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Feasibility Study to determine optimal capacity of hybrid wind/solar PV projects in Pakistan

Study Report
September 2021

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Renewable Energy and Energy Efficiency II - Pakistan

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Executive Summary

This report analyses the technical details for combinations of wind power and PV power production at the same site in the "Wind Corridor" in Sindh region. Currently, the sites in the mentioned region are producing power based on wind power technologies. Each site has a connection to the public grid and this connection allows for the evacuation of an agreed and limited capacity. The target of adding PV Power production at the same site is to use the high local solar irradiation to support wind power production without exceeding the agreed evacuation capacity. This, on the one hand, will lead to an increased amount of energy to be evacuated along identical installations, but will in many cases also ask for curtailments to keep the limit.

A site in the Wind Corridor with a wind power capacity of 50 MW has been defined and a layout has been prepared based on available measurement data for the wind conditions.

A first analyses, based on a densely with PV modules packed site, showed that even for this case only a very small amount of energy will be lost due to shading effects from the wind turbines onto the PV modules.

Finally seven variants for the PV plant ranging from 9.36 MWac to 65.52 MWac have been calculated to be added into the wind power plant. The small scale PV plants caused curtailments in a low region, but got the higher scaled layouts curtailments could reach around 35 GWh/a. It has been shown that a considerable increase of the capacity factor of the grid connection can be reached with small curtailment needs.

A financial analyses will be given in the follow-up report.

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List of Abbreviations

a.g.l.	Above ground level
a.s.l.	Above sea level
AC	Alternating Current
AEDB	Alternative Energy Development Board
AEP	Annual Energy Production
DC	Direct Current
GW	Gigawatt
IPP	Independent Power Producer
MCP	Measure Correlate Predict
MW	Megawatt
PoE	Probability of Exceedance
PV	Photovoltaic

1. Introduction

Pakistan has been and still is developing a number Renewable Energy projects. The country sets one of its focus onto wind and solar power generation. Pakistan decided to implement these technologies at areas where the specific resource (Wind or Solar) shows a high density.

This is why Pakistan defined "Wind Corridors". These are areas with a high annual average value in wind speed and with wide and open fields to install a huge number of wind turbines. The target is to "harvest" as much as possible power from wind while, at the same time, impacting the public as less as possible.

One of the wind corridors is located in the Sindh region. Here, Pakistan started the operation of wind plants more than 7 years back. Since then, plenty of wind parks have been developed, constructed and operated, all parks in "slices" of 50 MW capacity. The "50 MW" value is the maximum power to be evacuated into the public grid from each of the wind parks.

The mentioned boundary conditions led to an installed capacity of some GW in the area in total. The parks are always located in small but long "stripes", hosting up to 33 wind turbines per stripe, including an on-site substation with SCADA operational system and a camp area where the operators can live.

Having visited the area several times, it becomes very obvious that not only the wind resource is considerable high here, but also the solar resource. The area is facing a hot and arid climate and rainfall are really seldom. Just to clarify: There is no doubt that there are regions with higher solar resource values in Pakistan and the distribution of RE over the country can be an approach to reduce the impact onto the national grid. This is why currently the mentioned region in Sindh is focussing purely on wind power generation.

Both resources (wind and solar) are considered "variable" and "less predictable" with regard to the generated energy in a certain (short) timeframe. Even when reviewing the operation over a longer period (i.e. one year), it is transparent that the evacuation limit of 50 MW is reached rarely. In total, the wind parks currently under operation reach capacity factors between 35% and 40%.

The study in hand shall evaluate opportunities to install solar PV technologies between the wind turbines of a wind park. It is a sharp limit to use only the given maximum of the evacuation capacity of 50 MW to avoid extensive enhancements in the grid system. The analysis shall allow understanding of the hybrid effect caused by wind and solar plants on the same site. One important outcome is the increased capacity factor, comparing a "wind only park" (as installed currently) with a hybrid park of A) a wind and solar park and B) a wind and solar park plus a battery storage system.

