which is found to be low for each of the three sites. Besides the wind potential, the feasibility of local manufacturing of small-scale wind turbines is analyzed. To do so, the availability and costs of necessary materials, skills and tools were investigated during visits of Zimbabwean schools, universities, workshops and informal markets. The Jesuit-led vocational school “St. Peters Kubatana Technology Centre” in Harare is found to offer optimal prerequesites for the realization of a pilot project.

Based on the previous analyses, the final objective is to identify the optimal technology for the power supply of the three research sites. Therefore, decentralized hybrid energy systems are modeled and optimized using the linear programming model *urbs*. It is found that the installation of a small-scale wind turbine is economically not feasible due to the low wind potential. Solar-Diesel-Battery hybrid systems are identified to be the optimal technology for the three sites.

Key words: Developing country, Zimbabwe, rural electrification, small-scale wind power, wind resource assessment, local manufacturing, energy system modeling, *urbs*

Kurzzusammenfassung

Die Arbeit analyisiert das Potential der Energieversorgung durch Kleinwindanlagen in urbanen, semi-urbanen und ruralen Gebieten Simbabwes.

Zunächst wird das Windpotential analyisiert. Um die dafür notwendigen Winddaten zu erfassen, wurde eine kostengüstige Windmessstation entwickelt und an drei Standorten in Simbabwe installiert. Zusätzlich zu den Messdaten werden GIS-basierte Winddaten und Daten lokaler Experten genutzt, um das Windpotential zu bewerten. Es wird für alle drei Standorte als sehr niedrig eingeschätzt. Neben dem Windpotential wird auch die Machbarkeit lokaler Fertigung von Kleinwindanlagen analyisiert. Während der Besichtigung simbabwischer Schulen, Universitäten, Werkstätten und informeller Märkte wurden daher die Verfügbarkeit und die Kosten der notwendigen Materialien, Fertigkeiten und Werkzeuge untersucht. Die von Jesuiten geleitete Berufsschule "St. Peters Kubatana Technology Center" erfüllt alle Vorraussetzungen für die Umsetzung eines Pilotrojektes.

Basierend auf den vorangehenden Analysen wird abschließend die optimale Technologie zur Energieversorgung für die drei Standorte indentifiziert. Dazu werden dezentrale Energiesysteme mit dem linearen Progammier-Tool *urbs* modelliert und optimiert. Die Arbeit kommt zu dem Ergebniss, dass die Installation einer Kleinwindenergieanlage aufgrund des geringen Windpotentials wirtschaftlich nicht sinnvoll ist. Als optimale Technologie werden Solar-Diesel-Batterie-Systeme identifiziert.

Schlüsselwörter: Entwicklungsland, Simbabwe, ländliche Elektrifizierung, Windgutachten, Kleinwindanlagen, lokale Fertigung, Modellierung von Energiesystemen, *urbs*

Acknowledgement

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Task description
Master´s Thesis

of

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Topic:

Feasibility analysis of power supply by small-scale wind turbines in urban, semi-urban and rural districts of Zimbabwe

Motivation
Electricity needs are increasing rapidly throughout the developing world. Growing population requires to increase power generation capacities significantly. This, coupled with the increasing need and awareness to reduce CO_2 emissions, created the issue to put an emphasis on Renewable Energy sources. Strategies to include Renewable Energies in the generation mix are a significant part of the energy policies and grid development plans in most developing countries. However, there hasn´t been conducted sufficient research on the utilization of Renewable Energies in developing countries and thus, there is still very little actual on-ground impact of renewables in the lives of the people in these countries.

Objectives
In this thesis, the feasibility of small-scale wind turbines in Zimbabwe will be analysed. The first part of the thesis will be a detailed research on both small-scale commercial as well as DIY wind turbines for off-grid electricity generation. Furthermore, the prototype of a DIY wind measurement station will be prepared for on-ground usage. The next steps take place in three sites in Zimbabwe (urban, semi-urban, rural), where the technical and economic feasibility of manufacturing DIY wind turbines locally will be analysed. The DIY wind measurement stations will be installed at these three sites in Zimbabwe to measure the local wind speeds in order to assess the local wind energy potential. Based on the previous analyses, the final objective is to identify the ideal system topology for a small-scale wind turbine at these three different types of locations in Zimbabwe.

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Declaration

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I hereby declare that the Master thesis submitted with the title

Feasibility analysis of power supply by small-scale wind turbines in urban, semi-urban and rural districts of Zimbabwe

is my own unaided work. All direct or indirect sources used are acknowledged as references. Models and other software tools provided by the institute are listed as well. These models are property of the institute or the individual staff member. I will not use them for any other purpose beyond this thesis or disclose them to third parties.

I agree to the further use of my work and its results (including produced methods and models) for research and education.

This paper was not perviously presented to another examination board and has not been published.

Munich, 01.03.2017

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(Author: Mayr, Michael)

Table of Content

1 Introduction

1.1 Motivation

The south-saharan country Zimbabwe is one of the poorest countries in the world, ranked 155th among the 188 countries on the United Nations Human Development Index [1]. With a share of 68%, the majority of the country´s 16 million inhabitants lives in rural regions [2].

Despite the fact that Zimbabwe – as many other developing countries – has huge Renewable Energy potentials to show, the country is facing big scarcity of energy. Electricity generation is limited to very few coal-fired thermal power plants and one hydro power plant and the national electricity grid is weak and experiences many power cuts [3]. Also, with 41% the electrification rate is low and only 19% of the rural population has access to the electricity grid [4].

In areas with high wind speeds small-scale wind turbines can help to address this need for electrification on low costs. If these turbines are manufactured locally, they even contribute to local job creation and raise the knowledge that is needed for the maintenance of the turbines [5].

1.2 Objectives and thesis structure

As indicated in the title, the research is conducted each in an urban, a semi-urban and a rural site. For each type of location one examplary site was selected: Highfield, a township in the southern part of Zimbabwe´s capital Harare as urban site; Banket, a community of 10.000 people in the countryside as semi-urban site; and the very remotely located community of the mission station St. Rupert Mayer (St. Ruperts) as rural site.

In this thesis, the feasibility of power supply by small-scale wind turbines in Harare, Banket and St. Ruperts will be analyzed in order to understand if there is a potential existing for this technology at the three sites.

The first part of the thesis (Chapter 2) will be an assessment of the local wind potential. To gain the required data regarding the wind speeds a low-cost wind measurement station will be prepared for on-ground usage. It will be installed at the three sites. Besides the data obtained from measurements, wind data from local experts as well as GIS data will be used.

The second part (Chapter 3) will be an overview on both small-scale industrial as well as locally manufactured (DIY) wind turbines for off-grid electricity generation.

Furthermore, the feasibility of manufacturing small-scale wind turbines locally will be analyzed (Chapter 4). Therefore, the availability and costs of materials, skills and tools will be investigated by on-site research during visits of Zimbabwean schools, vocational training centers, universities local workshops and informal markets.

Based on the previous analyses, the final objective is to identify the ideal system topology for a small-scale wind turbine at the three sites (Chapter 5). The necessary information about the electricity demands will be obtained by a questionnaire, measurements and interviews of local experts. The results will be modeled using Monte Carlo simulation. Finally, hybrid energy systems for the three sites will be modeled and optimized using the linear programming model *urbs*.

2 Wind resource assessment of three regions in Zimbabwe by using local expert knowledge, GIS and on-site measurements

Wind resource assesments have been made for many regions of the world. However, for some regions reliable and detailed wind data is not available. In addition, the wind resource is depending very specificly on local conditions. E.g., even if a certain region is considered to have good wind conditions, this may not be true for some periods of a year or for some locations within this region. So, without assessing wind ressources on a very regional level, wind energy projects may be not successful at all [6]. Therefore, this chapter will assess the wind potential of three sites in Zimbabwe.

To gain the required data regarding the wind speeds, a low-cost wind measurement station was developed and installed at the three sites in Zimbabwe. Besides the short-term measurement data, wind data from local experts as well as GIS data will be used in order to have sufficient long-term wind data for a detailed wind resource assessment.

2.1 Data acquisition by local experts

During the research trip to Zimbabwe the existing collaboration between Technische Universität München (TUM) and University of Zimbabwe (UZ) proved to be beneficial as researchers from the Faculty of Engineering of UZ could provide wind datasets from the National Meteorological Service of Zimbabwe containing wind data from more than 20 weather stations around the country [7], [8]. Amongst those, Belvedere (a suburbian neighbourhood in the eastern part of Harare) and Chinhoyi (a medium-sized town, located close to Banket) are located close to the research sites of this thesis.

Belvedere, Harare

Figure 2-1 shows the wind speed distribution at 10 meters above the surface of five consecutive days in November 1991 in Belvedere. The 5-days average wind speed is 2.12 m/s, based on measurements with hourly resolution. Figure 2-1 also indicates that the wind speeds are varying between day and night, with higher wind speeds during daytime than at night.

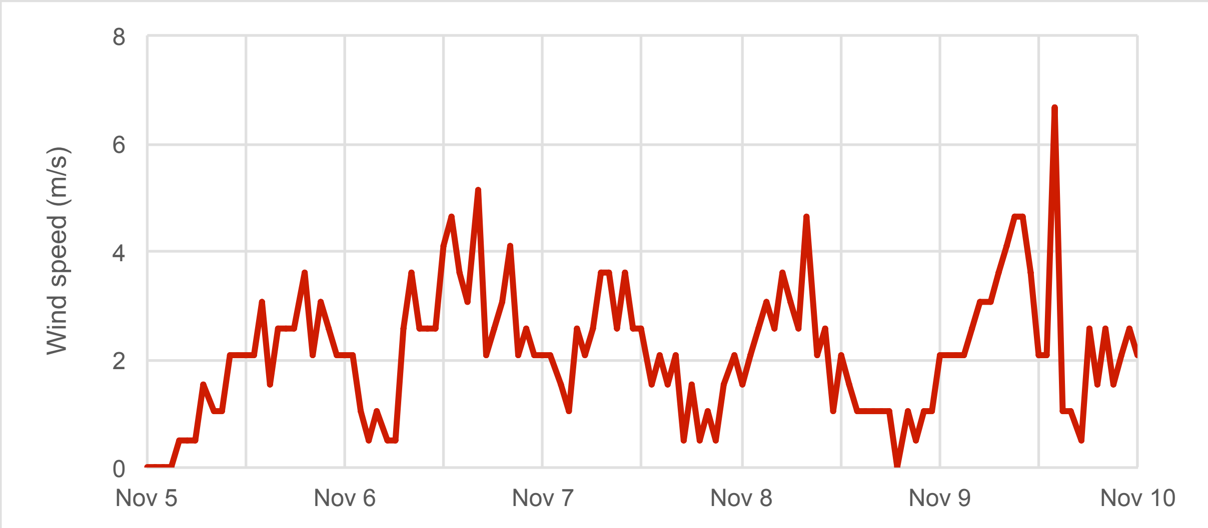


Figure 2-1 Five days wind distribution in 10m height in Belvedere, Harare

Figure 2-2 compares the annual wind speed distribution at 10 meters above the surface of two different datasets in Belvedere. The dashed line is based on hourly wind data from 1991 and 1992, its annual average wind speed is 2.62 m/s [7]. The straight line is based on 15-20 years wind data (resolution of measurements and exact measurement period unknown) and its annual average wind speed is 2.18 m/s [8]. Both timeseries show lower wind speeds during the first half of the year and peak in September, followed by a drop in October and November in the dashed line timeseries, which is not found in the straight line timeseries.

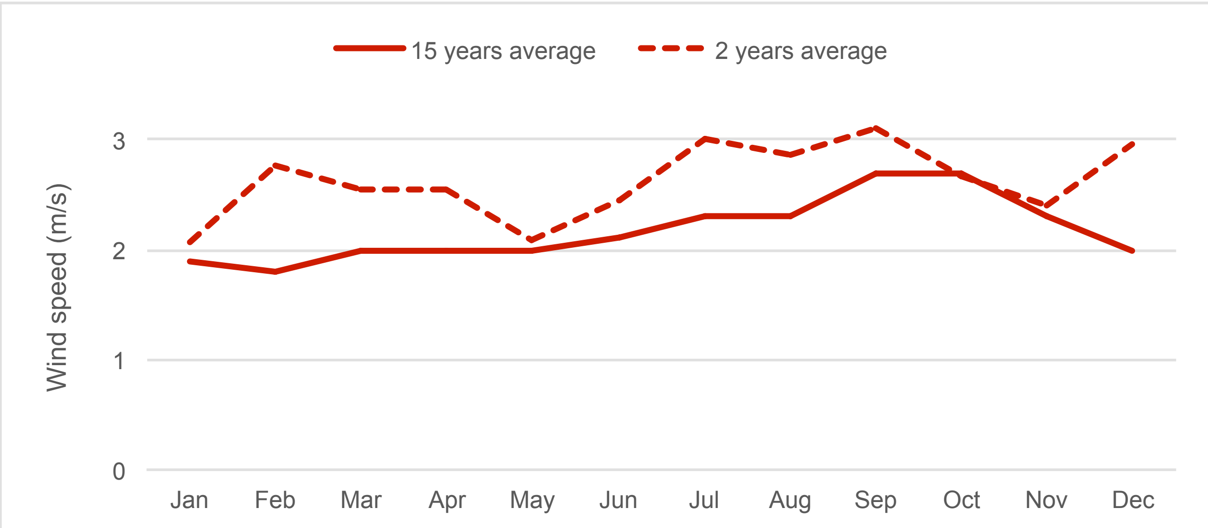


Figure 2-2 Annual wind distribution in 10m height in Belvedere, Harare

Chinhoyi

Figure 2-3 shows the annual wind speed distribution in Chinhoyi (exact height and location of the measurement unknown), based on a dataset containing the four wind seasons from July 1989 to July 1992 with monthly resolution and resulting in an annual average wind speed of 1.58 m/s [7]. The timeseries shows lower wind speeds during the first half of the year reaching its minimum in May and increased wind speeds during the hot season from September to November.

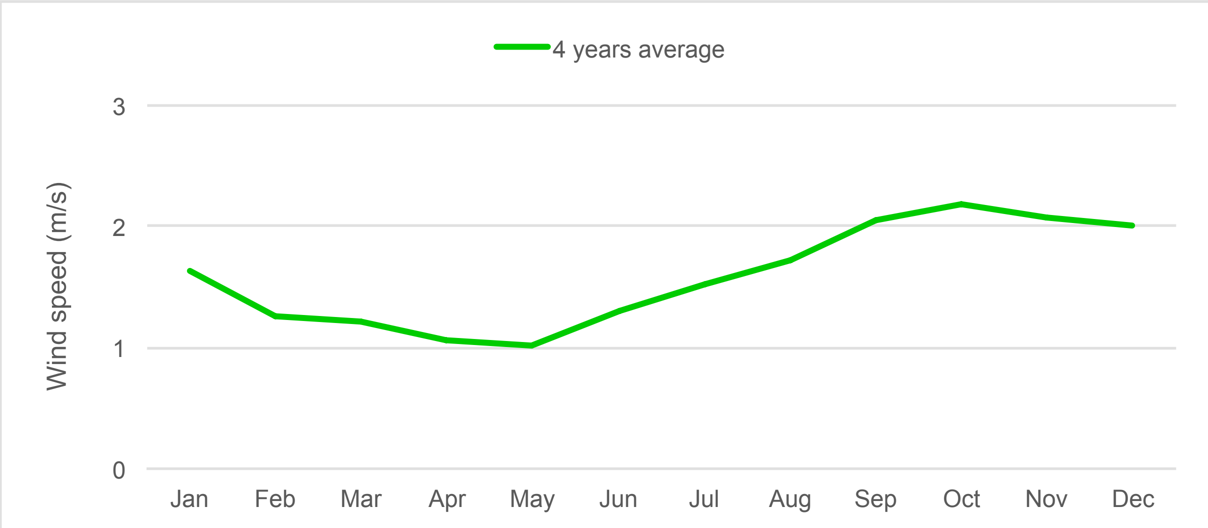


Figure 2-3 Annual wind distribution in unknown height in Chinhoyi

St. Ruperts

For St. Ruperts or nearby locations no wind data from local experts were available.

Summary

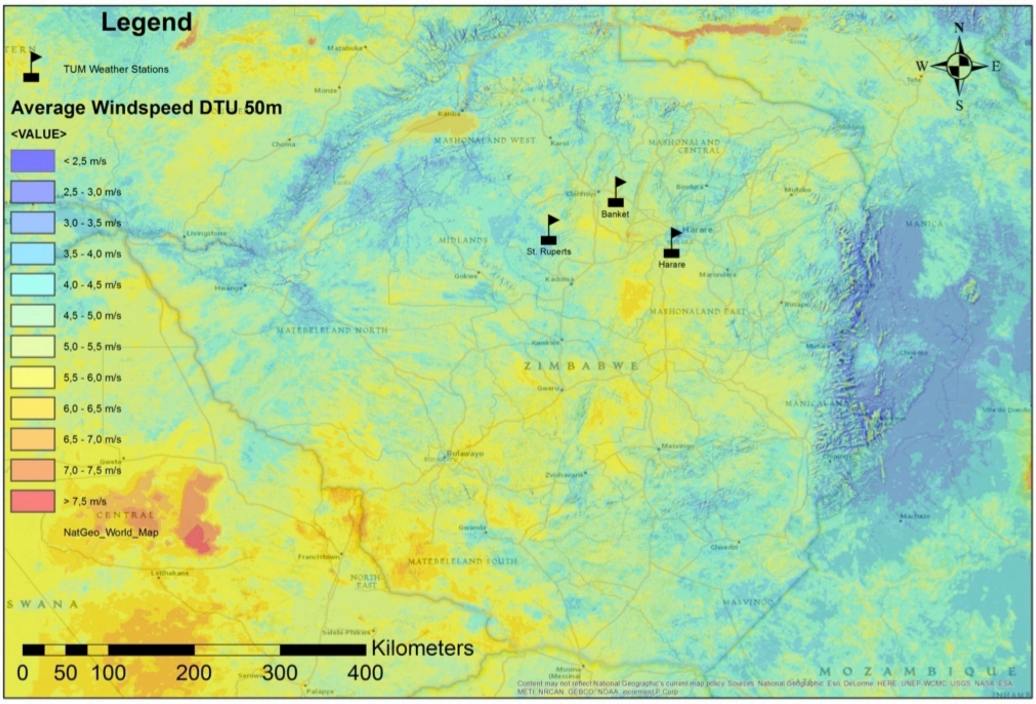
The data obtained from local experts can provide first indications of the wind potential of the research sites. The windiest period seems to occur during the hot season from September to November, whereas the first half of the year can be considered as low wind period. The data also indicate a diurnal variation of wind speeds, with higher wind speeds during daytime than at night. However, for a more detailed assessment of the wind potential of the three sites the information given by the presented data is insufficient and further investigations have to be made. For St. Ruperts no wind data was available, for Banket only monthly data. Hourly data was only available for Harare. The quality of the presented datasets was difficult to prove, as some gaps and inaccuracies were found and some specifications of measurement heights and exact years of measurements were not available.

2.2 Data acquisition by IRENA and other GIS-based tools

2.2.1 IRENA Global Atlas for Renewable Energy

The IRENA Global Atlas for Renewbale Energy provides information about the potentials of renewable energy resources in countries all around the world. It contains a number of wind datasets of which the dataset provided by Technical University of Denmark (DTU) is the most relevant one for the purpose of this thesis [9].

The DTU dataset provides wind climatology layers with spatial resolution of 1 km at heights of 50, 100 and 200 meters above the surface. These layers are produced by using microscale models that capture high resolution terrain effects such as elevation and surface roughness. The dataset contains information about wind direction, annual mean wind speed and annual wind cycle [10]. Figure 2-4 maps the average wind speeds in Zimbabwe at 50 meters above the surface and shows that the biggest wind potential is in the central and the south-western parts of the country. However, it can be seen that the overall wind potential of Zimbabwe is not too high as only very few areas exceed average wind speeds of 7 m/s at 50 meters above the surface.



Input map layer: Average Windspeed DTU 2015 height at 50m and 1-km resolution

Figure 2-4 Wind map of Zimbabwe [11]

Figure 2-5 zooms into the area of the research sites and indicates that average wind speeds at 50 meters above the surface are between 5 and 5.5 m/s in Harare as well as in Banket and between 4.5 and 5 m/s in St. Ruperts. It also indicates that St. Ruperts is located at frontier between a region with very low wind speeds and a region with medium wind speeds.