Next to the increase of the annual capacity factor, the topic of curtailment will gain an important role. When two parks add up maximum nominal capacities to values above the installed maximum evacuation capacity of 50 MW, it is obvious that for a certain period of each year of operation at least one of the park elements needs curtailment to avoid overloads in the public grid. Curtailment leads to "wasted" energies as the technical and the meteorological conditions would allow for a higher production with technologies being installed and invested into. This "lifts" the analysis of curtailed energy to the importance given in this report.

Finally, this report shall support the government of Pakistan to adapt the current approach of requesting for "one wind park with an evacuation capacity of maximum 50MW" to an RfP text opening the request to a combined wind and solar power plant.

The report will start with an introduction and an analysis of the proposed site (Chapter 2). An review of the resources for wind and, consequently, solar will follow in Chapter 3, including detailed reporting on the data source, its content and the needful measures taken in this field of expertise. Chapter 4 addresses the layout works and results for the different technologies, explaining micro siting for wind turbines, solar PV layout and considered exclusion areas plus resulting shadings from wind turbines onto parts of the PV park. This chapter 4 starts addressing boundary conditions resulting from the combined analysis of wind and solar power generation (hybrid power generation) in one field. Results of the expected yields for the different cases are presented in Chapter 5, whereas Chapter 6 addresses the conclusions taken from the analysis.

2. Site Description

The project site (Latitude +24.95°; Longitude +67.84°) is located to the east of Karachi, the largest city in Pakistan and the capital of the Pakistani province of Sindh (Figure 1 and Figure 2). Located in the southeastern parts of the country, the area around the project location is known for its wind parks.

Figure 1: Location of Project Site in the Country

Figure 2: Closer view of the PV plant in the region of Sindh

2.1 Plot Area

For this study a theoretical area in the Sindh region has been defined by the Alternative Energy Development Board (AEDB) from Pakistan. The wind park on this location is under construction and most likely this plot will not be selected for a hybrid approach. This plot represents the current situation with regard to conditions met on site.

The area, where this study considers installation of a hybrid plant, consist of one available contiguous area, with a total surface of approx. 128 ha (Figure 3). The shape of the available space is a narrow, elongated rectangle with dimensions of about 145 m x 8,740 m. Coordinates of the corners are: NW: 24.984820°, 67.812362°; NE: 24.985722°, 67.813443°; SW: 24.921775°, 67.864429°; SE 24.922527°, 67.865616°.

The site in general can be characterized as flat terrain with low roughness due to scattered bushes and scarce vegetation in the region. Elevation of the site is low towards southeast whereas it gradually increases towards the northwest direction. The elevation of the site is within a range of approximately 50 – 80 m a.s.l.

Areas with significant vegetation are considered to be protected with regard to earth works, tree and bush cutting and gradation. When reviewing the site an initial approach is the definition of these exclusion areas. The areas can be spotted in public available map systems like Google Earth and the like. They are covered with bushes and small trees, mainly located in grabens where water is collected when (few) rain falls in this area. In Figure 4 the Consultant exemplary shows this approach. "Exemplary" means, that there are further area to be defined in this way and that the picture only shows the general approach.

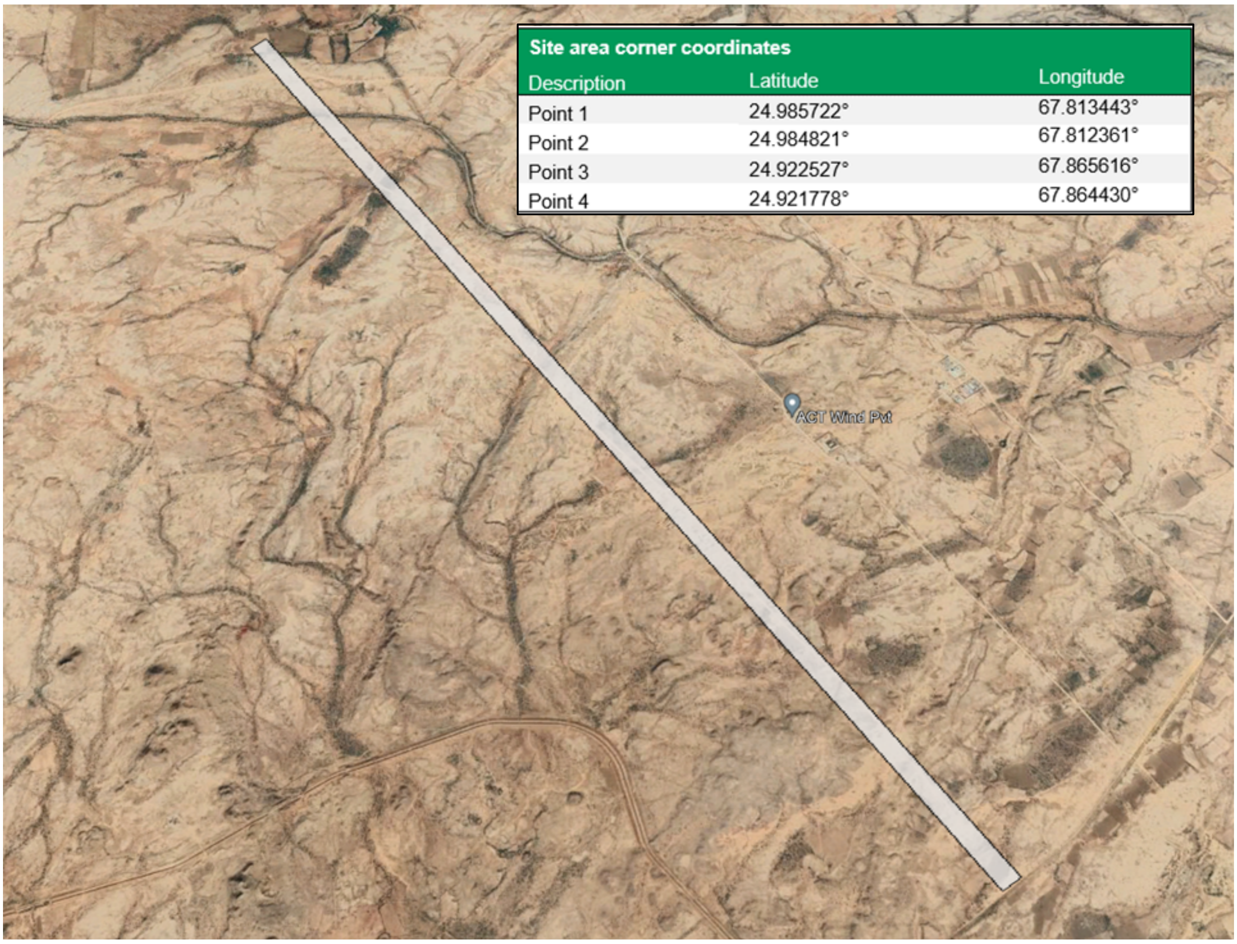

Figure 3: Plot Area of the proposed Site

Figure 4: Example for an exclusion area

3. Resource Data

The aim of the wind/solar resource analysis is to provide a reliable input of the resource the respective plant would receive throughout a year. In the following, the specific and different procedures for the wind and solar are explained and their results are given in the respective sections.

While wind data is basing on results of a specific measurement campaign, solar data is received in a more general approach along a PV power simulation tool. The reason for this essentially differing approaches is that wind resources are considered very local and significant changes might occur in short distances. This is why a properly executed measurement campaign is of utmost importance for understanding of the wind resource at a specific small area while solar resources are understood to be more general. For a solar resource, measurements can rely on many years of irradiation data and averages show sufficient quality of forecasted data for most regions of the world.

3.1 Wind

3.1.1 Local wind measurement data

The wind measurement data have been provided to the Consultant by AEDB. The measurement data have been collected at a met mast located within the plot area. The measurement period extends from 02.04.2016 to 25.12.2019, equivalent to 44.8 months in total. According to the measurement protocol, the top measuring height of the met mast is 120 m and it is equipped with eight anemometers, three wind vanes and three analog input channels dedicated to the measurement of temperature, pressure and humidity (Table 1).