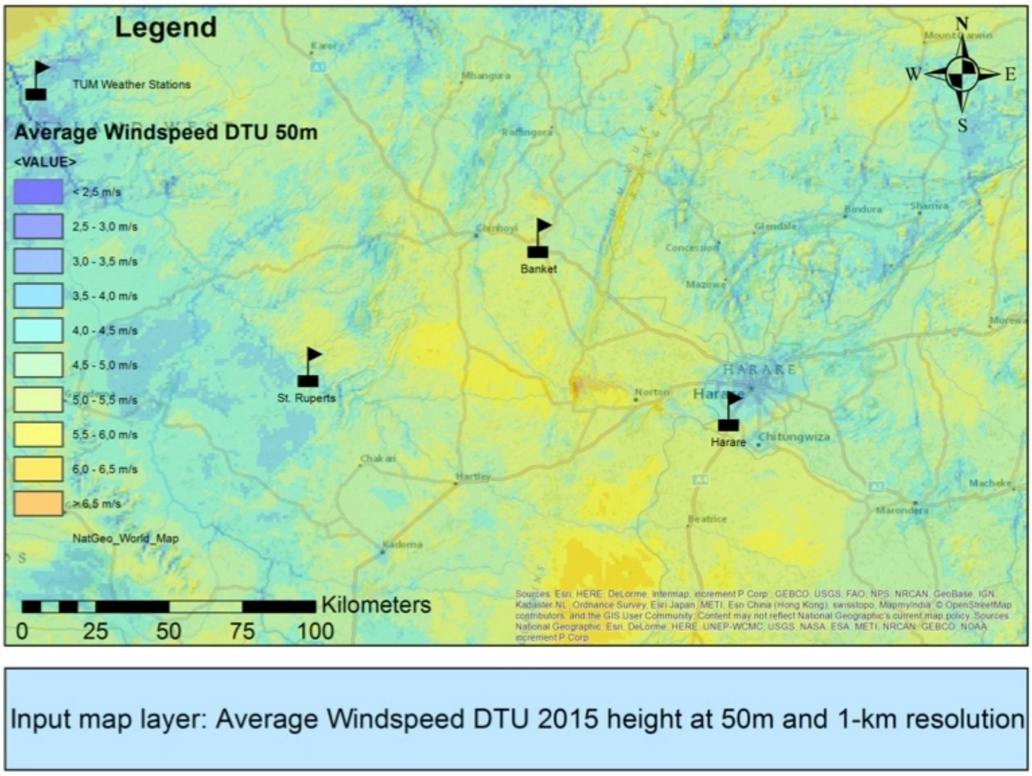


Figure 2-5 Wind map of the research area [11]

Selection of regions

For the specific coordinate of a site, the DTU wind database gives only the annual mean wind speed as output. In order to get additional, more detailed output data, the DTU wind database demands the user to select a regional area larger than 2,500 km². To do so, a regional area of 2700 km^2 was selected with the respective research site exactly in the center of a regular dodecagon (see Figure 2-6).

Figure 2-6 Selection of regions [10]: Harare region (left), Banket region (middle), St. Ruperts region (right)

Annual average wind speeds and wind directions

Table 2-1 sums up the annual average wind speeds and the main wind directions from DTU wind database at 50 meters above the surface. The wind speeds for the exact site and the regional wind speeds for Banket (1.5 % deviation) and St. Ruperts (1.3 % deviation) do match, whereas the regional wind speed of Harare deviates by 22.1 % from the wind speed found for the exact site. This results from the fact that the selected 2700 km^2 area for Harare not only includes an urban environment with lower wind speeds, but also includes a rural environment that shows better wind potential and thus increases the regional annual average wind speed significantly.

Table 2-1 Annual average wind speeds and main wind directions in 50m height at the research sites

Location	**Wind speed** (exact site)	**Wind speed** (regional)	**Main wind direction** (regional)
Harare	4.12 m/s	5.29 m/s	South-East
Banket	5.13 m/s	5.21 m/s	East
St. Ruperts	4.46 m/s	4.52 m/s	South-East

Figure 2-7, Figure 2-8 and Figure 2-9 show that the predominant wind direction is east, with a northerly component in Banket and a southerly component in Harare and St. Ruperts.

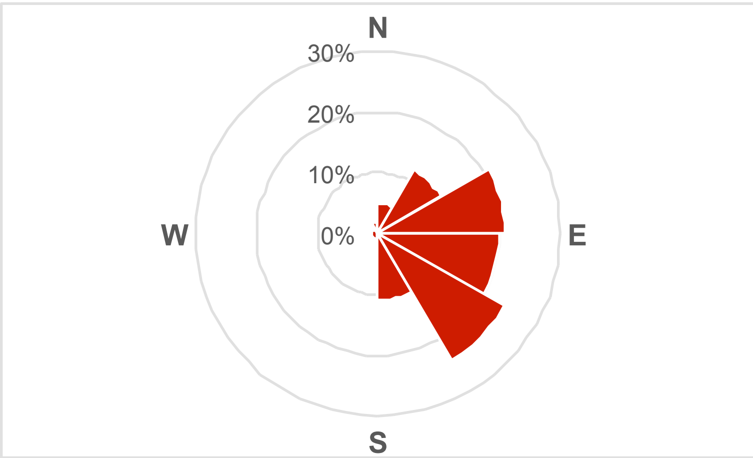


Figure 2-7 Wind rose – Harare

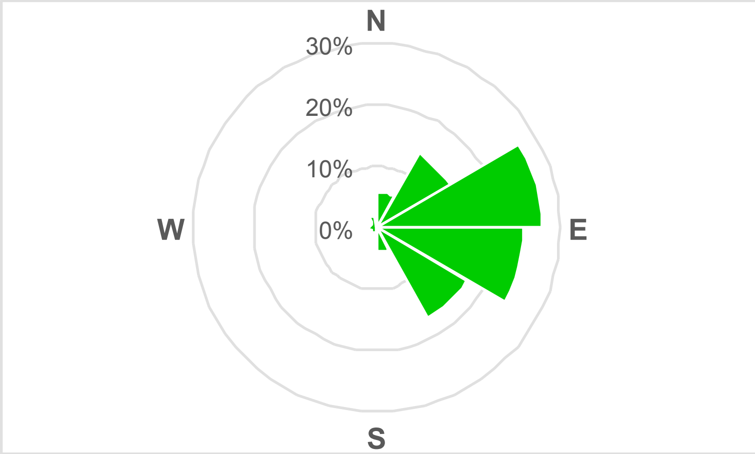


Figure 2-8 Wind rose – Banket

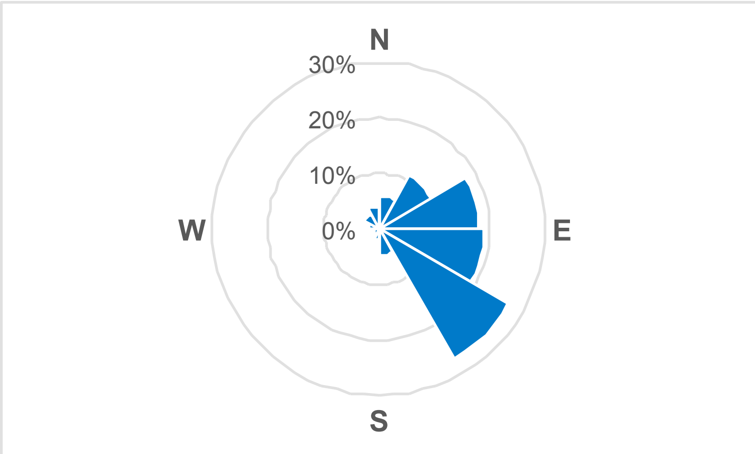


Figure 2-9 Wind rose – St. Ruperts

Annual wind cycle

The DTU wind database also gives the annual wind cyle in 50 meters above the surface for the three sites in the form of a normalized timeseries (see Table 2-2) that can be multiplied by the annual average wind speed in order to get the absolute values for the monthly average wind speeds.

Table 2-2 Normalized annual wind distribution of the three sites

Location	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Harare	0.91	0.98	0.94	0.96	0.88	0.92	1.01	1.08	1.17	1.16	1.07	0.93
Banket	0.89	0.92	0.87	0.87	0.82	0.90	1.03	1.13	1.23	1.22	1.12	0.98
St. Ruperts	0.94	1.01	0.94	0.94	0.86	0.90	0.98	1.05	1.14	1.16	1.09	0.98

Figure 2-10 shows the annual wind distribution for the three sites and indicates that at a height of 50 meters above the surface, Banket has the highest wind speeds, followed by St. Ruperts and Harare. Additionally it confirms that the highest wind speeds occur between end of August and the beginning of November, during the hot season and that the low wind season occurs in the first half of the year, reaching its minimum in May.

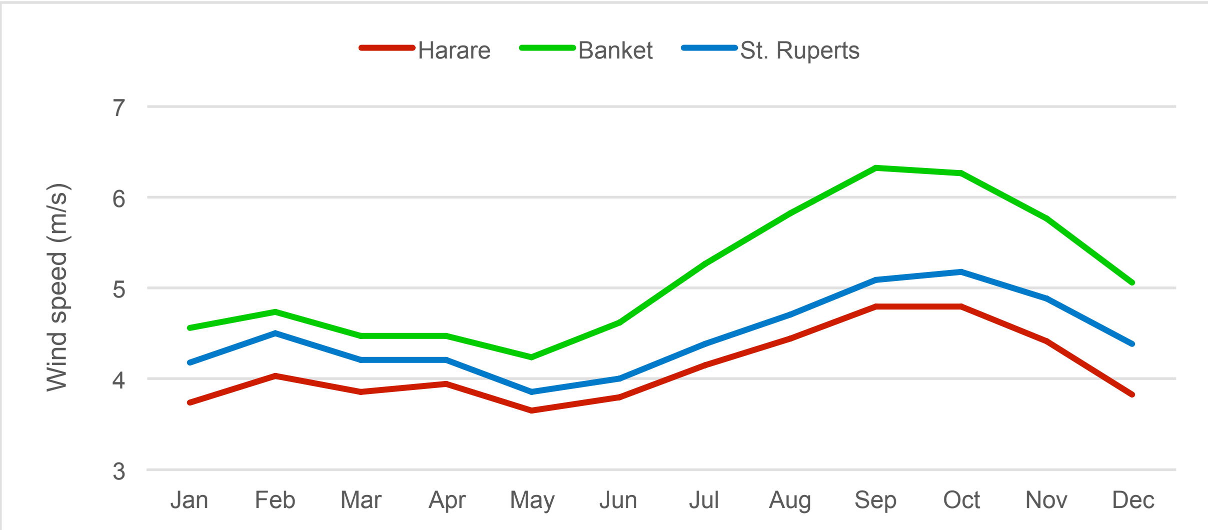


Figure 2-10 Annual wind distribution in 50m height at the three sites

Summary

The data obtained from DTU wind database enriches the local expert knowledge and can confirm its trends. However, DTU does not provide data with hourly resolution, and data is – except from annual average wind speeds – only available on regional basis and not for the exact site, which leads to inaccuracies, especially in the case of Harare.

2.2.3 Meteonorm

The commercial software Meteonorm, sold by the Swiss company Meteotest, contains worldwide weather data. The software uses longterm monthly average values and generates monthly or hourly values for several parameters including wind speeds by means of interpolation models [12].

Figure 2-11 shows the wind speed distribution of five consecutive days in November at unknown height in Harare. The 5-days average wind speed is 4.13 m/s, based on hourly data that was generated by interpolating monthly average wind data from 1981-1990. The first two days as well as the last day show again the variation of wind speeds between night and day, with higher wind speeds during the day. Day three to five all show constant low wind speeds.

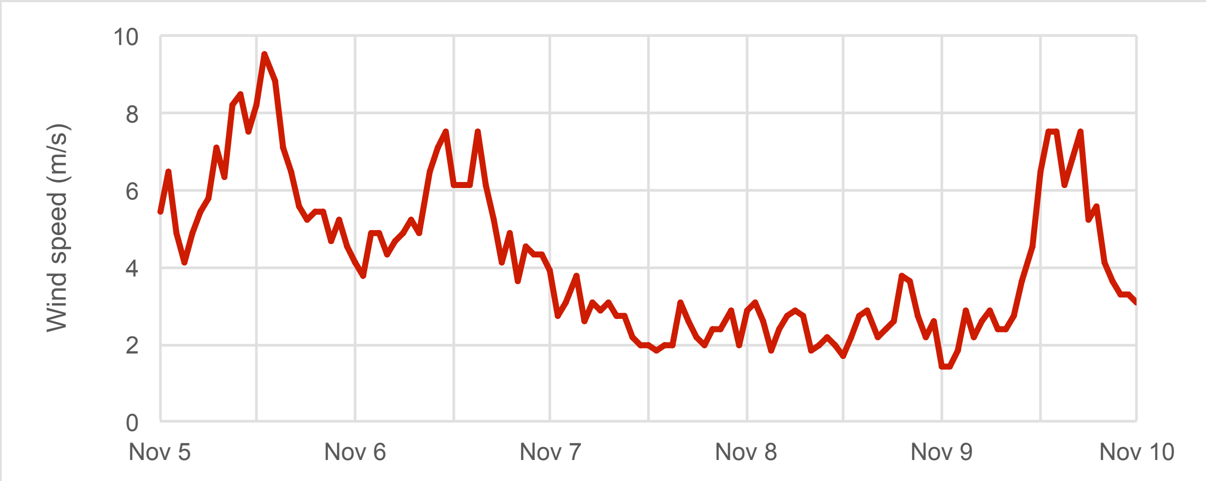


Figure 2-11 Five days wind distribution in unkown height in Harare

Figure 2-12 shows the annual wind distribution for the same site in Harare and again confirms the seasonal behavior of the wind as indicated by local data and DTU. The annual mean wind speed is 3.51 m/s at unknown height.

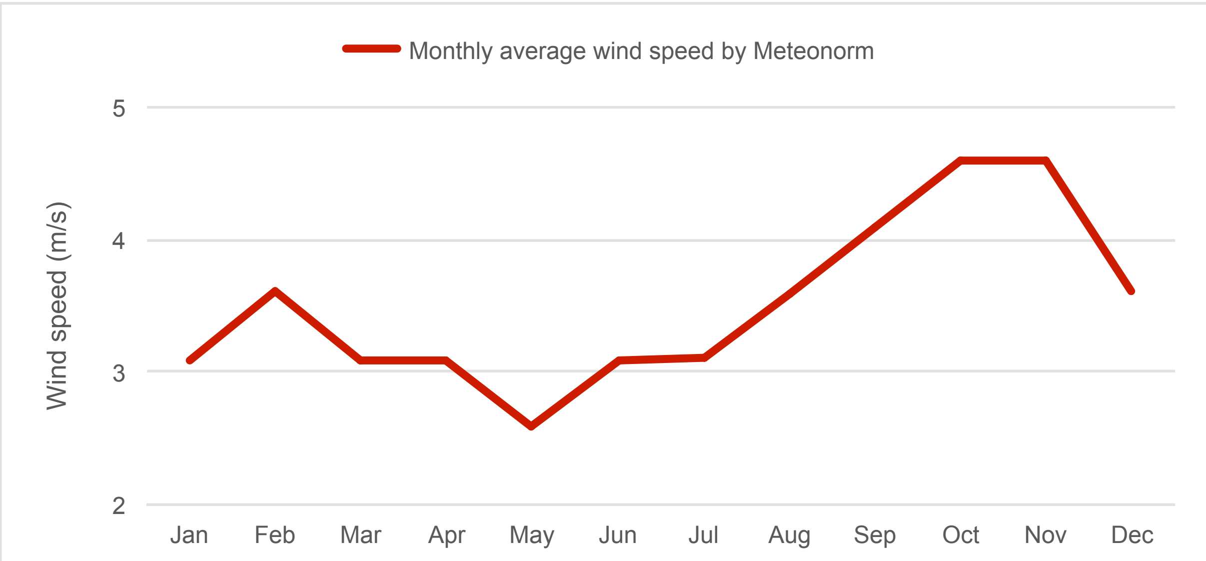


Figure 2-12 Annual wind distribution in unkown height in Harare

Summary

Meteonorm provides interpolated hourly timeseries based on longterm monthly average wind speeds. The five-day exemplary plot of Figure 2-11 shows also that the Meteonorm interpolations are able to reproduce the diurnal variations of wind speeds. The annual wind distribution of Meteonorm confirms both DTU and local expert data.

However, regarding the three research sites, the data is only available for one of them, Harare. Additionally the measurement height is unknown.

2.3 On-site data acquisition by self-made wind measurement stations

The self-made wind measurement stations that were installed in Zimbabwe have been under continuous development over a period of more than one year within different student research projects [13]. They aim to provide a low-cost solution for long-term data acquisition in remote areas. The basic setup of the measurement stations includes the following elements:

- A cup anemometer that serves as measurement sensor.
- A Raspberry Pi (a credit card-sized single-board computer) that is used as datalogger.
- A solar panel, a charge controller and lead batteries, which provide self-sustaining energy supply.
- An UMTS stick that enables internet connection, in order to transfer the measured data into a cloud server once per day.
- Python program codes that enable continuous data logging and transfer.

In order to test new ideas and to adapt the wind measurement station to the objectives of this thesis, some improvements and changes have been realized:

- Use of the smaller and cheaper Raspberry Pi Zero instead of Raspberry Pi B+,
- Optimized size and costs of the power supply,
- Optimized python coding for the internet connection via UMTS stick,
- Remote control of the Raspberry Pi via Ethernet connection for on-field access.

Based on that, three wind measurement stations have been prepared for on-ground usage. A detailed list of costs and components can be found in appendix A2.

2.3.1 Installation of three weather stations in Zimbabwe

The wind measurement stations were installed in three different locations: one at the rooftop of St Peter´s Kubatana School in Highfield, Harare; one on the ground of Sacred Heart High School in Banket; and one in the mission station St. Ruperts. The exact positions of the wind measurement stations can be found in Table 2-3.

Table 2-3 Positions of the self-made wind measurement stations

Location	Position		Elevation
Harare	Latitude	S17° 54.318	1435 m
	Longitude	E30° 59.026	
Banket	Latitude	S17° 22.460	1260 m
	Longitude	E30° 23.915	
St. Ruperts	Latitude	S17° 46.212	896 m
	Longitude	E29° 41.627	

All measurement sensors were installed in 10 meters height above the surface, a possible hub height of a future small-scale wind turbine. The optimal siting of the sensors was determined considering several parameters as the prevailing main wind direction (see Chapter 2.2), the surrounding landscape and vegetation, as well as possible obstacles that could disturb the air flow (see Figure 2-13, Figure 2-14 and Figure 2-15). The siting was only restricted by the fact that the wind measurement stations had to be installed inside the land of the Jesuits, the cooperating institution at all three sites.

Figure 2-13 Position of wind measurement, pointing towards main wind direction – Harare [14]

Figure 2-14 Position of wind measurement, pointing towards main wind direction – Banket [14]

Figure 2-15 Position of wind measurement, pointing towards main wind direction – St. Ruperts [14]

In Harare, a 2.5-meter pole for a Wifi repeater was already attached to the rooftop of St. Peter´s Kubatana School and could also be used as pole for the wind sensors. The school´s rooftop was found to be the highest place at the site. However, the place is surrounded by some high trees and can be characterized as generally very covered area (Highfield township, many small houses).

In Banket, a foldable 10-meter pole that was build by students and teachers of St Peter´s Kubatana School was errected close to plane fields in the main wind direction. This place can be considered as one of the most favorable places in Banket regarding the wind rersource.

In St. Ruperts a fixed 10-meter pole made from scrap was errected at the highest elevation inside the mission station. It is located next to a steep (30-40 meters) downhill gradient in the main wind direction, which ends at the bank of a small river. Generally, the landscape is very mountainious and the location is very exposed, but not the highest hill around.

2.3.2 Data validation

The measurement sensors used with the self-made wind measurement station are cup anemometers from the manufacturer Eltako. The sensor is counting impulses per second (one rotation gives two impulses), and to convert the number of impulses per second to wind speed in meters per second, Eltako gives the following formula:

$$v_{Eltako} = \frac{n+2}{3} \qquad \text{Eq. 1}$$

where n is the number of impulses per second counted by the sensor and v_{Eltako} is the wind speed [15]. As one can see, if the sensor does not count any impulse (n = 0 1/s), the computed wind speed v_{Eltako} should be 0 m/s, but will be 0.667 m/s. This indicates a lack of accuracy of the Eltako sensor for low wind speeds.

In order to increase the accuracy, a wind tunnel calibration was conducted and a linear correlation coefficient approach was derived [13]. This approach was found to be not accurate after further testing of the wind measurement station and thus the commercial weather station "Onset HOBO® Micro Station" was used to validate the wind speeds measured by the self-made wind measurement station in Zimbabwe. To do so, the commercial weather station was installed next to the self-made wind measurement station for a few days at each research site in Zimbabwe, so that the measured values could be compared to each other. Table 2-4 sums up the most important information about the two measurement systems and their sensors.

Table 2-4 Wind sensors used in Zimbabwe [15], [16]

	Eltako Windsensor WS	**Wind Speed Smart Sensor (S-WSA-M003)**
Used in	Self-made wind measurement station	Commercial HOBO® Weather Station
Measuring range	2 to 32 m/s	0 to 45 m/s
Price	45 €	225 €

It was found that the self-made wind measurement station measures slightly higher values with a constant offset, which is different at each of the locations. Lacking other options[1], the values measured by the commercial weather station were considered to be correct and accurate and a separate correction offset value was derived for each of the locations.

To define the exact correction offset value, the following examinations were made:

- Harare: For a timeseries of 2000 timesteps (see Figure 2-16 for the first 480 timesteps) the difference between the wind speeds measured by the two measurement systems was computed and a constant offset value of 0.5999 m/s was found.

$$\Delta_{Harare} = 0.5999\ m/s \qquad \text{Eq. 2}$$

[1] As it is not possible to look into the algorithms and mimics of the Onset HOBO® Micro Station, no exact statement on the accuracy of the commercial weather station can be made. Therefore it is still recommended to recalibrate the Eltako wind sensor to improve the data quality.