Table 1: Measurement System

Measurement System			
Location	Artistic Wind Power		
Coordinate System	WGS84		
Latitude	24.967335		
Longitude	67.89265		
Logger	SymphoniePRO Logger (8206)		
Channel	**Height [m]**	**Type**	**Description**
1	120	Anemometer	RNRG Class 1
2	120	Anemometer	RNRG Class 1
3	100	Anemometer	RNRG Class 1
4	100	Anemometer	RNRG Class 1
5	80	Anemometer	RNRG Class
6	80	Anemometer	RNRG Class
7	60	Anemometer	RNRG Class 1
8	30	Anemometer	RNRG Class 1
13	118.5	Vane	RNRG 200P Vane
14	78.5	Vane	RNRG 200P Vane
15	28.5	Vane	RNRG 200P Vane
16	5	Analog	RNRG 110S Temp
17	5	Analog	RNRG BP20 Baro
18	5	Analog	RNRG RH5X Humi

3.1.2 Data analyse and validation

During the quality check of the raw data, the Consultant detected several data gaps as well as implausible data records of wind speed and wind direction. The error frequency differs significantly between the channels and instruments. Such detection is common in data analyse and validation of wind measuring campaigns.

The data quality check of wind data included:

- Check and verification of data integrity,
- Check for error values and anomalies,
- Check for completeness,
- Value range test,
- Rejection of periods where anemometers did not send signal (defect sensors),
- Rejection of periods where wind vanes sent continuously the same signal (defect sensors)
- Rejection of measurements (velocity, direction) which deviate a significantly from the general trend of concurrent measurement (other sensors with good correlation coefficient)

Table 2 shows the data recovery rate for the whole period for wind speed and direction.

Table 2: Data recovery rate of the wind data before and after quality check

Channel	Height [m]	Type	Available	Valid
1	120	Anemometer	97.2%	34.7%
2	120	Anemometer	97.2%	51.0%
3	100	Anemometer	97.2%	63.7%
4	100	Anemometer	97.2%	89.0%
5	80	Anemometer	97.2%	80.8%
6	80	Anemometer	97.2%	87.9%
7	60	Anemometer	97.2%	84.8%
8	30	Anemometer	97.2%	76.5%
13	118.5	Vane	97.2%	88.2%
14	78.5	Vane	97.2%	70.1%
15	28.5	Vane	97.2%	94.0%

Implausible data was disabled. For that reason valid data after quality check differs from the original availability of data of 97.2%. With 89% valid data, Channel 4 (anemometer mounted at 100 m and oriented towards NW) has the highest data availability, while the anemometers in Channel 1 & Channel 2 have the lowest (34.7% and 51.0%). The low recovery rate for almost all anemometer and wind vane channels rendered necessary reconstruction of data applying MCP methodology. The MCP process was carried out with the dedicated WindPRO tool “Meteo analyser”. This tool works with multiple meteorological time series in parallel and allows disable/enable and substitute/fill data, among other tasks, through a visual interface. The MCP processed was carried out until sufficient data was reconstructed to obtain a wind measurement period of 12 consecutive months with acceptable data recovery rate (availability of valid data). Table 3 below shows the improvement in the recovery rate of the whole period of wind speed and direction channels after conclusion of the MCP process.

Table 3: Data recovery rate of the wind data after data generation (MCP)

Channel	Height [m]	Type	Valid after MCP
1	120	Anemometer	89.0%
2	120	Anemometer	89.2%
3	100	Anemometer	89.0%
4	100	Anemometer	89.0%
5	80	Anemometer	96.6%
6	80	Anemometer	97.2%
7	60	Anemometer	96.6%
8	30	Anemometer	93.4%
13	118.5	Vane	88.2%
14	78.5	Vane	70.1%
15	28.5	Vane	94.0%

3.1.3 Correction of the wind direction data

Figure 5 show of the wind direction frequency distribution and the wind energy rose at 100 m a.g.l. of the wind measurement period from 2th of April 2016 to 25th of December 2019.