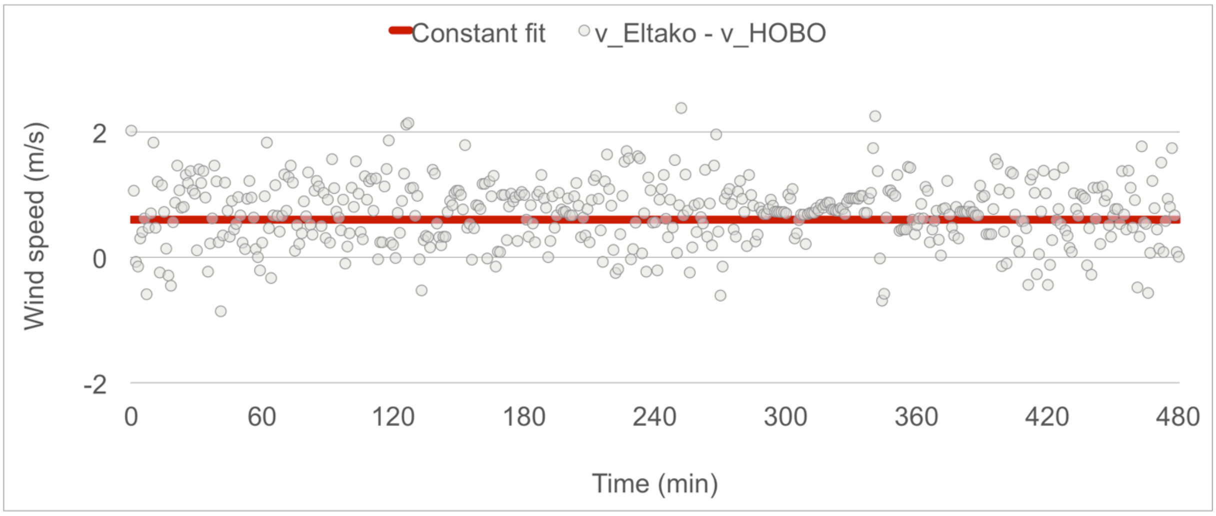


Figure 2-16 Constant fitting of offset value – Harare

- St. Ruperts: For a timeseseries of 500 timesteps (see Figure 2-17) the difference between the wind speeds measured by the two measurement systems was calculated and a constant offset value of 0.8786 was found.

$$\Delta_{St.\ Ruperts} = 0.8786\ m/s \quad \text{Eq. 3}$$

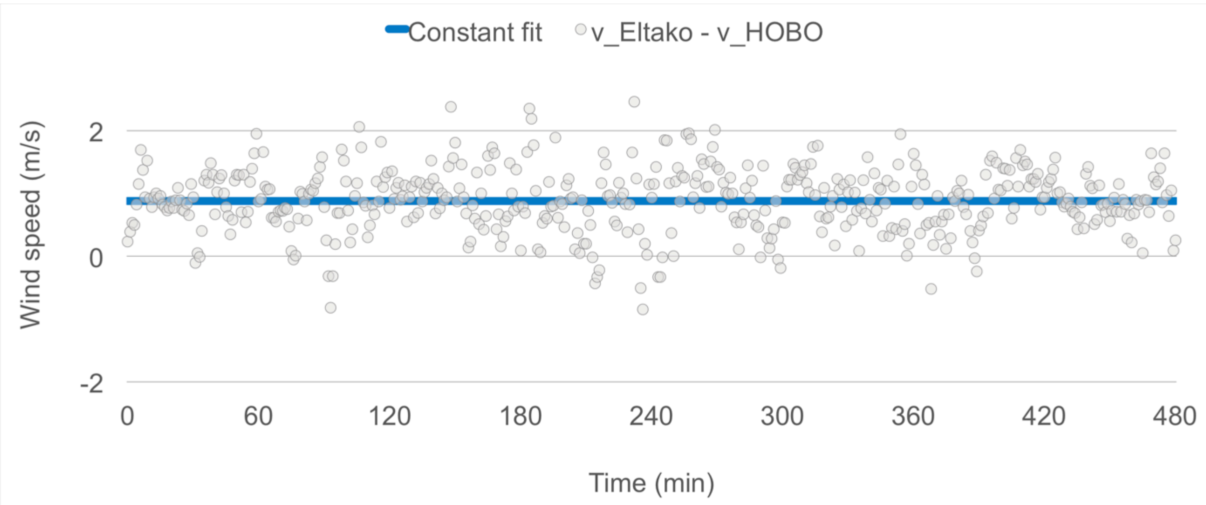


Figure 2-17 Constant fitting of offset value – St. Ruperts

- Banket: The two measurement systems where installed on two different, not comparable locations. Therefore, the Banket offset value was derived from the Harare and the St. Ruperts offset values by weighting these two offset values differently. As the St. Ruperts (10m, freestanding) measurement is more similar to the Banket case (10m, freestanding) than the Harare (rooftop) measurement, the St.

Ruperts offset was weighted by 2/3 and the Harare offset was weighted by 1/3, and the offset value for Banket was found to be 0.7855.

$$\Delta_{Banket} = \frac{2}{3}\,\Delta_{St.\ Ruperts} + \frac{1}{3}\,\Delta_{Harare} = 0.7855\ m/s$$ **Eq. 4**

- The final wind speeds were calculated using the following, corrected manufacturer formula:

$$v_{corrected} = v_{Eltako} - \Delta$$ **Eq. 5**

- As v_{Eltako} is minimum 0.667 m/s, but can be smaller than Δ, negative values for $v_{corrected}$ can appear. All these negative values for $v_{corrected}$ were set to 0 by default.

Over an exemplary time of 8 hours and for the three sites, Figure 2-18, Figure 2-19 and Figure 2-20 display the measured timeseries by the two different measurement systems as well as the corrected timeseries that was finally used for the further analysis of the wind data.

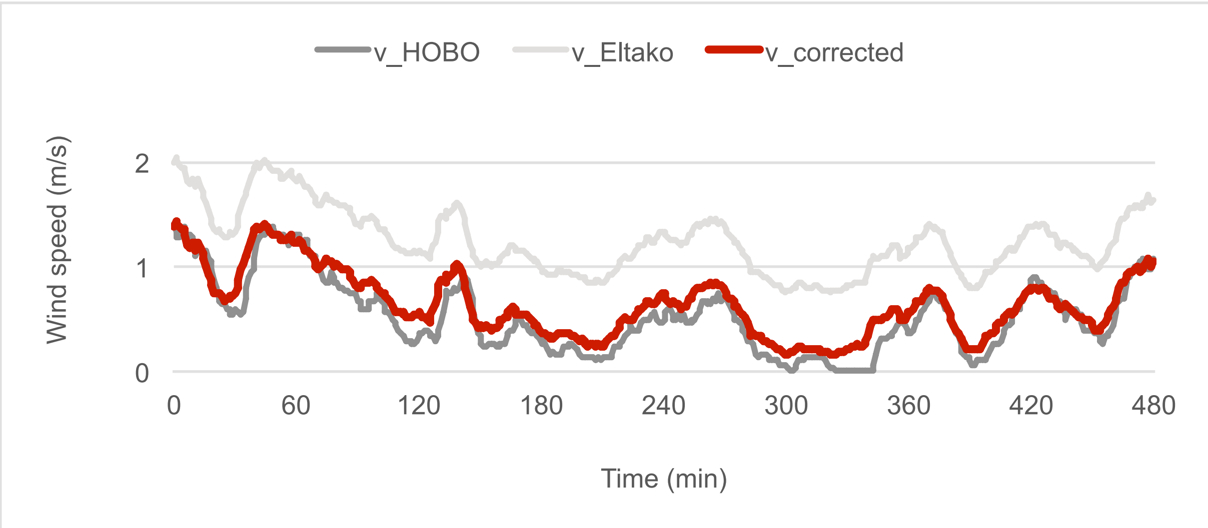


Figure 2-18 Comparison of measured and corrected wind speeds – Harare

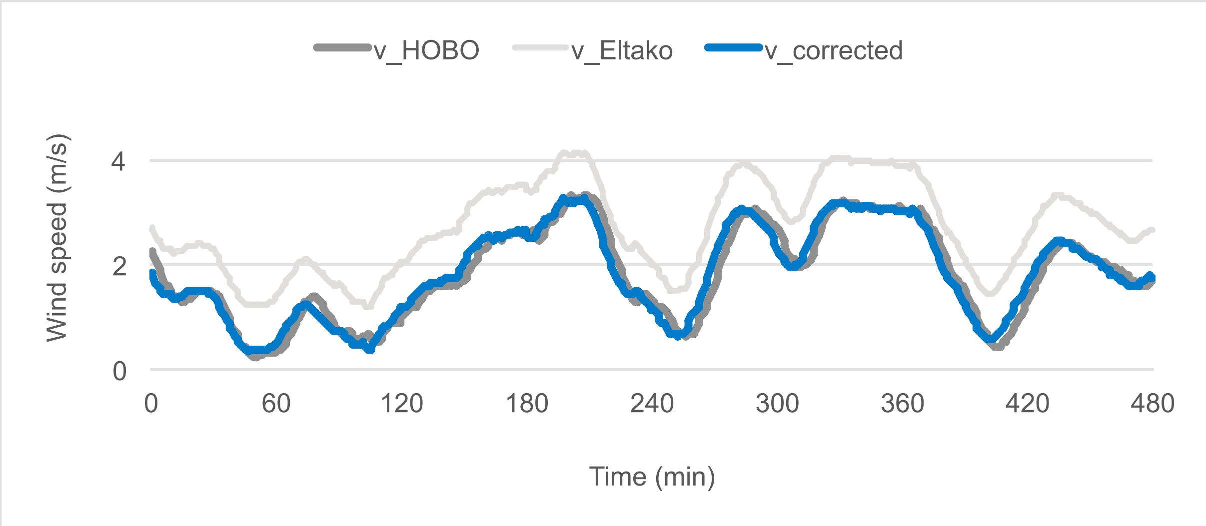


Figure 2-19 Comparison of measured and corrected wind speeds – St. Ruperts

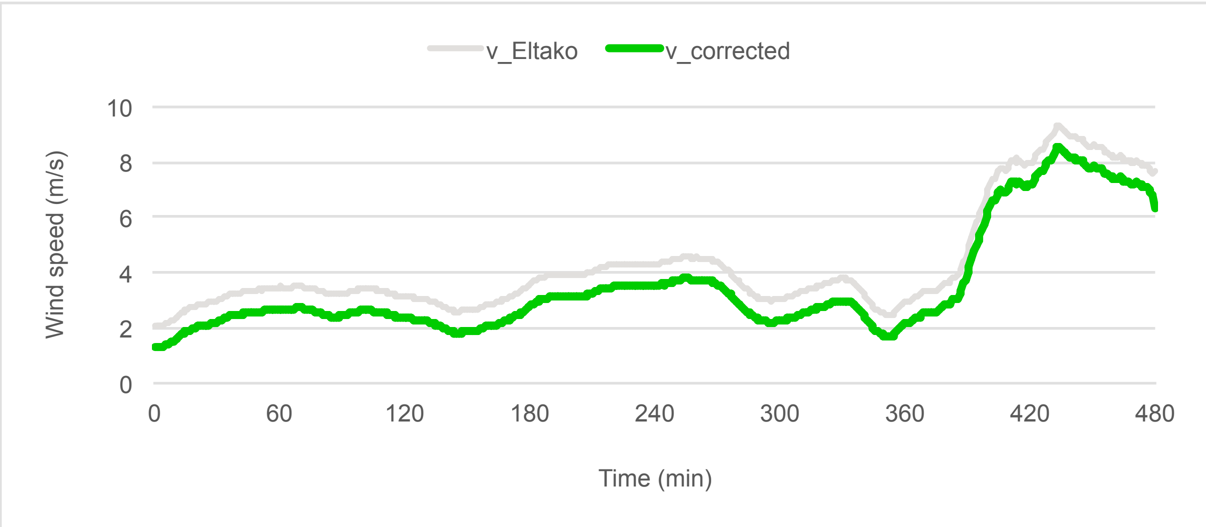


Figure 2-20 Comparison of measured and corrected wind speeds – Banket

2.3.3 Results of the measured timeseries

As already described, low-cost wind measurement stations have been installed at three sites in Zimbabwe to gain site-specific wind data. The siting and installation as well as the data validation are discussed in the previous sections. This section now focuses on the results of the measurements.

All measurements were taken with a resolution of 60 seconds.

Harare

For Harare, measurements are available for the period from October 11 to November 11 of 2016. Figure 2-21 shows five days in November. The average measured wind speeds are

- 2.15 m/s for the entire measured timeseries,

- 1.98 m/s for the 20 days in October,
- 2.49 m/s for the 11 days in November,
- 2.76 m/s for the plotted timeseries.

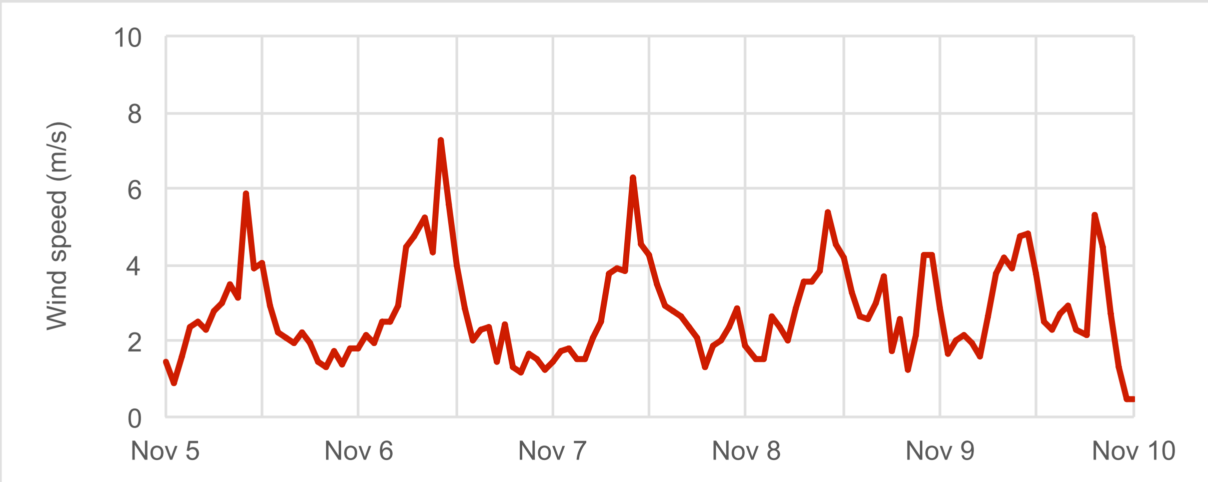


Figure 2-21 Five days on-site wind speed measurement data in 10m height – Harare

Banket

Measurements from Banket are available for the period from November 1 to November 30 of 2016. Figure 2-22 shows the same five days in November as above and the average measured wind speeds are

- 3.20 m/s for the entire measured timeseries,
- 4.12 m/s for the plotted timeseries.

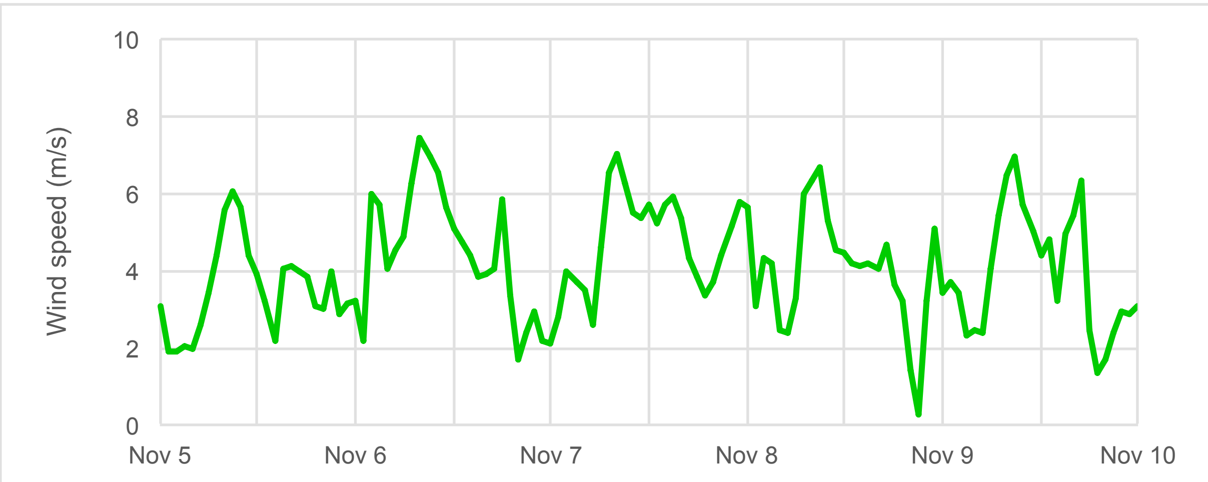


Figure 2-22 Five days on-site wind speed measurement data in 10m height – Banket

St. Ruperts

Measurements from Banket are only available for the period from November 4 to November 10 of 2016. Figure 2-23 shows the same five days in November as above. The average measured wind speeds are

- 3.18 m/s for the entire measured timeseries,
- 3.20 m/s for the plotted timeseries.

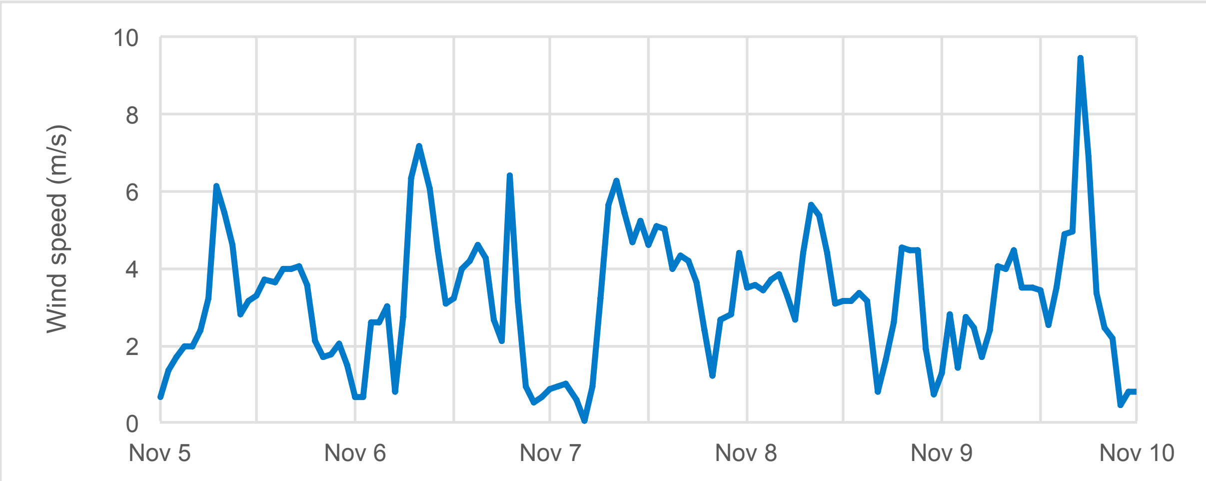


Figure 2-23 Five days on-site wind speed measurement data in 10m height – St. Ruperts

All three plotted wind distributions show the already known variations between day and night. Additionally it can bee seen that wind speeds in Banket and St. Ruperts are more fluctuating than in Harare.

Summary

The self-made wind measurement stations can provide data with a high resolution of 60 seconds for all of the three research sites at the exact posititons where small-scale wind turbines could be installed. Unfortunately these measurements are so far only available for the short period of one month or even less[2].

2.4 Digression: Extrapolating wind speeds

Small-scale wind turbines usually operate in heights between 10 and 20 meters [17]. Therefore, all measurements were taken in 10 meters height above the surface. In contrast to that, the absolute values for wind speeds from DTU wind database are given for a reference height of 50 meters.

[2] As explained in the beginning of chapter 2.3, the wind measurement stations are supposed to transfer the measured data automatically into a dropbox folder. It was not possible to enable a stable internet connection that guarantees this automatic data transfer. Missing data has to be taken manually from stations during the next research trip to Zimbabwe. Therefore, only data measured in October and November 2016 could be used in this thesis.

In order to compare the measured values to the DTU data and in order to make the DTU data suitable for the assessment of the wind potential for small-scale wind turbines, both the measured and the DTU data can be extrapolated from their given reference height to lower or higher levels.

The following relationship

$$\frac{U(z)}{U(z_r)} = \frac{\ln\left(\frac{z}{z_0}\right)}{\ln\left(\frac{z_r}{z_0}\right)} \qquad \text{Eq. 6}$$

that can be derived from the formula for the logarithmic wind profile is often used for this purpose [6]. U is the horizontal component of the velocity of the wind, z is the desired height, z_r the reference height (i.e. the height at which the measurement was taken), and z_0 is the surface roughness value. The surface roughness is a parameter that is used to describe the natural vegetation of a location. Forests or urban areas come with high roughness values leading to lower wind speeds in the air above.

Table 2-5 gives an overview on approximated surface roughness values depending on the type of terrain. The surface roughness values for the three sites were self-estimated on-site during the research trip with the help of this table and can be found in Table 2-6.

Table 2-5 Approximated surface roughness values [6]

Terrain description	z_0 (m)
Very smooth, ice or mud	0.00001
Calm open sea	0.0002
Blown sea	0.0005
Snow surface	0.003
Lawn grass	0.008
Rough pasture	0.01
Fallow field	0.03
Crops	0.05
Few trees	0.10
Many trees, hedges, few buildings	0.25
Forest and woodlands	0.50
Suburbs	1.50
Centers of cities with tall buildings	3.00

Table 2-6 lists the average wind speeds of November, resulting from the extrapolations for 10, 20 and 50 meters height. The wind speeds in Harare deviate by almost 9 %, what can be explained by the fact that the DTU data is based on regional data of Harare and its surrounding, whereas the measurement is site-specific and was taken inside the city. The Banket data show the biggest deviation (25%). The DTU database tends to overestimate wind speeds over lands [10] and therefore shows values that are by far higher than the measured values. However, the St. Ruperts data of the measurements and DTU match.

Table 2-6 Comparison of measured and extrapolated wind data

		Harare	**Banket**	**St. Ruperts**
	z_0 (estimated)	0.75 m	0.1 m	0.4 m
Wind speeds at 50m	DTU	4.42 m/s	5.77 m/s	4.88 m/s
	Measurement, extrap.	4.03 m/s	4.31 m/s	4.77 m/s
	Deviation	8.8%	25.3%	2.3%
Wind speeds at 20m	DTU, extrap.	3.45 m/s	4.92 m/s	3.95 m/s
	Measurement, extrap.	3.15 m/s	3.68 m/s	3.86 m/s
	Deviation	8.8%	25.3%	2.3%
Wind speeds at 10m	DTU, extrap.	2.72 m/s	4.27 m/s	3.25 m/s
	Measurement	2.49 m/s	3.20 m/s	3.18 m/s
	Deviation	8.5 %	25.1 %	2.2 %

2.5 Assessment of the wind potential of the three regions

2.5.1 Linking of timeseries and Weibull wind distribution

For a detailed assesment of the three sites none of the presented winddata is optimal:

- The DTU dataset contains information about wind direction, annual mean wind speed and annual wind cycle. However, DTU does not provide data with hourly resolution, and data is – except from annual mean wind speeds – only available on regional basis and not for the exact site, which leads to inaccuracies, especially in the case of Harare. Additionally, the DTU database tends to overestimate wind speeds over lands.
- Meteonorm provides interpolated hourly timeseries based on longterm monthly average wind speeds. However, regarding the three research sites, the data is only available for one of them, Harare. Additionally, the measurement height is unknown.
- The selfmade weather stations can provide data with a high resolution of 60 seconds for each of the three research sites at the exact posititons where small-scale wind

turbines could be installed. Unfortunately these measurements are so far only available for the short period of one month or even less.

The above listed facts made it necessary to link the different timeseries. Therefore the following methodology was developed.

Linking measured timeseries from November 2016 with DTU annual cyce

The annual wind cyle by DTU (see Table 2-2 chapter 2.2) was normalized to the reference month November, when the measurements by the self-made weather station were taken. The resulting new annual wind cycle, normalized to November, is displayed in Table 2-7.

Table 2-7 Normalized monthly average wind speed of the research sites, reference month: November

	DTU: Normalized monthly average wind speed (-)											
	Jan	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
Harare	0,85	0,92	0,88	0,90	0,82	0,86	0,94	1,01	1,09	1,08	1,00	0,87
Banket	0,79	0,82	0,78	0,78	0,73	0,80	0,92	1,01	1,10	1,09	1,00	0,88
St. Ruperts	0,86	0,93	0,86	0,86	0,79	0,83	0,90	0,96	1,05	1,06	1,00	0,90

The values from this new annual wind cycle were multiplied by the monthly average wind speed values of the measured timeseries in November 2016 (see Table 2-8).

Table 2-8 November 2016 on-site measurement average wind speeds of the research sites in 10m height

	Measurements: Average wind speed (m/s)
	November 2016
Harare	2.49 m/s
Banket	3.20 m/s
St. Ruperts	3.18 m/s

The result is an annual wind distribution for each of the three sites, based on the normalized timeseries by DTU and the absolute values of the average wind speed of the measured timeseries in November 2016 (Table 2-9).

Table 2-9 Annual wind distribution of the research sites in 10m height

	DTU and measurements: Monthly average wind speed (m/s)											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Harare	2,12	2,28	2,19	2,23	2,05	2,14	2,35	2,51	2,72	2,70	2,49	2,16
Banket	2,54	2,63	2,49	2,49	2,34	2,57	2,94	3,23	3,51	3,49	3,20	2,80
St. Ruperts	2,74	2,95	2,74	2,74	2,51	2,63	2,86	3,06	3,33	3,38	3,18	2,86

Linking hourly Meteonorm timeseries to generated annual distribution

To generate an hourly timeseries for each of the three sites, the hourly Meteonorm timeseries has been normalized separately for each month, to its respective monthly average wind speed (displayed in Table 2-10).

Table 2-10 Annual wind distribution in Harare at unknown height

	Meteonorm: Monthly average wind speed (m/s)											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Meteonorm	3,09	3,61	3,10	3,09	2,59	3,10	3,10	3,60	4,10	4,60	4,59	3,60

The result is a normalized hourly timeseries for one year. This time series was then multiplied by the values from the annual wind distribution, displayed in Table 2-9, separately for each month and each site.

The final result is an hourly timeseries for one year for each of the three sites, based on DTU´s annual cycle, the average wind speed of the measured timeseries in November 2016 and the hourly timeseries of Meteonmorm.

Summary

Different data sources have been used to mutually compensate the weakness of each of the data sources and to generate a final hourly wind time series. Thus, the developed methodology combines three wind data sources in order to guarantee an ideal wind resource assessment. The only absolute values that have influence on the derived timeseries are the measurement values. However, longterm on-site measurements for every site would have been the optimal solution. Although, this process has just been initiated by this thesis and its preceding projects.

2.5.2 Final assessment

Finally, the probability density of the derived hourly wind speed timeseries has been computed. Therefore, bins of 1 m/s have been created. I.e. that all the wind data between 0.0

and 1 m/s are in the first bin, and that all the wind speed data between 1.01 and 2 m/s are in the second bin, and so on.

The experimental probability density describes the number of times the respeticve wind speed bin occurs divided by the total number of timesteps and is plotted in columns in the figures below.

The best-known curve fit for the probility density of wind data is the Weibull distribution. There are two parameters used to describe the Weibull distribution, the C scale factor and the k form factor. The Weibull fitted curves can also be found in the figures below [6].

Harare

Table 2-11 Weibull parameters for Harare

Scale factor C (m/s)	Form factor k (-)	Exp. Average speed (m/s)	Weibull average speed (m/s)
2.6848	1.8075	2.2903	2.3865

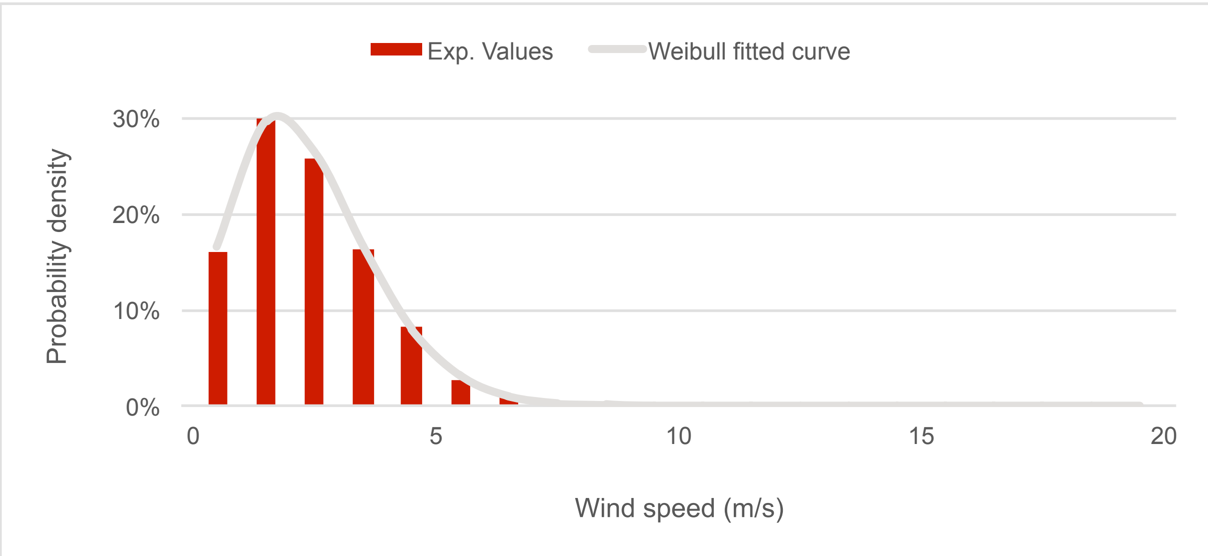


Figure 2-24 Probability density of wind speeds in Harare

Banket

Table 2-12 Weibull parameters for Banket

Scale factor C (m/s)	Form factor k (-)	Exp. Average speed (m/s)	Weibull average speed (m/s)
3.2394	1.7521	2.8094	2.8842

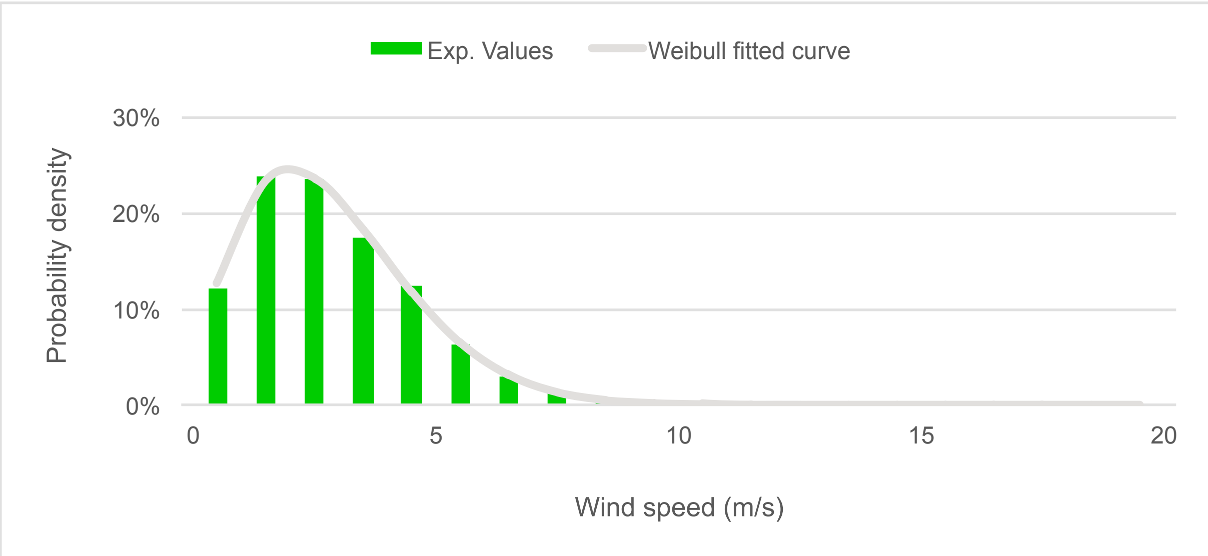


Figure 2-25 Probability density of wind speeds in Banket

St. Ruperts

Table 2-13 Weibull parameters for St. Ruperts

Scale factor C (m/s)	Form factor k (-)	Exp. Average speed (m/s)	Weibull average speed (m/s)
3.3201	1.7977	2.8812	2.9515

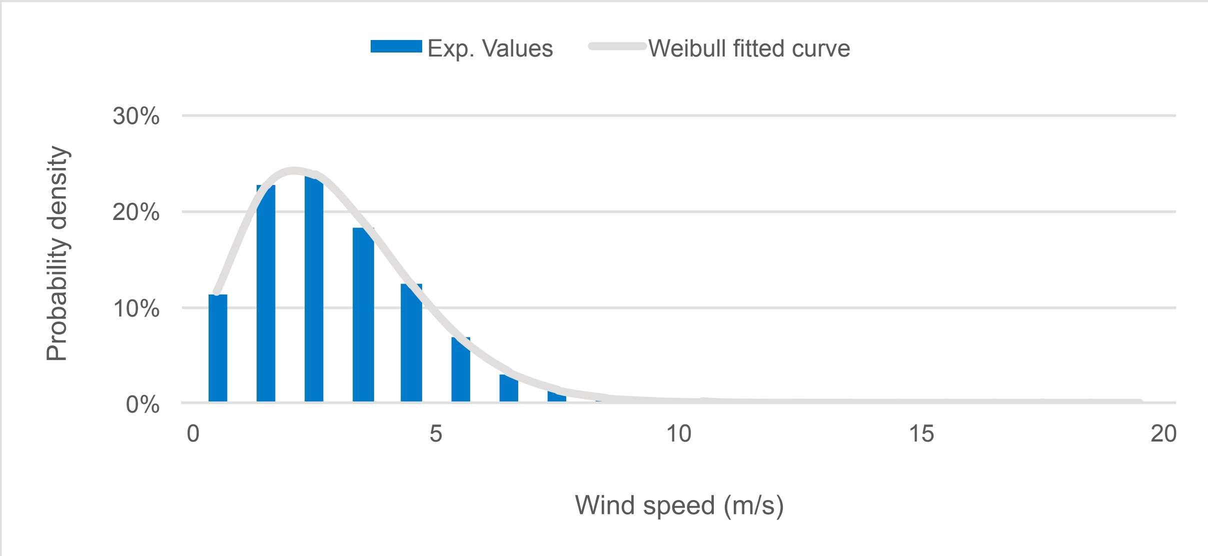


Figure 2-26 Probability density of wind speeds in St. Ruperts

Harare shows the lowest annual average wind speed of the three sites due to its urban environment. However, also Banket and St. Ruperts come with very poor annual average wind speeds, so that the general wind potential of the three sites is expected to be too low to install small-scale wind turbines at reasonable costs.

Solar wind complementarity

The figures below show that the solar and wind resources do not have complementary behavior, neither regarding their daily variations (Figure 2-27) nor regarding their seasonal variations (Figure 2-28). Wind and solar resource are both peaking at midday and are low during the night. From September to November, both resources reach their annual peaks and in times of lower irradiance between April and July also the wind resource is low. This not existing complementary behavior is very unfortunate. If wind resources are high in times of low solar resources and vice versa, a hybrid system including solar and wind power generation can either reduce storage sizes or the diesel consumption and thus the total cost of the system.

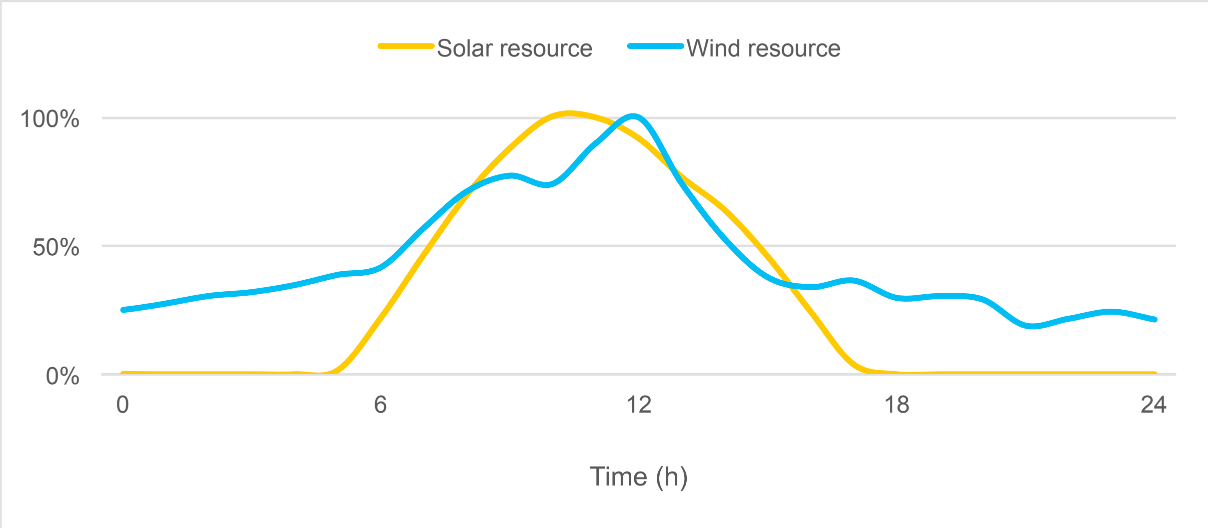


Figure 2-27 Daily variations in solar and wind resource

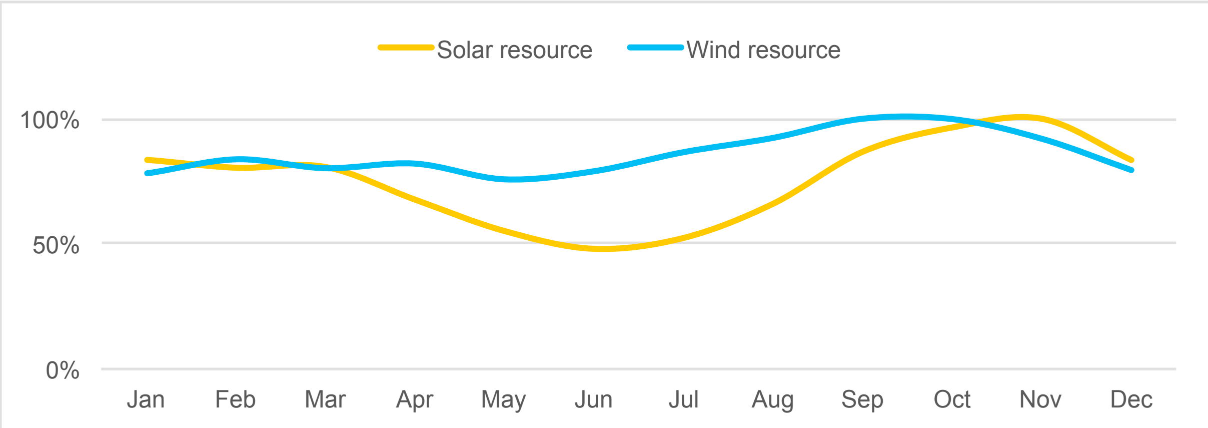


Figure 2-28 Seasonal variations in solar and wind resource

3 Analysis of small-scale wind turbine technologies with focus on locally manufactured wind turbines

This chapter will give a short overview on the small-scale wind technologies that are most suitable for the use in rural electrification projects.

3.1 Technological analysis

Definition and terminology

Small-scale wind turbines often are be classified in vertical axis wind turbines (VAWT) and horizontal axis wind turbines (HAWT). Although VAWTs are popular among a number researchers and DIY enthusiasts, the most successful design is still a three-bladed HAWT as it is more efficient, more reliable and cheaper [18]. Therefore this thesis will focus on HAWT.

Regarding the size of a small-scale wind turbine, there is no consistent definition in the literature. Various sources find different approaches and use different parameters. In the scope of this thesis the terminology “small-scale wind turbines” will be used for turbines with rated power ranging from 0 kW to 10 kW.

Commercial turbines or local manufacturing (Do-it-Yourself)?

Small-scale wind turbines can either be commercial, i.e. massproduced machines from high tech factories or locally manufactured, using local resources and basic tools.

Commercial small-scale wind turbines are widely available and their price levels range from an average price per kW of 1900 USD/kW for turbines from the Chinese market to more than 6000 USD/kW average price on the U.S. market [19]. According to experts the price level also indicates the level of quality, as very cheap turbines often have very short lifetimes and low quality [5]. When it comes to maintainance issues, commercial turbines can be problematic as the required knowledge for repairs is often lacking and spare parts are not available or only on high cost.

Do-it-Yourself small-scale wind turbines can be manufactured locally for costs of about 3000 USD/kW (see chapter 3.2) and thus can be considered as cost-competitive, especially if compared to high quality, expensive commercial turbines. Their quality depends strongly on the locally available skills, materials and equipment knowledge as well as on the local quality standards and is by far more unpredictable than the quality of commercial turbines. The big advantage of Do-it-Yourself turbines is that they can contribute to local job creation, build local capacities and raise the knowledge which is needed for the turbines´ operation and maintenance [5].

Table 3-1 sums up the main advantages of commercial and locally manufactured small-scale wind turbines.

Table 3-1 Advantages and disadvantages of small-scale commercial and DIY turbines

	Commercial turbine	DIY turbine
Advantages	Well tested and reliable	Cheap
	Good efficiency at rated wind speed	Local capacity building for operation and maintainance
Disadvantages	Good quality machines are expensive	Less efficient
	Problematic availability of spare parts remote regions	Crude appearance
	Lack of knowledge for local maintainance	Unpredictable quality

The Piggott design

Over 30 years ago, Hugh Piggott started to develop an open-source design of a small-scale horizontal-axis wind turbine that can be manufactured locally on low costs. His guide "A Wind Turbine Recipe Book" gives instructions for the manufacturing using only basic equipment and materials [17]. His design has continually improved. It has been installed by DIY enthusiasts, universities and NGOs across the globe and proved to meet the requirements of rural electrification in many different projects [20]. Table 3-2 shows the key components of Piggott´s turbine design.

Table 3-2 Key components of a typical Piggott turbine

Component	Materials
Blades and tail vane	Three blades, carved from wood and attached to a plywood/steel disk
	Steel pipe and plyboard for tail vane
Alternator (Axial flux permanent magnet alternator)	Two rotor disks with neodymium/ferrite magnets cast in polyester resin
	Stator with handwound enamelled copper coils cast in polyester resin
Mounting	Steel pipe, angle and plate, bearing (rear car hub/trailor stub bearing)
Electronic parts	Diodes, bridge rectifier, load controller, dump loads, short-circuit switch
Tower	Steel pipe, steel wire rope, ground anchors, chain, turnbuckles, gin pole

3.2 Cost analysis

Figure 3-1 gives a rough approximation of the initial costs (without considering the installation) for a 1 kW Do-it-Yourself small-scale wind power system. This cost breakdown is based on the on-site research that was performed in Zimbabwe (see 4.1) as well as as on the cost analysis of manufacturing a 1 kW Piggott turbine in Ethiopia [20]. It shows that that the turbine itself is only responsible for less than one third of the total system costs, with the alternator causing the biggest part of the turbine costs. Considering 58 man-days at 13 USD per day, which is an average salary for a trained worker in Zimbabwe, labor is a 25 % fraction of the total costs. The tower comes with high material costs and is responsible for about on third of the manufacturing costs. Electricity prices are low in Zimbabwe and the total share of electricity costs for the manufacturing is almost negligible. Electronic parts include e.g. fuses, charge controller, ground or connection and cause about 12% of the total costs.