The collected data at the plot area (blue) and the long-term reference data ERA5 (red) show different wind direction frequency distribution and energy rose. This difference was also observed in comparison with all other long-term reference data assessed in this study. Consultant's experience in the region also coincides with this finding.

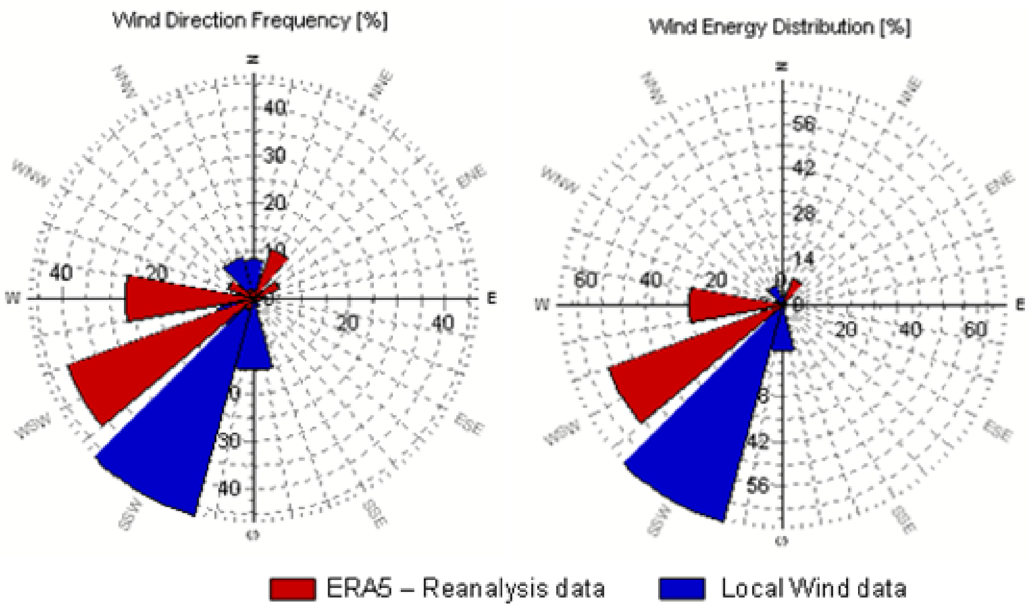

Figure 5: Wind data - Comparison Local and Reanalysis data

With an adjustment of 47.5 degrees (clockwise offset) local wind direction data was corrected and the correlation with long-term data improved.

Figure 6 shows the wind direction frequency distribution and wind energy rose after correction.