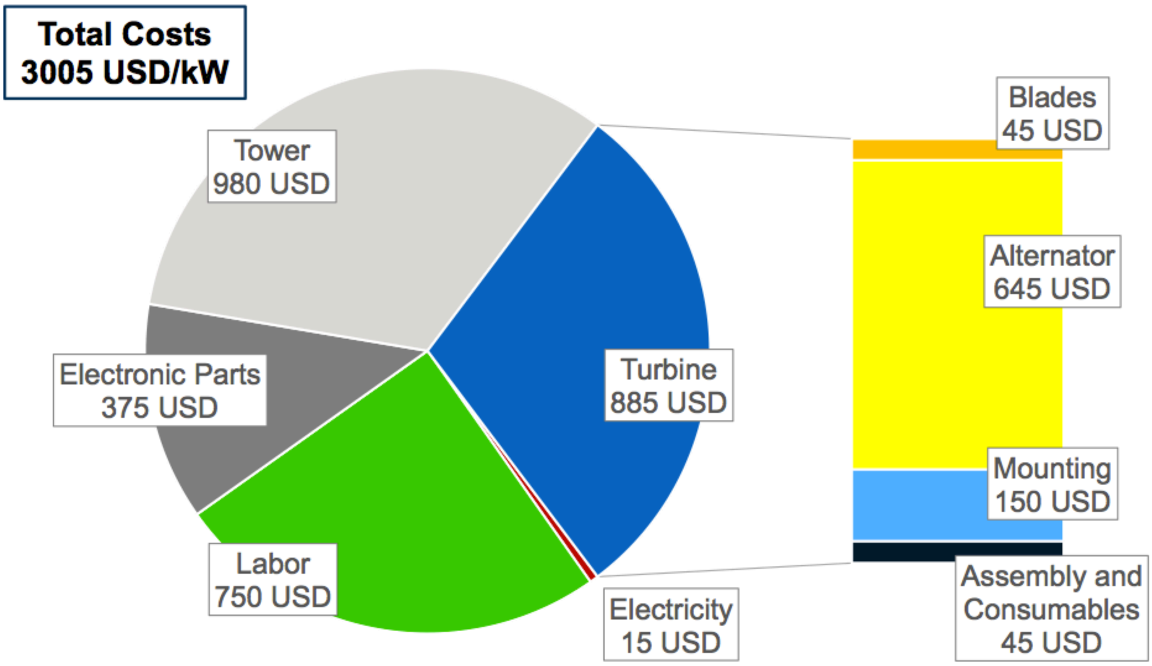


Figure 3-1 Costs of a locally manufactured 1 kW wind turbine, based on the Piggott design

4 On-site research on the feasibility of local manufacturing of wind turbines in three regions of Zimbabwe

In this chapter, the feasibility of the local manufacturing of small-scale wind turbines will be analyzed. The analysis is conducted on the basis that one pilot project would be realized, and does not aim to already establish a business model for the local manufacturing of wind turbines. However, on the long run a successful pilot project can facilitate the creation of future business models. The availability and costs of materials and components, the availability of qualified manpower, as well as of tools and workshops will be investigated in this chapter as they are the most crucial parameters for the feasibility of local manufacturing and the successful realization of a future pilot project.

4.1 Availability and costs of materials and components

The local availability of materials and components was investigated during many informal talks to a local technician in St. Ruperts, to teachers of the vocational centres in Chinhoyi and in Harare, to vendors at the informal market “Gazaland” in Harare, as well as to lecturers and students of Harare´s university UZ. They key findings of these talks are:

- Almost everything needed is available, mostly on informal markets and at very fair costs if the purchase is made under local guidance.
- Good availability of copper wires for alternators at fair costs, as the country has big resources of copper.
- Availability of good quality permanent magnets for alternators is problematic, but as an alternative many recyclable automotive alternators can be found and the practical expertise on rewinding and recycling of automotive alternators is high.
- Good availability of pinewood for the manufacturing of rotor blades.
- The country´s economy and all markets are concentrated on Harare. The more rural the more complicated it gets to find all necessary materials.
- Good availability of electric components for decentralized energy sysetms from solar shops.

The costs of materials and components were investigated in the same way as their availability. However, it was only possible to get a general idea of the situation in the short period of time, as most of the material supply would be based on purchasing from the very opaque informal market

Table 4-1gives a first overview on the costs of the most crucial raw materials of a small-scale wind turbine.

Table 4-1 Costs of materials

Component	Cost	Comment
Bearing	5 USD per unit	Small bearing
Shaft	12-14 USD per meter	Diameter: 12 mm
Brake disc	0 USD per unit	Easily available from scrap
	15 USD per unit	New
Steel sheet	150 USD per unit	2400mmx1200mmx5mm
Angle	16 USD per unit	6m length, 40mmx40mmx4mm
Metal pipe	18 USD	6m length, 40 mm diameter
Copper wires	19 USD per kg	Good availibility
Nuts/bolts/screws	1 USD per 5/10 units	Good availibility
Paint	38 USD per unit	5l
Permanent magnet	10 USD	From scrap, bad quality, not easily available
Diodes	0 USD	Good availability from scrap
Fence wire	1.2 USD per kg	
Pine wood	880 USD per cube	Good availability

4.2 Availability of qualified manpower, tools and workshops for manufacturing

Regarding Zimbabwe, only very few small-scale wind projects are known. All have been carried out several years ago [21], [22] and thus it is very unlikely to find people experienced with wind power technology in the country. Although experience in wind power is not an essential requirement for the local manufacturing of a small-scale wind turbine, a certain standard of qualification and equipment is crucial. Zimbabwe´s vocational training centres and technical colleges present an opportunity where these crucial requirements could be met. Such schools can be found in every bigger town of the country. The schools offer various vocational training programs, e.g. in automotive engineering, construction and civil engineering, mechanical engineering, wood technologies, computer technologies, electronic engineering [23]. They offer a good quantity of manpower (19.000 students enrolled, 4000 graduates per year) and are equipped with all basic tools and workshops that would be necessary for a small-scale wind turbine pilot project [24].

During the research trip to Zimbabwe two vocational training centres could be visited: the “St. Peter´s Kubatana Technology Centre” in Harare and the “Rural Vocational Training Centre” in Chinhoyi, which is located close to Banket.

The “St. Peters Kubatana Technology Centre” can offer almost optimal prerequesites for the realization of a pilot project. The school administration and its principal, a Jesuit priest, are highly reliable. The complete course program of 2016 can be found in appendix A3. Different workshops (carpentry, automotive, tool fitting, etc.), equipped with a high number of old, but good working tools and machines can be found there The teachers show good entrepreneurial spirit and already realized several projects like the manufacturing of a biogas plant, of a plastic recycling facility or of a soap production facility. The school´s location close to a big industrial area and the informal market place “Gazaland” facilitates the supply with necessary materials and components.

The “Rural Vocational Training Centre” in Chinhoyi is a smaller school. It offers few courses on automotive engineering, carpentry and mechanical engineering. Generally, it is less favored with good functioning equipment and due to its more rural location great parts of the necessary materials have to be purchased from Harare. Therefore, the capacity for small-scale wind turbine pilot projects is limited compared to the “St. Peters Kubatana Technology Centre”.

In St. Ruperts and the surrounding area there is no vocatonial school, the Chinhoyi school is the closest. In the St. Ruperts community itself, only very basic tools for easy manufacturing like welding and carpentry are available. The place is lacking qualified manpower, equipment and required materials. The local manufacturing of a small-scale wind turbine is not recommended there.

4.3 Assessment of feasibility of local manufacturing

To sum up shortly, small-scale wind turbines can be manufactured in Zimbabwe. However, for a first pilot project it is strictly recommended to do this in Harare as ideal structures can be found there and structures in semi-urban and rural regions will complicate the manufacturing process. However, the awareness of wind power as energy source in Zimbabwe is low and so is the experience with the technology. This increases the importance of knowledge transfer and local capacity building, which is crucial for both the successful manufacturing as well as for the operation and maintainance. A practical construction course in the “St. Peters Kubatana Technology Centre” could be an effective and motivating first step for the local capacity building.

5 Identifiying optimal technology for each of the three sites

In this chapter the optimal technology for the three research sites will be identified. Therefore, small, decentralized hybrid energy systems will be modeled and optimized, using the linear programming model *urbs* [25]. The focus of this chapter will be on the effects of including small-scale wind turbines to hybrid energy systems as well as on the effects of choosing different turbine types.

As input data, *urbs* requires timeseries for demand and intermittent supply, as well as economic data. The input data used, will be presented in the first part of this chapter, followed by the results and their discussion.

5.1 Generation of approximated demand timeseries

urbs optimizes the total system cost for a given demand (i.e. that the minimum value of the variable total system cost determines the most reasonable solution for the modeled energy system). Therefore, it requires one timeseries that describes the power demand (kWh/h) per timestep. It is a crucial input parameter, as the whole optimization aims to meet this demand with minimal costs. The following section shows how the demand timeseries used in this thesis was developed.

5.1.1 Selection of main consumers

In the course of a comprehensive, socio-empirical questionnaire that was conducted in 2016 in St. Peter´s Kubatana, Harare, in Sacred Heart, Banket and in St. Rupert Mayer, Makonde people were asked to indicate their use of electric devices [26]. In particular, the respondents were asked if they are using a certain electric device and if so, for how many days per week and at what time of the day they are using it. Having knowledge of the electric devices used and their respective power ratings, the typical electricity demands of various Zimbabwean consumers such as households with different income levels, different school types, an ordinary hospital or a small store can be derived. To verify the data gathered by the questionnaire, relevant invoices of hospitals and schools were reviewed and further people like local technicians were interviewed. The power ratings of the devices were found by measurements and by documenting the information of nameplates on site as well as by literature research. Finally, five simple households, a high school and a hospital were selected to generate a load profile for modeling and optimizing a decentralized hybrid energy system with *urbs*.

Table 5-1 shows the devices that were found to be used by the selected consumers.

Table 5-1 Use of electric devices by different consumers

	Device	Rating	Run time	Days of use per week
Household	Lighting	125 W	6pm - 8am	Daily
	Phone	5 W	6pm - 8pm	3 - 4 days
	TV	80 W	6pm - midnght	Daily
	Fan	60 W	6pm - 10pm	3 - 4 days
	Iron	1500 W	6pm - 8pm	1 - 2 days
	Fridge	130 W	All day	Daily
High School	Lighting	1800 W	8am - 3pm	3 - 4 days
	Phone	5 W	1pm - 3pm	3 - 4 days
	TV	80 W	10am - 5pm	1 - 2 days
	Fan	60 W	10am - 5pm	3 - 4 days
	Science Lab	1000 W	11am - 4pm	3 - 4 days
	Water Pump	5500 W	8am - 4pm	Daily
Hospital	Lighting	520 W	6pm - 10am	Daily
	Phone	5 W	11am - 3pm	3 - 4 days
	Kettle	2000 W	8am - 10am	1 - 2 days
	Freezer	150 W	All day	Daily
	Sterilizer	9500 W	6am - 7am	1 - 2 days
	Medicine Cooling	85 W	All day	Daily
	Water Pump	5500 W	8am - 4pm	Daily

5.1.2 Monte Carlo Simulation

Urbs requires a one-year load time series with hourly resolution. Monte Carlo simulation[3] was used to convert the data from Table 5-1 into hourly load profiles. Doing so, the following steps were examined separately for each of the devices.

- a "power-on" probability W ϵ [0;1] - i.e. the probability that a device is turned on at a specific time - was defined for every hour of one day (see example of household and school in appendix A4).
- Also, a random number Z ϵ [0;1] was generated for every hour of that day by a random number generator (e.g. "=RAND()" in Microsoft Excel).
- The probability value W was then compared to the random number Z for every time step. For Z > W, the device was considered to be turned off (no load) and for Z < W,

[3] The Monte Carlo method is a stochastic method that is "making use of random numbers to solve a problem" [27]. One possible application is the generation of time series, e.g. if exact data are not available.

the device was considered to be turned on (load is defined by power rating of the device).

- The required one year load time series with hourly resolution was created by repeating it 365 times for every day of the year.

5.1.3 Definition of final load scenarios

The load profiles of the three selected consumers were created by adding up the load profiles of the single devices. Finally, a moving average over six hours was applied in order to avoid unrealistic scenarios without any load. The addition of the profiles of the three selected consumers gives the final base load scenario used in this thesis. The total energy demand for the generated load profile is 29311.6 kWh per year with an average daily load of 80.3 kWh.

Figure 5-1 illustrates this load scenario during two typical days. The five households draw the smallest part of the load, mainly during the night, when lights and TV are in use. The total load peaks at midday, when both water pumps are in use and therefore increase the load drawn by the high school and the hospital. The high school draws no load during the night, in contrast to the hospital where patients and employees are present also during the night.

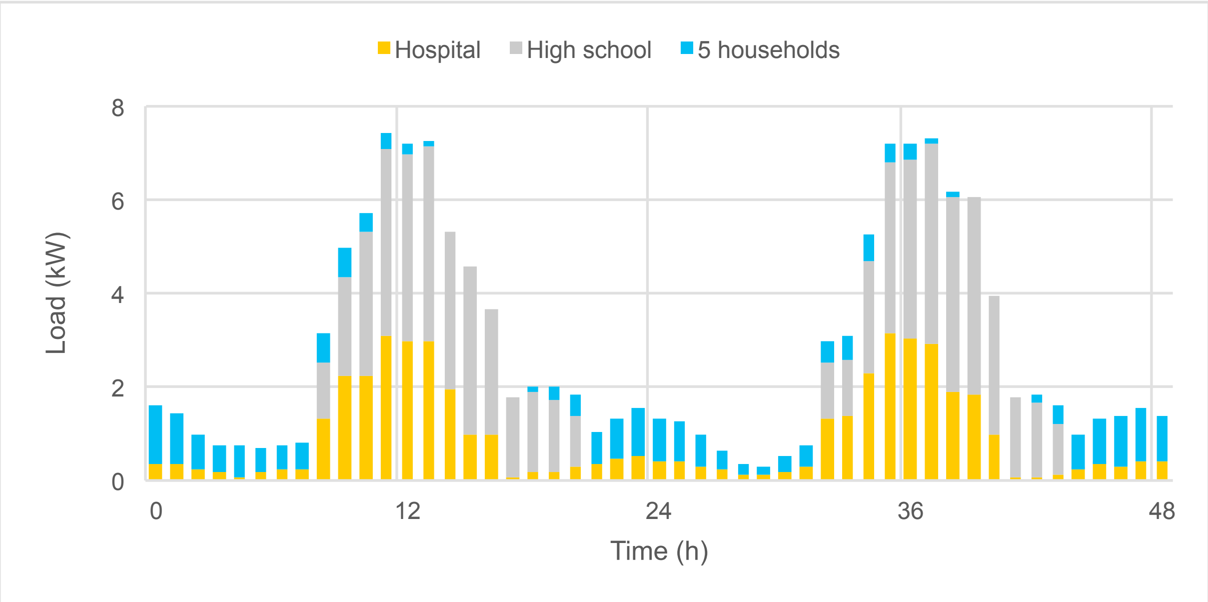


Figure 5-1 Exemplary two days of the hourly demand timeseries

In addition to the base load scenario, Figure 5-2 shows the load scenarios 2 and 3, which are generated by shifting the load of the water pumps towards the night. Whereas in the base load scenario both pumps are pumping water during the day, in load scenario 2 one pump is pumping during the day and the other one during the night. This leads to a second peak load during the night and additionally decreases the peak load by approximately 1 kW. In load scenario 3 both pumps are pumping at night. This leads to a complete shift of the peak load to the night and decreases the load drawn during the significantly.

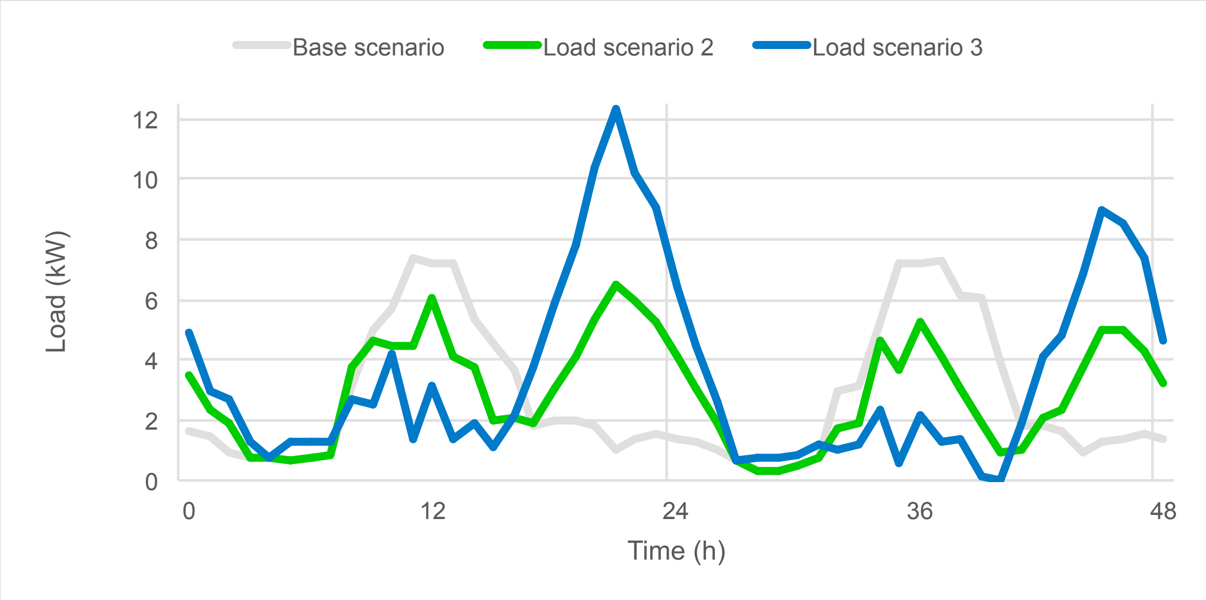


Figure 5-2 Exemplary two days of the hourly demand timeseries, comparing different scenarios

5.2 Generation of approximated timeseries for intermittent power supply

Besides the demand timeseries, *urbs* requires information about the performance of the energy generating technologies. This includes one timeseries that describes the technologies with intermittent behavior, like wind and solar power generation. The generation of these timeseries is explained in the following section.

5.2.1 Definition of technical specifications

Small wind turbines

In order to compare DIY and Comm., three different small wind turbine systems were selected and modeled in *urbs*: a locally manufactured Piggott turbine with a diameter of 4.2 meters, the commercial 1 kW turbine Bergey XL.1, as well as another locally manufactured turbine, which is optimized for the use in low wind speed areas and which is also based on the Piggott design.

Table 5-2compares the key performance parameters of the three turbines.

Table 5-2 Key performance parameters of three wind turbines

	Locally manufactured turbine (DIY)	**Commercial turbine** (Comm.)	**Low wind speed optimized turbine** (DIY opt.)
Turbine name	Comet-ME Center	Bergey XL.1	Horizon
Installation site	Palestine	All over the world	Malaysia
Diameter	4.2 m	2.5 m	4.5 m
Cut-in wind speed	2 m/s	2.5 m/s	2 m/s
Rated wind speed	9 m/s	11 m/s	5 m/s
Furling/control wind speed	13 m/s	13 m/s	7 m/s
Rated power	1500 W	1000 W	400 W
Peak power	1800 W	1200 W	1050 W
RAEY at 5 m/s	4000 kWh/a	1900 kWh/a	3500 kWh/a
Rated power coefficient	0,25	0,29	0,33
Type	3 Blade Upwind, Fixed Pitch, Autofurl, Direct-drive, PM alternator	3 Blade Upwind, Fixed Pitch, Autofurl, Direct-drive, PM alternator	3-Blade upwind, Optimized fixed pitch and blade length, active speed control, Direct-drive, PM alternator

Performance data for the Comm. was taken from the data sheet provided by the manufacturer Bergey [28], whilst performance data for the two locally manufacured turbines was measured and provided by the organization Comet-ME [29] (DIY) and by Gitano-Briggs [30] (DIY opt.).

Figure 5-3 shows the Weibull wind distribution (scale parameter A = 5,58 m/s, form parameter k =1,73) for a generic site with annual mean wind speed of 5 m/s as well as the normalized performance curves of the three turbines. Both locally manufactured turbines perform better at lower wind speeds, especially the DIY opt., which reaches its power peak at a wind speed of 7 m/s. In contrast, the smaller Comm. performs better at higher wind speeds and reaches its peak power at 13 m/s. The DIY and the Comm. use a passive furling control mechanism. They both start furling at around 13 m/s. The DIY opt. requires an active speed control mechanism that effectively reduces the power output above 7 m/s wind speed, as due to the increased blade length the centrifugal load would reach destructively high values for higher wind speeds.

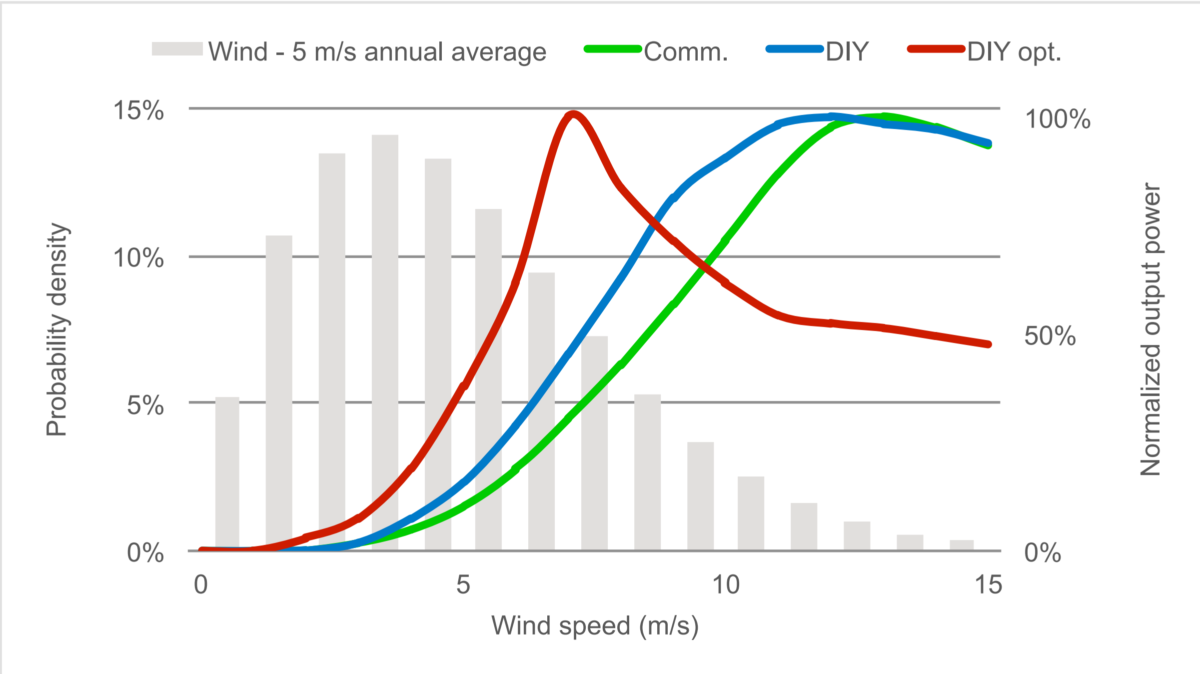


Figure 5-3 Performance curves of three different turbine types

Figure 5-4 compares the power density of the three turbines. Due to its smaller diameter the Comm. clearly outperforms the other machines at higher wind speeds and at its maximum power point. Still, the diagram shows the big benefit of the DIY opt. at low wind speeds between 3-7 m/s.

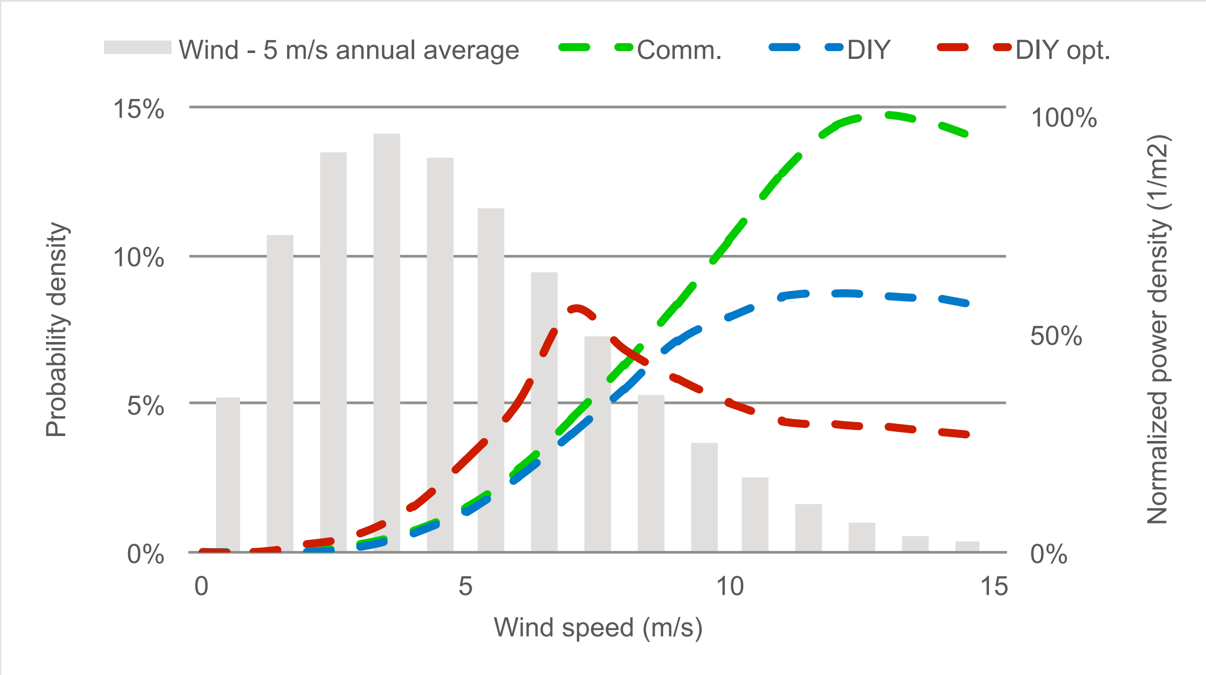


Figure 5-4 Power density of three different turbine types

Solar

A standard crystalline silicon solar module with an approximate efficiency of 15%, glass module cover and temperature coefficient of -0.47 %/°C was used.

5.2.2 Linking energy resources and technical specifications

For the *urbs* model, the timeseries for intermittent energy resources like wind and solar has to be normalized to a maximum value of 1, relative to the maximum capacity. This assures that the non-linear behavior of intermittent processes is already incorporated within the input timeseries of the respective energy resource.

Wind

The wind time series from Chapter 2.5 was linked to the performance curve of the three turbines introduced in chapter 5.2.1 in order to generate a power output timeseries. Finally, this power output timeseries was normalized, by dividing every timestep of the power output timeseries by the maximum power output. So, the wind power timeseries reaches value 1 for the wind speed that prevails at the modeled turbine's maximum power output and already incorporates both the intermittent wind resource and the non-linear performance curve of the modeled turbines.

Solar

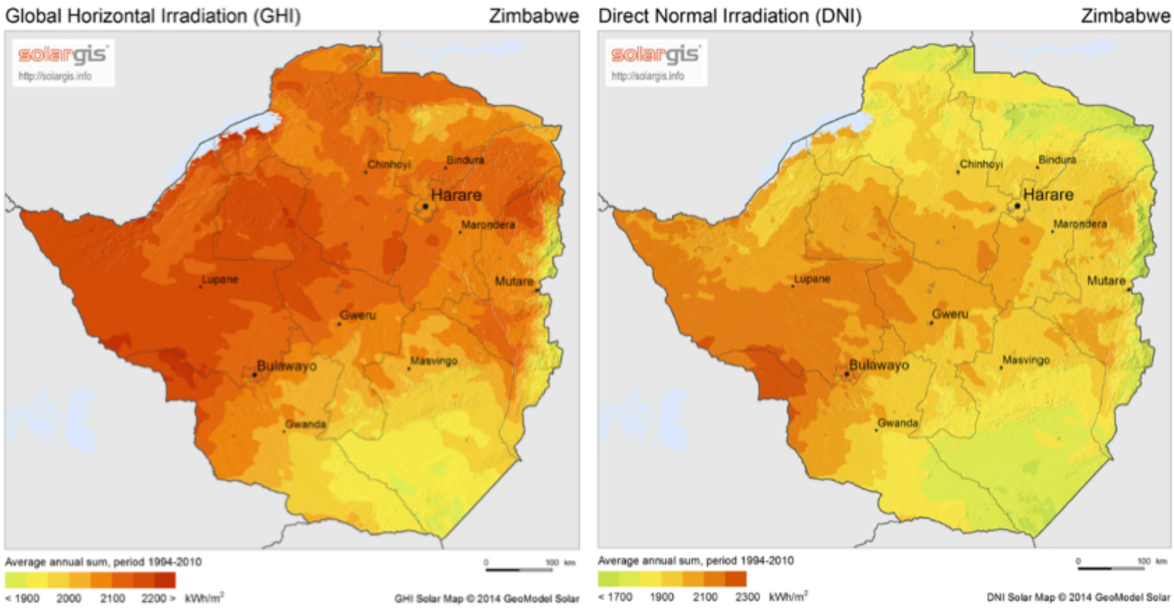


Figure 5-5 Irradiation maps of Zimbabwe [31]

Zimbabwe´s solar resource is not exceptionally varied and the countries´ annual incident solar radiation exceeds 2100 kWh per square meter. Whilst in the south-eastern part of the country as well as in the eastern and northern mountainious areas the annual radiation partly drops below 2000 kWh per square meter (see Figure 5-5), the three sites Harare, Banket and St. Ruperts show very similar solar radiation profiles. Therefore the same solar radiation time series, based on the solar radiation of Harare, was considered as input parameter for all three sites for *urbs*.

The normalized time series for solar was obtained from the online solar tool "PVWatts Calculator" from NREL [32]. Based on the local solar radiation of Harare (17.92° S, 31.13° E) and a user-defined system size it provides an hourly power output timeserie for the standard crystalline silicon solar module presented in chapter 5.2.1. By dividing the value of every time step of the power output timeseries by the system size one can generate the normalized solar capacity timeseries required by *urbs*.

5.3 Economic data of the hybrid system components

Finally, *urbs* requires economic data of each of the system components. Table 5-3 sums up the initial economic input parameters and their respective values that were used in the *urbs* model: fixed costs for required investment per capacity (inv-cost), fix-cost per capacity (fix-cost) and variable costs per output (var-cost) for operation and maintenance (O&M) as well as interest rate (wacc), depreciation and fuel cost. Storage is characterized by capacities both for energy content and charge/discharge power. Both capacities have independent sets of investment, fixed and variable cost parameters.

Table 5-3 Economic data of hybrid energy system components

Technology	Inv-cost	Fix-cost	Var-cost	Wacc	Depreciation	Fuel cost
Commercial wind	2500 USD/kW	5% of Inv-cost per a	0.02 USD/kWh	0.15	20a	-
DIY wind/ DIY opt. wind	2300 USD/kW	5% of Inv-cost per a	0.06 USD/kWh	0.15	20a	-
Solar	1250 USD/kW	5% of Inv-cost per a	0.03 USD/kWh	0.15	20a	-
Diesel	240 USD/kW	30 USD/kW/a	0.03 USD/kWh	0.15	20a	0.11 USD/kWh
Storage (charge/discharge power)	1000 USD/kW	-	-	0.15	20a	-
Storage (energy content)	600 USD/kWh	5% of Inv-cost per a		0.15	20a	-

The first reference for the investment costs of the Comm. was the cost of the Bergey XL.1, which is availbable for 6000 USD, including the cost for a selfmade tower (turbine: 4800 USD, tower: 1200 USD). The costs for the DIY and the DIY opt. were derived from manufacturing a 1kW Piggott turbine in Ethiopia [20] and the results of the on-site research in Zimbabwe (see chapter 4.1). They include also a selfmade tower as well as labor costs, altogether total costs to manufacture a 1kW Piggott turbine are 3050 USD.

As the costs of 6000 USD for the Bergey Comm. signify extremely high costs per installed capacity, further research was made and finally a cheaper 1 kW Comm. from the Chinese manufacturer HYE, which is available for 2500 USD [33], also including the 1200 USD selfmade tower was used as investment cost in the *urbs* model for the commercial turbine. The investment cost of a DIY can be lowered if not considering labor during the manufacturing process [34], which is realistic if the turbine and the tower e.g. are built during a wind turbine construction course. Therefore, the finally used investment costs for DIY and DIY opt. were 2300 USD (turbine: 1300 USD, tower: 1000 USD).

Table 5-4 Investment cost scenarios for different turbine types

Technology	Inv-cost high costs	Inv-cost low costs, as used in *urbs* model
Commercial wind	6000 USD/kW	2500 USD/kW
DIY wind/ opt. DIY wind	3050 USD/kW	2300 USD/kW

Investment costs for solar were assumed as 1250 USD/kW [35]. For the Diesel generator, they were assumed as 240 USD/kW. Investment costs for storage were assumed as 1000 USD/kW (charge/discharge power) and as 600 USD/kWh (energy content) [36].

Installation cost, delivery and transportation cost, as well as shipping prices and import taxes were not considered for none of the system components. As DIY are expected to have slightly higher O&M cost than Comm. [34], the variable cost were increased by a factor of 3. An interest rate of 0.15 was found to be realistic for projects Zimbabwe [37]. Depreciation of 20 years was defined by the typical lifetime of a Comm. and indicates the approached project lifetime. Possible replacement cost e.g. for DIY or batteries are included in the respective initial investment cost, using the interest rate to discount future expenses on replacements. Therefore, the same depreciation could be used for all system components.

Figure 5-6 illustrates the rise of diesel prices in Zimbabwe during the past decade from 0.059 USD/kWh up to 0.137 USD/kWh in 2014 [38]. The 2016 Diesel price 0.11 USD/kWh was found during the research trip and does not reflect the price trend indicated by World Bank. For the *urbs* model a diesel price of 0.11 USD per kWh was used as input value.

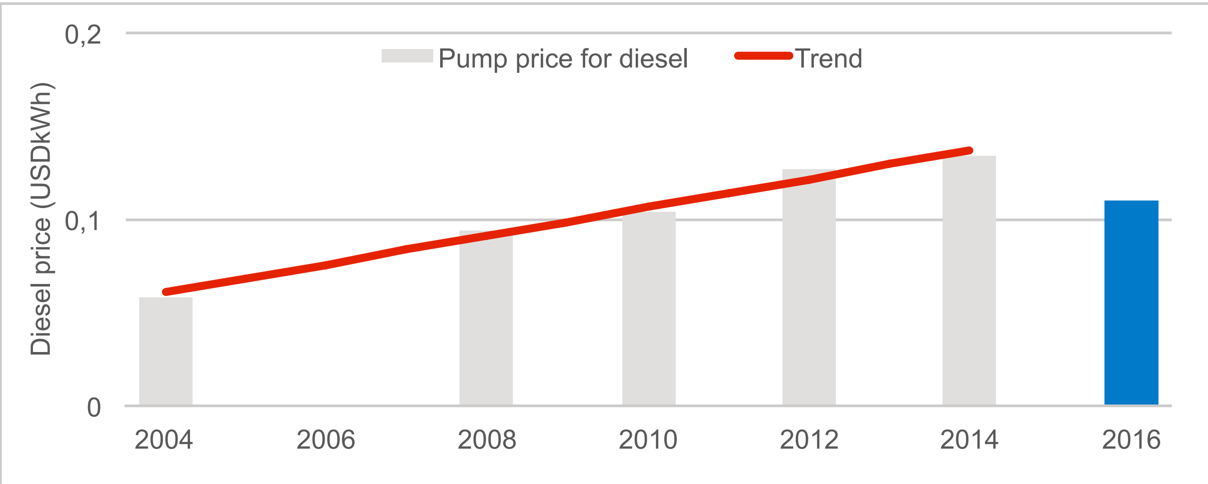


Figure 5-6 Diesel prices in Zimbabwe since 2004

5.4 Optimization results and discussion

Urbs was used to identify the optimal technology for the three sites Harare, Banket and St. Ruperts. The focus of the optimization was on the effects of including small-scale wind turbines to decentralized hybrid energy systems as well as on effects of choosing either locally manufactured or commercial turbines. Therefore different scenarios were analyzed and sensitivities to the following key parameters were established:

- Annual average wind speed: from 0 m/s to 10 m/s
- Turbine type: locally manufactured (DIY), commercial (Comm.), locally manufactured and optimized for low wind speed (DIY opt.)
- Load profiles: water pumping only during day, during day and night and only during night
- Diesel fuel prices

Based on the optimized total system cost, the Levelized Cost of Electricity (LCOE) was computed for each of the modeled scenarios using the formula

$$LCOE = \frac{Annualized\ total\ system\ cost\ (USD/a)}{Total\ annual\ energy\ demand\ (kWh/a)} \quad \text{Eq. 7}$$

where the annualized total system cost are the sum of all annualized costs of each cost type and each system component and the total annual energy demand is 29311.6 kWh/a (see chapter 5.1)

5.4.1 Base case

DIY wind turbine at 10 meters hub height in Harare, Banket and St. Ruperts, base load scenario

Figure 5-7 and Figure 5-8 show the power output and the storage levels of a Solar-Diesel-Battery hybrid system over the same two exemplary days as in chapter 5.1. This system was identified as the optimal hybrid system for all three sites. It satisfies the demand of the base load scenario with minimal costs. The *urbs* model was allowed to install wind power capacities, but it did not consider wind as an option under the wind conditions prevailing at 10 m height; neither in Harare, with annual mean wind speeds of 2.39 m/s, nor in Banket (2.88 m/s), nor in St. Ruperts (2.95 m/s).

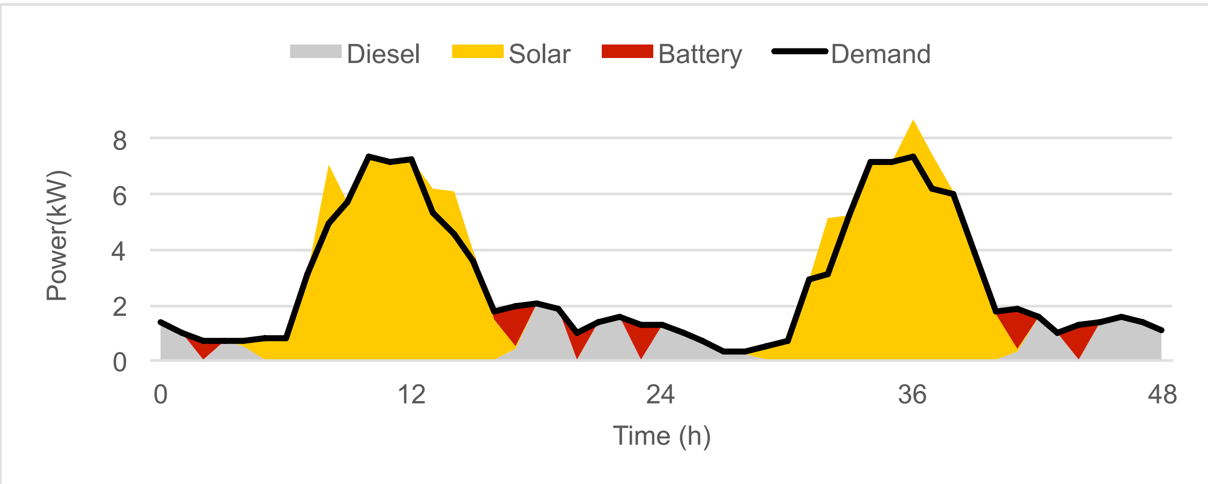


Figure 5-7 Power output of a Solar-Diesel-Battery hybrid system over two exemplary days

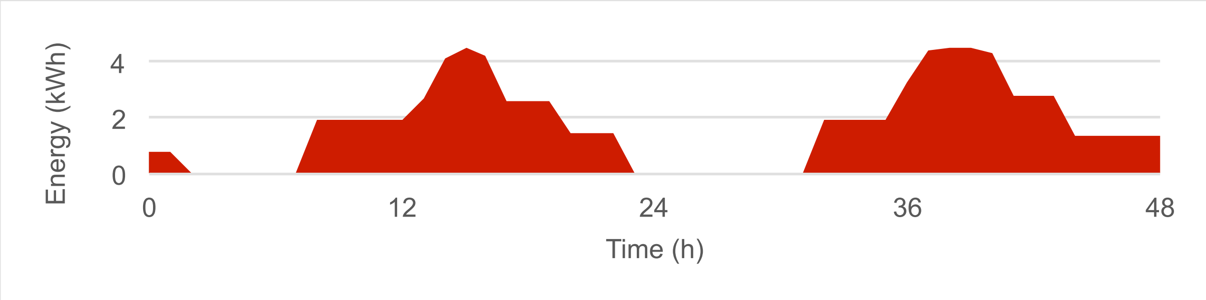


Figure 5-8 Storage levels of a Solar-Diesel-Battery hybrid system over two exemplary days

Figure 5-9 shows why *urbs* has identified the Solar-Diesel-Battery hybrid system as the optimal hybrid system. A Diesel generator can satisfy the given demand only with cost of 0.514 USD/ kWh and a Solar-Battery system comes with an even higher LCOE of 0.622 USD/kWh. In that case, with LCOE of 0.376 USD/kWh the Solar-Diesel-Battery hybrid system is by far the cheapest.