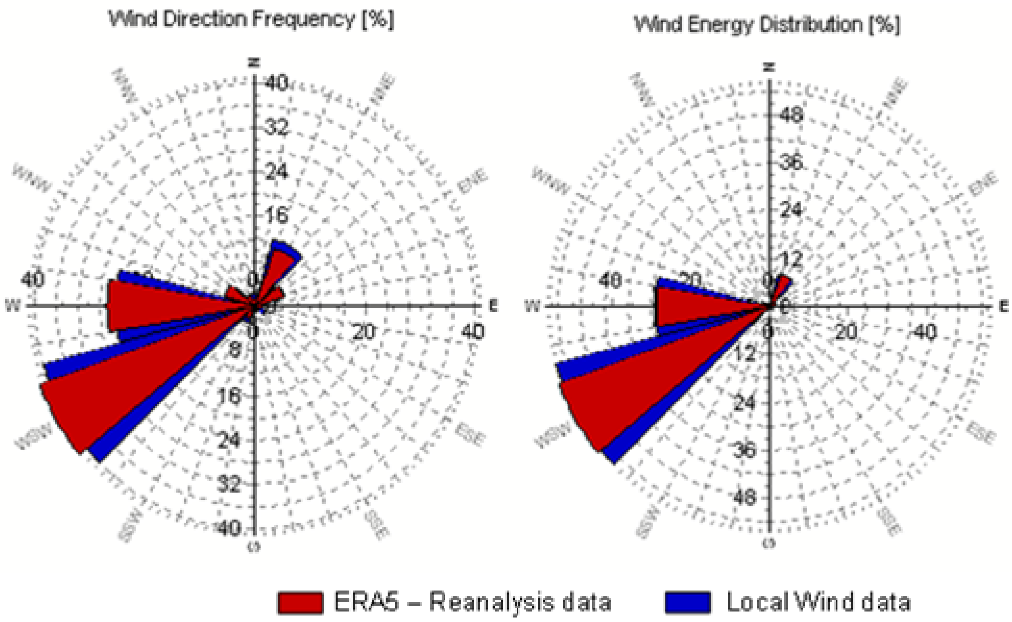

Figure 6: Wind data – Comparison Local and Reanalysis data after wind direction adaption

3.1.4 Wind shear

The variation of the wind speed with the height above ground is the vertical wind speed profile or wind shear. The vertical wind speed profile is calculated fitting a power law function between at least two anemometers with a vertical height distance of 20 m according to DIN EN ISO/IEC. The met mast was equipped with anemometers at five different heights between 30 m and 120 m.

The resulting power law wind shear from only valid data for the whole measuring period is estimated to α = 0.135, which represents a common value for flat terrain with low roughness landscapes surrounding met masts. Figure 7 displays the profile of extrapolated values for the wind speed.