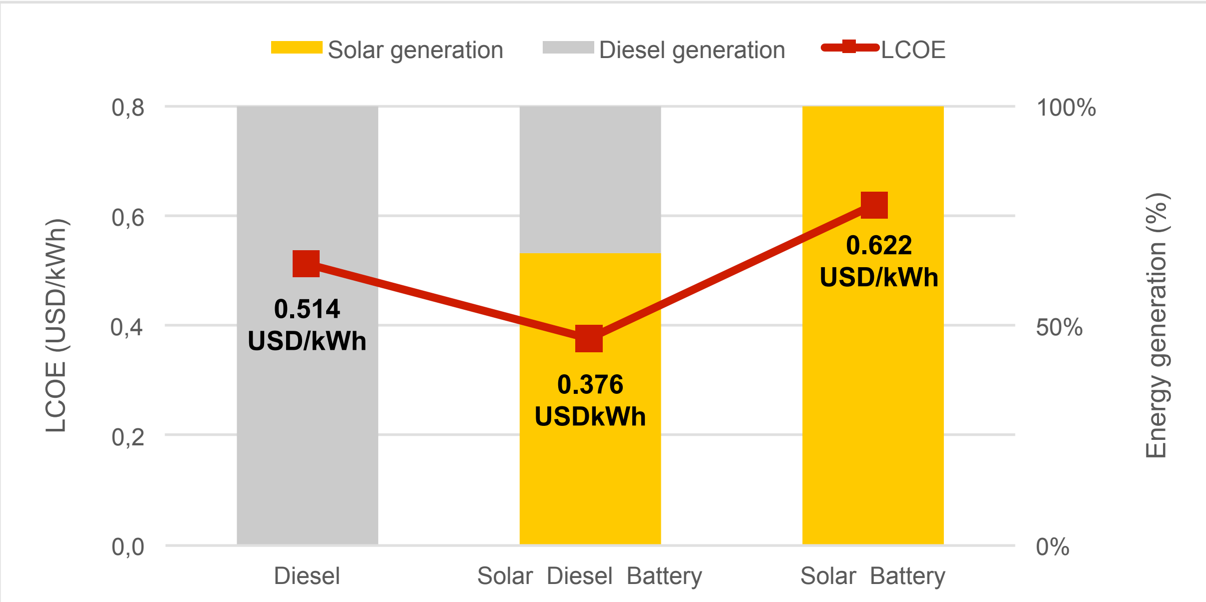


Figure 5-9 LCOE of different energy system configurations, without wind power

5.4.2 Sensitivity analysis: wind speeds

DIY wind turbine at generic wind sites with varying annual average wind speed at hub height, base load scenario

As the wind speeds at 10 m height are too low at all three sites and thus *urbs* does not considered wind power, it was investigated from which wind speeds small-scale wind turbines can play a significant role. Therefore generic wind sites with annual average wind speeds from 0 m/s to 10 m/s have been generated. The hourly one-year timeseries of Banket in 10m height above the surface has been used as a basis to extrapolate the timeseries for these generic wind sites.

Figure 5-10 displays the optimal system types for increasing annual average wind speeds. For low wind speeds a Solar-Diesel-Battery hybrid system is the optimal system, as seen before. Starting from 5 m/s a Solar-Wind-Diesel-Battery hybrid system can satisfy the demand of the base load scenario with lower costs than a Solar-Diesel-Battery hybrid system. The LCOE drops continuously with increasing wind speeds and more and more wind power capacity is considered by *urbs*.

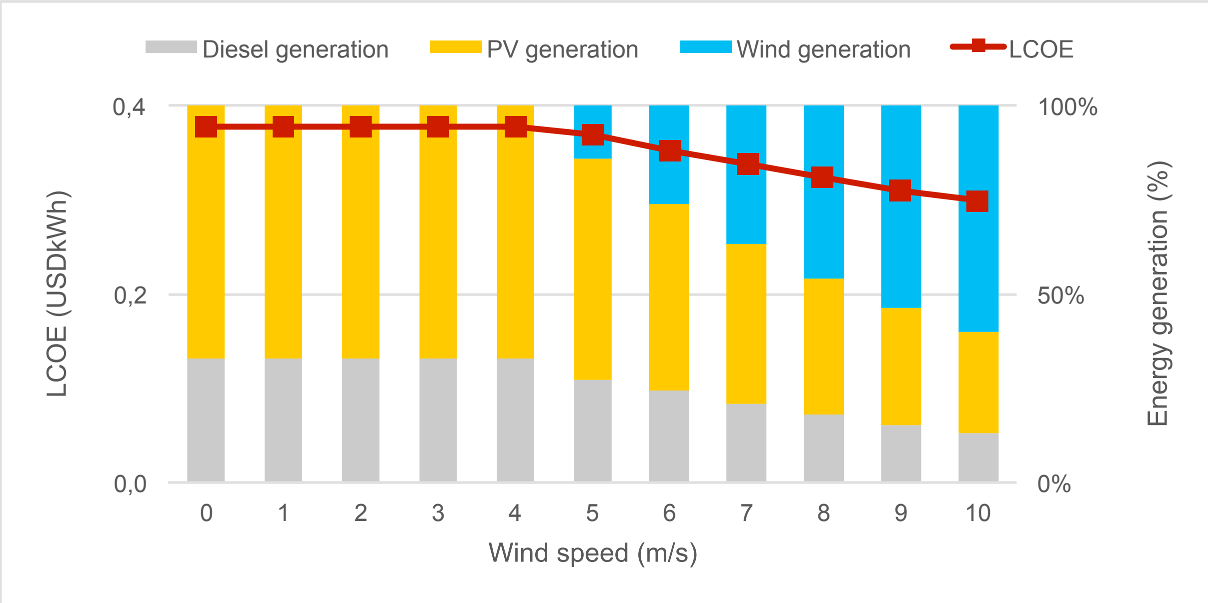


Figure 5-10 Sensivity analysis: wind speed

DIY wind turbine at a generic wind site with annual average wind speed of 5 m/s at hub height, base load scenario

Figure 5-11 compares the LCOE of different system types at a generic wind site with annual average wind speed of 5 m/s and shows why *urbs* has identified the Solar-Wind-Diesel-Battery hybrid system as the optimal hybrid system in that case. The Solar-Wind-Diesel-Battery hybrid system (0,368 USD/kWh) is slightly cheaper than the Solar-Diesel-Battery hybrid system (0,376 USD/kWh), which is the cheapest system for all sites with annual average wind speeds lower than 5 m/s. Wind-Diesel-Battery (0,472 USD/kWh) and and Solar-Wind-Battery (0,617 USD/kWh) hybrid systems are no option due to their clearly higher costs.

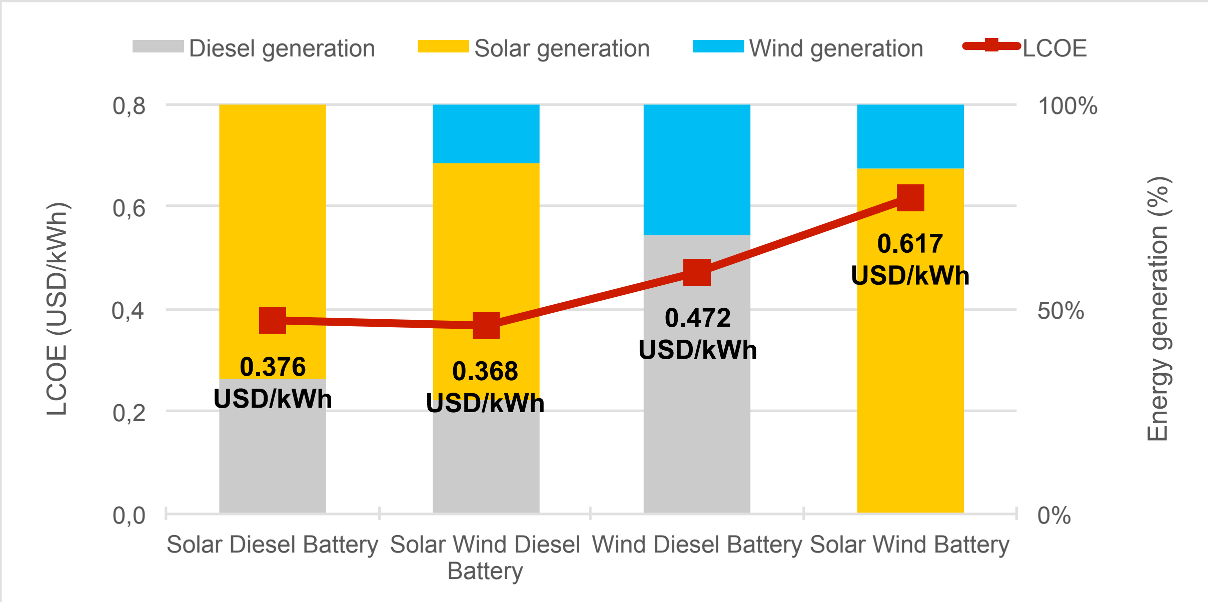


Figure 5-11 LCOE of different energy system configurations, including wind power at 5 m/s annual average wind speed

The generic wind site with annual average wind speed of 5 m/s has been used for the following sensivity analyses of chapter 5.4.3, 5.4.3 and 5.4.5.

5.4.3 Sensivity analysis: wind turbines

Different turbines at a generic wind site with annual average wind speed of 5 m/s at hub height, base load scenario

Next, the difference between the three turbine types DIY, Comm. and DIY opt. (as introduced in chapter 5.2) was investigated. Therefore, two optimizations with different pre-defined hybrid system type were performed:

- In the first optimization the *urbs* model was allowed to install capacities of solar, wind and diesel power as well as storage capacities (see Figure 5-12, Solar-Wind-Diesel-Battery). In this case, *urbs* is still not considering a Comm. to be installed at 5 m/s annual average wind speed.
- A second optimization was performed, where the *urbs* model was only allowed to install capacities of wind and diesel power and storage, no solar power capacities were allowed (see Figure 5-12, Wind-Diesel-Battery).

Depending on the turbine type and the pre-defined hybrid system type, different system configurations were identified to be optimal.

Generally, the Comm. has the lowest wind power generation share (and is not installed in the first optimization), because of both its bad performance at low wind speeds as well as its higher costs compared to the DIY / DIY opt.

The biggest wind power generation share comes with the DIY Opt., as it has the best performance at low wind speeds and thus is able to produce more energy at a site with 5 m/s annual average wind speed (see performance data from chapter 5.2) than DIY and Comm.

So, two factors lead to the different wind power capacities installed: turbine performance data and costs.

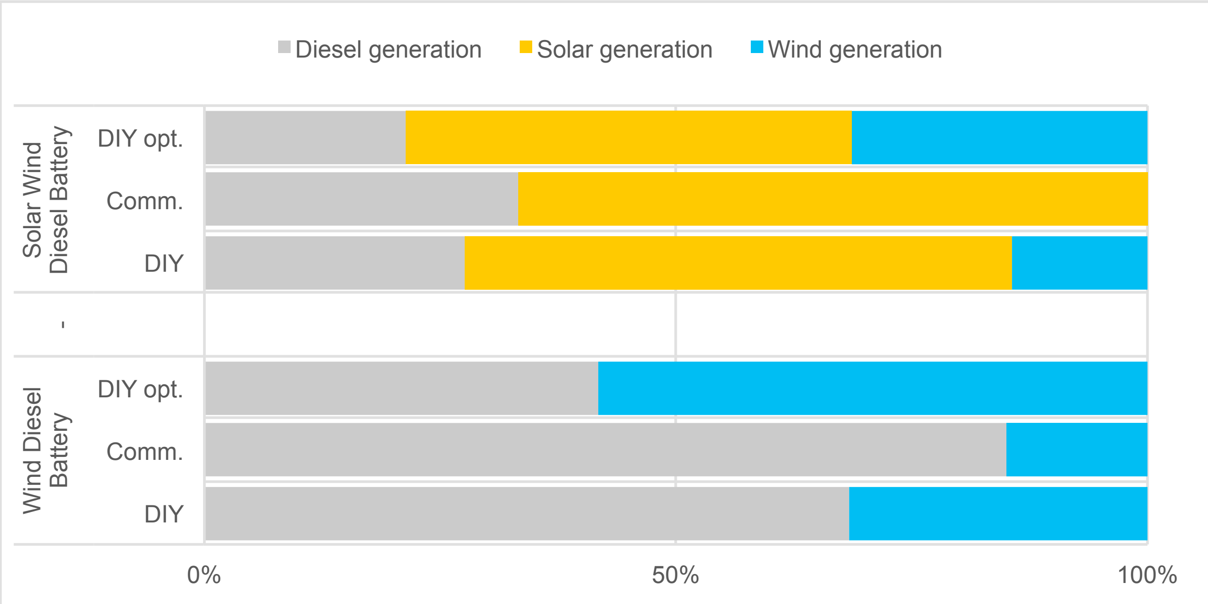


Figure 5-12 Sensitivity analysis: wind turbine

Table 5-5 compares the LCOE of the system configurations shown in Figure 5-12 above. The LCOE of of the Solar-Wind-Diesel-Battery hybrid system can be decreased from 0.368 USD/kWh to 0.347 USD/kWh if using DIY opt. instead of DIY.

As seen before, Wind-Diesel-Battery hybrid systems at sites wind annual average wind speeds of 5 m/s come with higher costs than Solar-Wind-Diesel-Battery hybrid systems. The Comm. has the highest LCOE of the three turbine types, the DIY opt. the lowest.

Table 5-5 LCOE of different wind turbine types in Solar-Wind-Diesel and Wind-Diesel hybrid systems

	DIY	**Comm.**	**DIY opt.**
LCOE (USD/kWh) Solar Wind Diesel Battery	0.368	0.376 (no wind installed)	0.347
LCOE (USD/kWh) Wind Diesel Battery	0.472	0.499	0.419

5.4.4 Sensivity analysis: loads

DIY wind turbine at a generic wind site with annual average wind speed of 5 m/s

In this section the effects of changed load scenarios (as introduced in chapter 5.1) are examined. Again, two optimizations with different pre-defind hybrid system types were performed:

- In the first optimization the *urbs* model was allowed to install capacities of solar, wind and diesel power as well as storage capacities (see Figure 5-13, Solar-Wind-Diesel-Battery).
- In the second optimization the *urbs* model was only allowed to install capacities of wind and diesel power and storage, no solar power capacities were allowed (see Figure 5-13, Wind-Diesel-Battery).

Figure 5-13 shows that, depending on the load scenario and the pre-defined hybrid system type, different system configurations were identified to be optimal. Generally, higher loads at night require increased storage or increased Diesel capacities. As it can be seen in the figure, *urbs* favors the installation of additional Diesel capacities in that case, because the given demand can be satisfied at lower costs by increasing Diesel capacities than by increasing storage capacities.

Only in load scenario two, the wind generation share increases slightly by 2% compared to the base scenario. In that case, the Diesel generation decreases for the Wind-Diesel-Battery hybrid system. As the major part of the wind resource is available during daytime (see chapter 2.3), a further shift of the loads completely to the night as in load scenario 3 again just favors the installation of additional Diesel capacities.

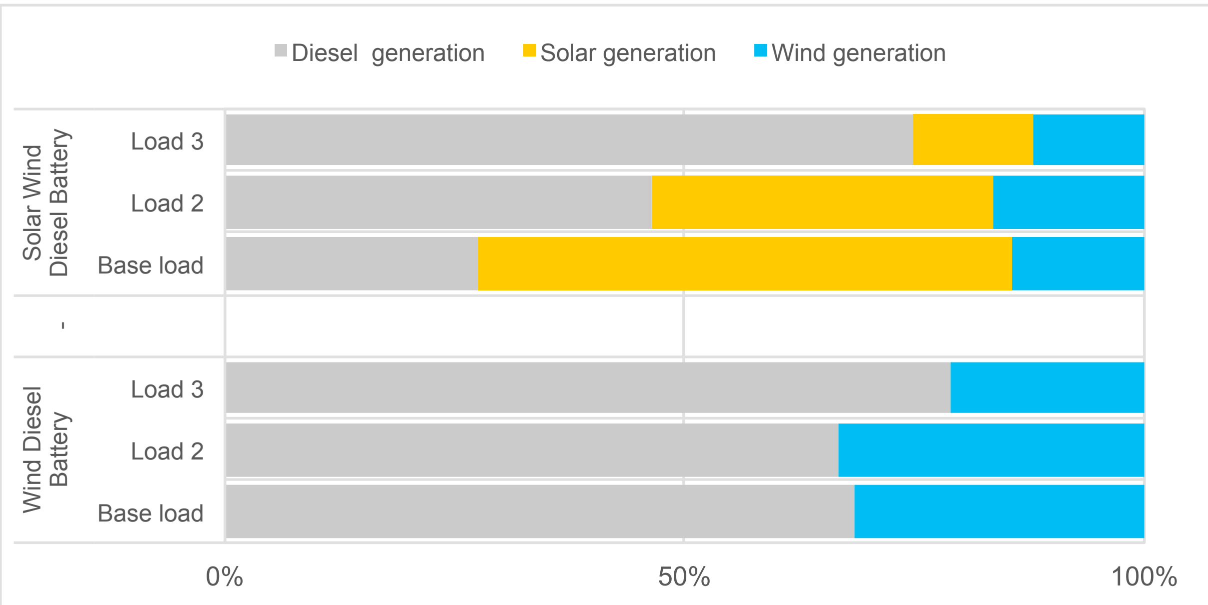


Figure 5-13 Sensivity analysis: loads

Table 5-6 compares the LCOE of the system configurations shown in Figure 5-13 above. If the loads are shifted towards the night, the LCOE increases for Solar-Wind-Diesel-Battery hybrid system. The Wind-Diesel-Battery hybrid system in load scenario 2 comes with a decreased LCOE of 0.447 USD/kWh compared to 0.472 USD/kWh in the base scenario. Load scenario 3 comes with the highest LCOE for both system types.

Table 5-6 LCOE in different energy system configurations, depending on the load

	Base load	**Load 2**	**Load 3**
LCOE (USD/kWh) Solar Wind Diesel Battery	0.368	0.402	0.509
LCOE (USD/kWh) Wind Diesel Battery	0.472	0.447	0.521

5.4.5 Sensivity analysis: fuel prices

DIY wind turbine at a generic wind site with annual average wind speed of 5 m/s at hub height, base load scenario

Diesel generators are still the standard backup system for power supply in many rural communities. Often long travels are necessary to guarantee the supply with Diesel fuel and can increase the fuel prices drastically. Therefore, this section investigates the effects of changed Diesel fuel prices.

Figure 5-14 shows the effects of increasing Diesel fuel costs on a Solar-Wind-Diesel-Battery hybrid system. The higher the Diesel fuel costs the higher the energy generation share of solar and wind. The “lost” Diesel capacity is mainly compensated by increased solar capacities and does not really force wind into the systems. Even for a very high fuel price of 0.81 USD/kWh the *urbs* model considers a small capacity of Diesel power.

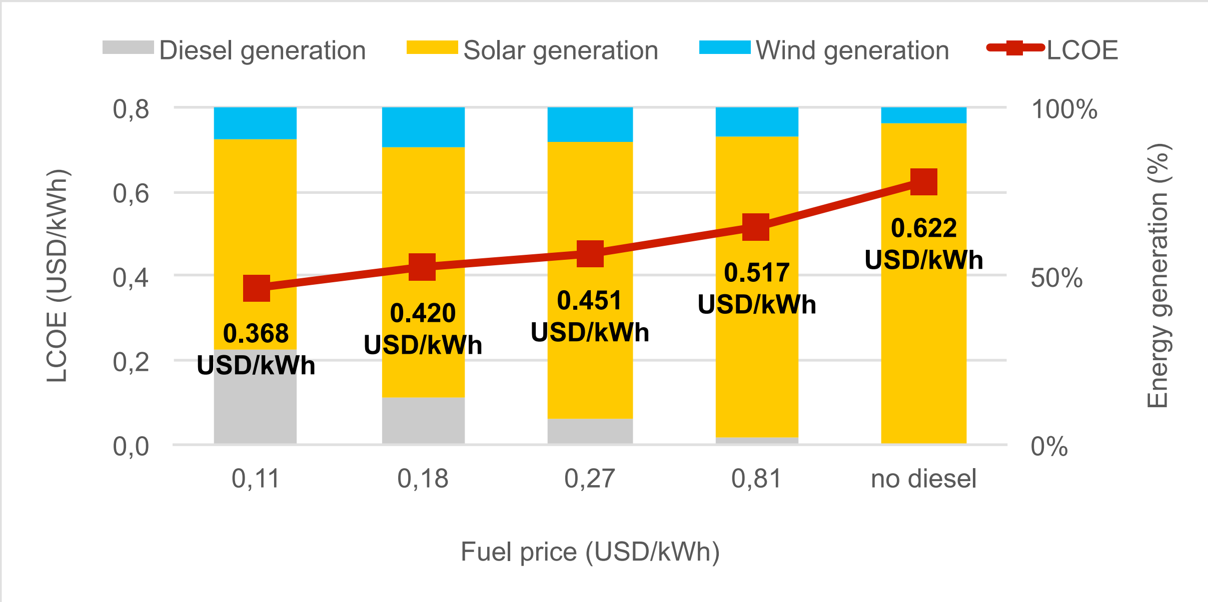


Figure 5-14 Sensivity analysis: increasing Diesel fuel price, Solar-Wind-Diesel-Battery hybrid system

Figure 5-15 displays a Wind-Diesel-Battery hybrid system. As for the Solar-Wind-Diesel-Battery hybrid system LCOE is higher if less Diesel is installed. This results from the fact that under the given solar and wind resources the total capacity that has to be installed to satisfy the demand increases with an increasing share of Renewables. I.e. that for a Wind-Diesel-Battery hybrid system 41 kW of wind power capacity would be necessary to satisfy the demand if no Diesel capacity is installed, compared to 10 kW Diesel capacity and 5 kW wind power capacity if Diesel fuel is available for 0.11 USD/kWh.

The figure shows also the high dependence of wind power from additional power sources. The LCOE of the Wind-Diesel-Battery hybrid system is about 290% higher if wind is the only source for energy generation, compared to the medium fuel price scenario of 0.27 USD/kWh and even almost 500% higher, compared to the base Diesel fuel price scenario of 0.11 USD/kWh.

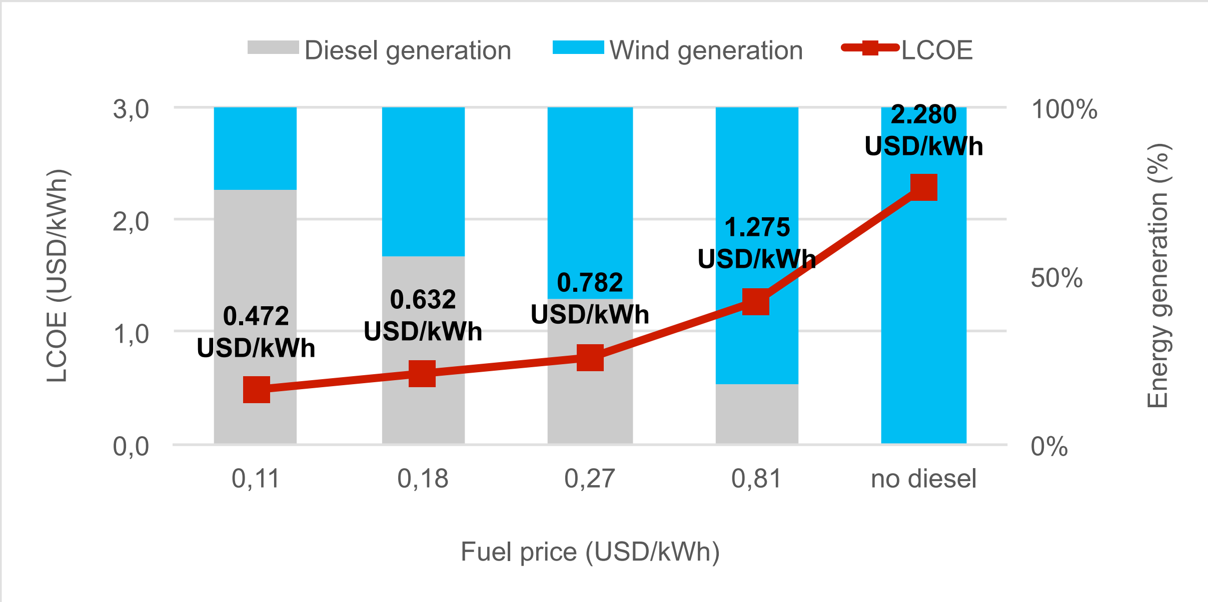


Figure 5-15 Sensivity analysis: increasing Diesel fuel price, Wind-Diesel-Battery hybrid system

5.4.6 Optimized base case

DIY opt. wind turbine at 20 meters hub height in Harare, Banket and St. Ruperts, base load scenario

It was found that, starting from an annual mean wind speed of 5 m/s DIY can play a role. None of the three sites exceeds this wind speed, even at 50 meters height the annual mean wind speeds are lower than 5 m/s at all three sites (Harare: 4.0 m/s, Banket: 4.3 m/s, St. Ruperts: 4.8 m/s). However, it was also found that DIY Opt. could already play a very significant role at 5 m/s annual average wind speed. In a Solar-Wind-Diesel-Battery hybrid system the DIY Opt. provides about 30% of the generated electricity.

Therefore, it was investigated if a DIY opt. already can be installed below 5 m/s annual mean wind speed. Annual average wind speed at 20 meters above the surface at the three sites (Harare: 3.2 m/s, Banket: 3.7 m/s, St. Ruperts: 3.9 m/s) was used as reference height. This hight can be considered as the highest possible hub height of a small-scale wind turbine and therefore describes a still realistic scenario for the three sites, in contrast to the generic 5 m/s annual average wind speed scenario, which is not realistic for none of the three sites.

Figure 5-16 shows the optimized system configurations for Harare, Banket and St. Ruperts. For Harare the annual average wind speed is still too low at 20 meters and a Solar-Diesel-Battery hybrid system can satisfy the demand at lowest cost there. In Banket (1 kW wind capacity installed) and in St. Ruperts (1.8 kW wind capacity installed) Solar-Wind-Diesel-Battery hybrid systems were identified to by the optimal system. DIY Opt. can provide a small share of the energy generation in these two sites.

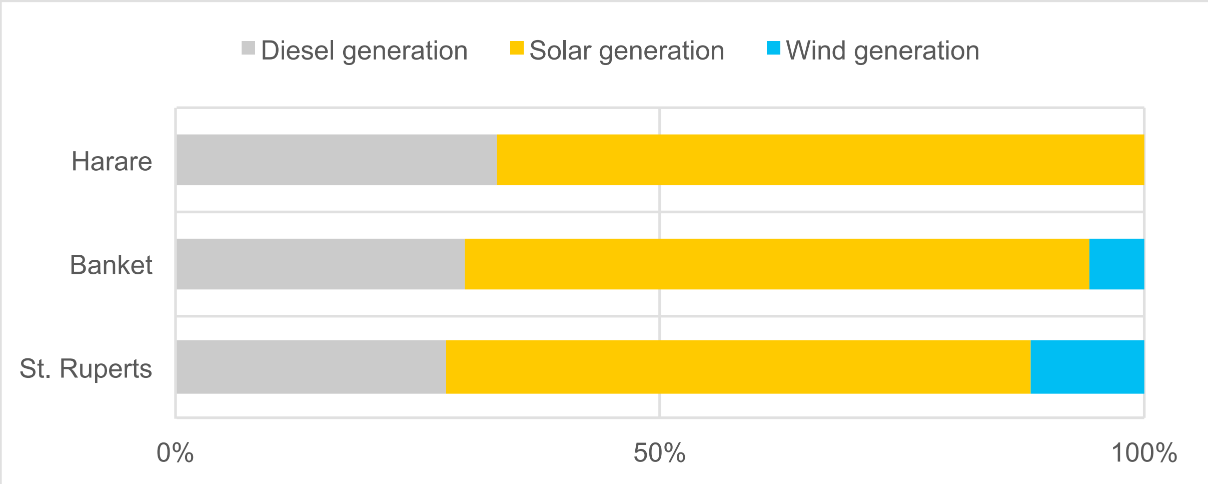


Figure 5-16 Optimized energy system configurations for optimized base case at the research sites

Table 5-7 LCOE of the optimized base caseshows the LCOE and the annualized cost of the thre optimized system configurations. Installing DIY opt. in Banket brings just a very slight decrease of costs. In St. Ruperts the costs decrease a bit more. But also there, no significant decrease in costs can be achieved by installing wind power.

Table 5-7 LCOE of the optimized base case

	Harare	**Banket**	**St. Ruperts**
LCOE (USD/kWh)	0.3764 (no wind installed)	0.3757 (wind installed)	0.3709 (wind installed)
Annualized cost (USD/a)	11035	11012	10872

Figure 5-17 compares the total system cost of the system installed in every site, calculated by the sum of all annualized costs of each cost type and each system component. Thus, total system costs represent the annual expenses incurred in order to meet the given load. Annuity factor AF is derived from the parameters interest rate (wacc) i and deprecitation period n (see chapter 5.3) using the formula

$$AF = \frac{(1+i)^n * i}{(1+i)^n - 1} \qquad \textbf{Eq. 8}$$

Installing additional wind power capacities increases both O&M costs and investment costs. However, the savings due to decreased Diesel fuel costs exceed the additional costs and altogether the total costs, and so the LCOE decrease.

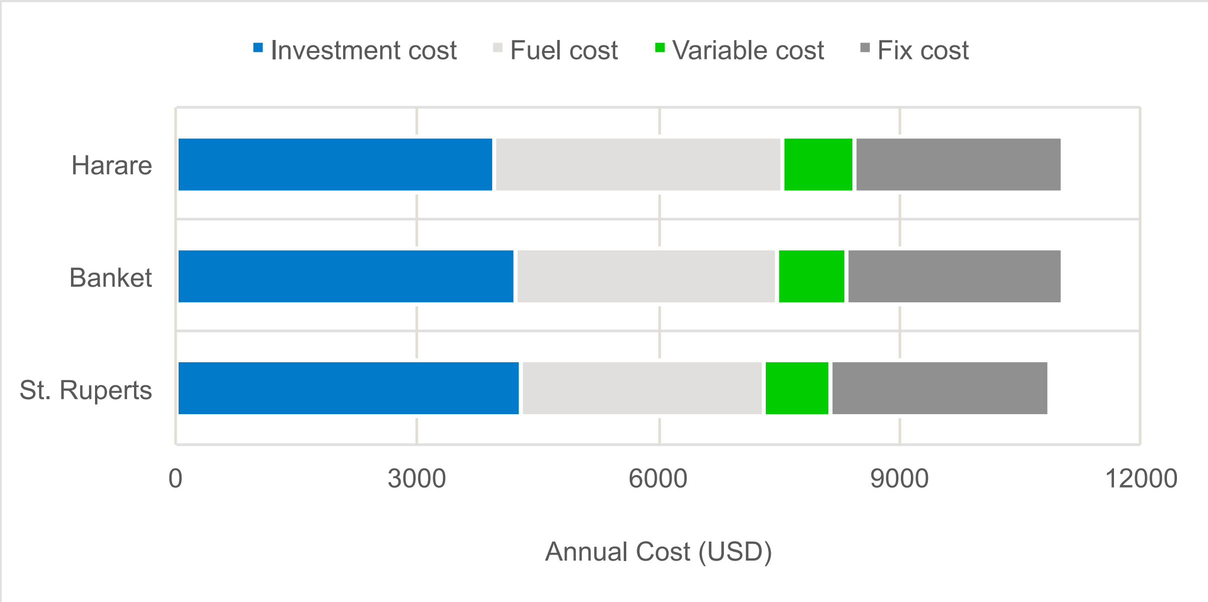


Figure 5-17 Total annualized system costs of the optimized base case

Figure 5-18 and Figure 5-19 show the power output and the storage levels of a Solar-Wind-Diesel-Battery hybrid system over the same two exemplary days as in chapter 5.1. and as in chapter 5.4.1. This plotted system was identified as the optimal hybrid system for St. Ruperts. Wind power now provides a small share of the energy generated. However, the power output is low, compared to the given demand.

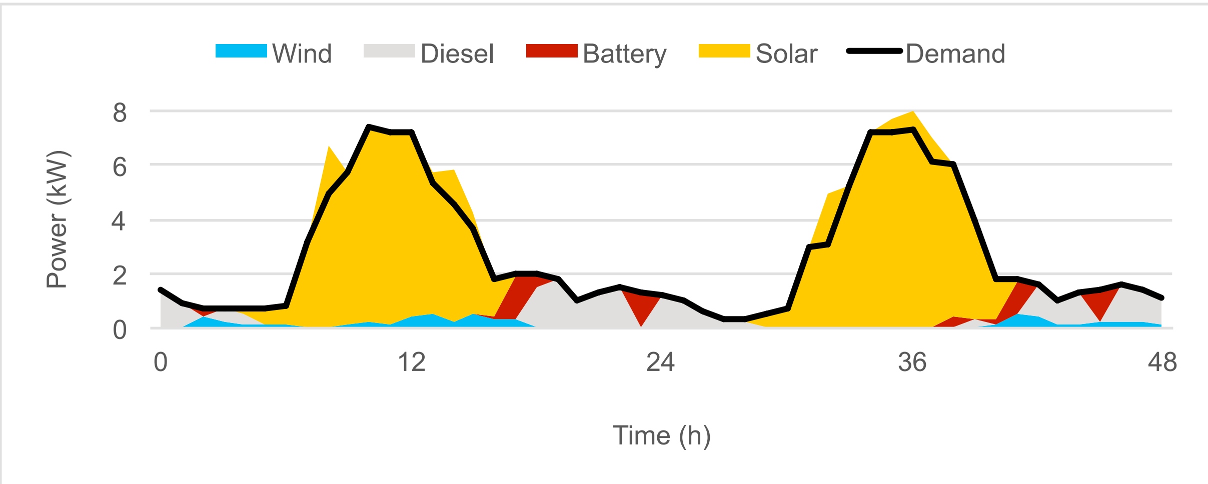


Figure 5-18 Power output of a Solar-Wind-Diesel-Battery hybrid system over two exemplary days

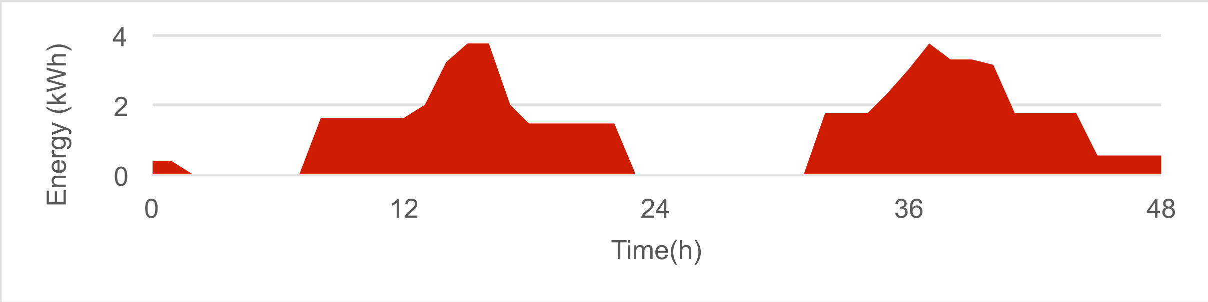


Figure 5-19 Storage levels of a Solar-Wind-Diesel-Battery hybrid system over two exemplary days

5.5 Summary of the optimization results

Solar-Diesel-Battery hybrid systems were identified as the optimal systems for all the three sites. DIY wind turbines can only play a role at sites with annual average wind speeds of 5 m/s and higher, which are not found at the three sites. Commercial small-scale wind turbines are still critical at 5 m/s sites due to their very bad performance at low wind speeds. A DIY wind turbine that is optimized for the use in low wind speeds (DIY opt.) could be considered in Banket or St. Ruperts. However, the decrease in costs in that case is small and the additional effort of adding a wind turbine to the hybrid system is questionable.

6 Conclusion and outlook

The thesis analyzed the feasibility of power supply by small-scale wind turbines in three sites (Harare, Banket, St. Ruperts) in Zimbabwe and comes to the result that there is no potential existing for this technology at the research sites. The wind potential was analyzed using a low-cost wind measurement station for short-term as well as local expert knowledge and GIS for long-term data. It was found to be low for each of the three sites. Besides the wind potential, the feasibility of local manufacturing of small-scale wind turbines was analyzed by on-site research and the Jesuit-led vocational school "St. Peters Kubatana Technology Centre" in Harare was found to offer optimal prerequesites for the realization of a pilot project. Finally, Solar-Diesel-Battery hybrid systems were identified as the optimal technology for the power supply of the three research sites using the linear programming model *urbs*.

So, whilst it would be quite possible to realize a pilot project of manufacturing a small-scale wind turbine in cooporation with the "St. Peter´s Kubatana Technology Centre" in Harare, the wind potential at the research sites is too low and makes the installation of wind power capacities unfeasible. As the thesis also showed that small-scale wind turbines can decrease the total cost of a decentralized energy system at sites with higher wind speeds and that Solar-Wind-Diesel-Battery would be the optimal systems for such sites it could be still an option to establish contacts with partners in regions of better wind speeds, e.g. in the southern part of the country. If more suitable places for the installation of wind power capacities can be identified, the *urbs* model could be applied on these sites in order to design optimal hybrid energy system including small-scale wind turbines.

However, even if a good wind site can be identified and a pilot project would be successful, the scalability and thus the potential of business models based on the manufacturing of wind turbines is problematic, as Zimbabwe shows lack of wind potential in most parts of the country. So, also job creation and local capacity building as drivers of the local manufacturing of small-scale wind turbines has his limits in this country.

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A2 Components and costs of the wind measurement station

Table A below shows the components and their costs as used in the basic setup of the self-made wind measurement stations that have been installed in Zimbabwe. The costs correspond to the prices that were paid to the respective sellers in fall 2016 and include shipping cost.

Table A Components and costs of the wind measurement station

Article	**Price in €**
Raspberry Pi Zero chip and accesoires	10,50
Micro SD card (8GB)	4,00
USB to Micro-USB cable	5,00
OTG Micro-USB (male) to USB (female) cable	2,00
Step-down unit (12V to 5V USB converter)	11,00
UMTS stick	13,00
Prepaid Sim Card (10 $ credit)	9,50
Solar charge controller (10A, 12V)	9,00
Lead battery (12V, 7.2 Ah)	18,00
Polycristalline solar panel ($20W_p$)	29,00
Wind speed sensor	46,50
Junction box and accesoiries for installation	30,00
Miscellaneous electrical components (resistor, breadboard, connecting wires and cables, screws and pins, etc.)	5,00 *(estimated)*
Total Cost	**192,50**

Addtional cost

- Extra costs for a slightly more expensive UMTS stick (27,00 €) and an additional antenna (18,00 €) in order to enhance the mobile reception in St. Ruperts, as poor reception was expected there.
- Extra costs for a second wind sensor (46,50 €), both in St. Ruperts and in Banket, for improved wind measurements.
- Extra costs for poles in order to reach the required height of 10 meters for the measurements: a foldable pole in Banket (130,00 €); a fixed pole in St. Ruperts (40,00 €); no extra costs for a pole in Harare

The following Table B summarizes the total costs of the wind measurement stations at each site.

Table B

Location	Total Costs
Harare	192,50 €
Banket	369,00 €
St. Ruperts	310,00 €

Finally, to access the Raspberry Pi Zero with a Laptop, a few cheap electronic components are are necessary to bring:

- USB-Hub (min. 2 ports): 5,00 €
- USB to Ehternet adaptor: 8,00 €
- Ethernet cable: 4,00 €

A3 Examplary course program of vocational training centres

MINISTRY OF HIGHER AND TERTIARY EDUCATION, SCIENCE AND TECHNOLOGY DEVELOPMENT

ST PETER'S KUBATANA TECHNOLOGY CENTRE

2016 INTAKE IN PROGRESS

FOR N.C COURSES

Qualifications: Five "O" levels subjects including Maths, English and Science
Duration 3 years including one year of industrial attachment during the second year of training
Fees $250-00/ term plus registration fees (non refundable) of $20.00

- NC Machineshop Engineering (Fitting & Turning)
- N.C in Motor Vehicle Mechanics
- N.C in Automobile Electrics and Electronics (Auto-Electrics)
- N.C in Wood Machining and Manufacturing Technology.
- N.C in Carpentry and Joinery
- N.C in Brick and Block laying
- N.C in Information Technology

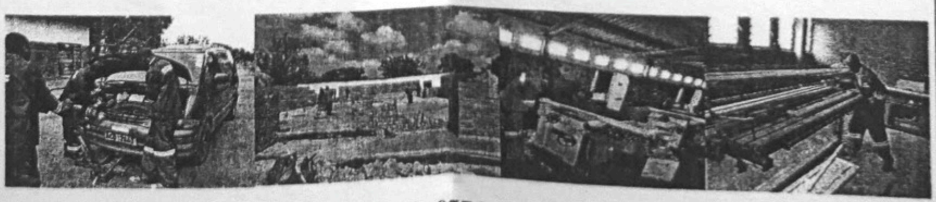
FOR N.F.C COURSES

Qualifications: four years secondary education
Fees $200.00 per term plus registration fees $20.00

- N.F.C Machineshop Engineering (Fitting & Turning)
- N.F.C Car Maintenance
- N.F.C Welding Techniques
- N.F.C Cabinet Making
- N.F.C Carpentry and Joinery
- N.F.C Brick and Block laying
- N.F.C Information Technology

WEEKEND CLASSES ALSO AVAILABLE

College Certificates Welding Techniques, Cosmetology, Computers



04-611513, 04-612775, 0712 556 140, 0776 286 142

A4 Monte Carlo probabilities

Household Time	Lighting 125 W	Phone 5 W	TV 80 W	Fan 60 W	Iron 1500 W	Fridge 130 W
0	10%	0%	0%	0%	0%	20%
1	10%	0%	0%	5%	0%	20%
2	10%	0%	0%	0%	0%	20%
3	10%	0%	0%	0%	0%	30%
4	50%	0%	0%	0%	0%	30%
5	50%	0%	0%	0%	0%	30%
6	20%	0%	0%	0%	0%	60%
7	20%	0%	0%	0%	0%	60%
8	20%	0%	0%	0%	0%	70%
9	0%	0%	0%	0%	0%	70%
10	0%	0%	0%	0%	0%	20%
11	0%	0%	0%	0%	0%	20%
12	0%	0%	0%	0%	0%	20%
13	0%	0%	0%	0%	0%	20%
14	0%	0%	0%	5%	0%	20%
15	0%	0%	0%	0%	0%	20%
16	0%	0%	0%	0%	0%	30%
17	0%	0%	0%	0%	0%	50%
18	20%	50%	50%	0%	0%	70%
19	40%	50%	90%	40%	20%	70%
20	90%	10%	90%	40%	20%	70%
21	90%	0%	80%	50%	0%	40%
22	70%	0%	10%	50%	0%	30%
23	70%	0%	10%	0%	0%	30%

High School Time	Lighting 1800 W	Phone 5 W	TV 80 W	Fan 60 W	Science Lab 1000 W	Water Pump 5500 W
0	0%	0%	0%	0%	0%	0%
1	0%	0%	0%	0%	0%	0%
2	0%	0%	0%	0%	0%	0%
3	0%	0%	0%	0%	0%	0%
4	0%	0%	0%	0%	0%	0%
5	0%	0%	0%	0%	0%	0%
6	0%	0%	0%	0%	0%	0%
7	0%	0%	0%	0%	0%	0%
8	50%	0%	0%	0%	0%	50%
9	50%	0%	0%	0%	0%	50%
10	50%	0%	20%	40%	0%	90%
11	50%	0%	20%	40%	50%	90%
12	50%	50%	20%	40%	50%	30%
13	50%	40%	20%	40%	50%	30%
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18	0%	0%	0%	0%	0%	0%
19	0%	0%	0%	0%	0%	0%
20	0%	0%	0%	0%	0%	0%
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22	0%	0%	0%	0%	0%	0%
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A5 Digital appendix

- Final presentation
- Midterm presentation
- Written report
- Relevant data files
- *Urbs* model
- Used sources