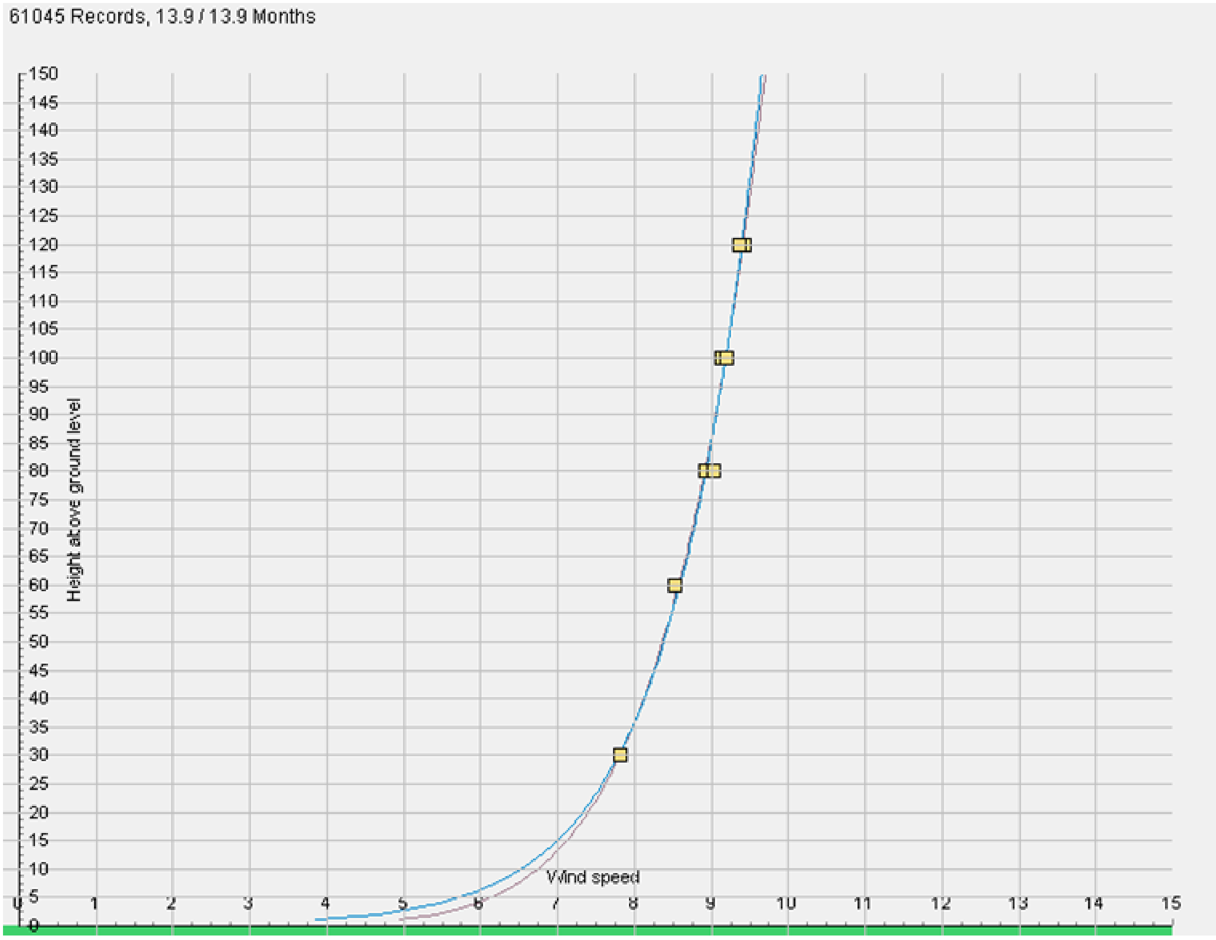

Figure 7: Vertical Profiles and wind speed extrapolation

3.1.5 Long-term correlation and adjustment

The average annual wind speed fluctuates around a long-term average value, typically between 2% and 8% at most wind farms. In order to obtain a reliable estimate of the wind conditions in the long-term, it is necessary to compare the available short-term data (from met mast at site/ local data) with a long-term reference data set. In order to do such comparison and correlation, reliable and consistent long-term reference data sets (or a suitable index) are required. The aim is to decrease short-term wind fluctuations and to derive long-term representative wind statistics.

For the wind/ solar hybrid project, several sources have been identified such as ERA5 and EMD-WRF reanalysis data. The ERA5 grid point (N25.00; E67.75), clearly showed the best correlation with the validated, reconstructed and direction corrected local wind data and was, therefore, used for the present long-term analysis.

ERA5 reanalysis dataset is calculated out of satellite measurements and have an hourly resolution. The data cover the whole globe with a grid resolution of 0.25° in latitude and 0.25° in longitudinal direction.

Table 4 shows the checked, processed long-term adjusted wind data for 100 m wind speed and direction time series. The Consultant presents in this chapter the long-term representative Weibull parameters corresponding to 100 m height because that height corresponds to the anemometer connected to Channel 4 with the best original data availability at height close to the intended hub height of wind turbines for the project.

Table 4: Processes long-term data for 100 m above ground

Sector	A parameter	k parameter	Frequency	Mean wind speed
Mean	8.77	2.6505	100	7.795
N (345°-15°)	7.071	2.7434	9.417	6.292
NNE (15°-45°)	4.987	2.6153	1.993	4.43
ENE (45°-75°)	4.321	2.5441	1.293	3.836
E (75°-105°)	3.599	2.0007	0.712	3.189
ESE (105°-135°)	3.514	2.3732	0.625	3.115
SSE (135°-165°)	4.8	2.2775	1.946	4.252
S (165°-195°)	8.951	3.7619	13.503	8.085
SSW (195°-225°)	10.378	3.4004	42.341	9.324
WSW (225°-255°)	7.222	3.078	10.226	6.457
W (255°-285°)	5.899	2.0347	3.911	5.226
WNW (285°-315°)	5.044	2.0607	1.999	4.468
NNW (315°-345°)	8.756	3.346	12.033	7.86

3.1.6 Description of the flow model

Digital Elevation model

A digital elevation model (DEM) has been created based on Shuttle Radar Topography Mission (SRTM 1 arc-second) and it covers more than 6 km radius from all corners of the plot area. The DEM actually covers a square of approx. 22 km side. In Figure 8, the planned wind farm area is marked as black strip. The elevation of the project site (plot area) ranges between 50 m and 80 m a.s.l.

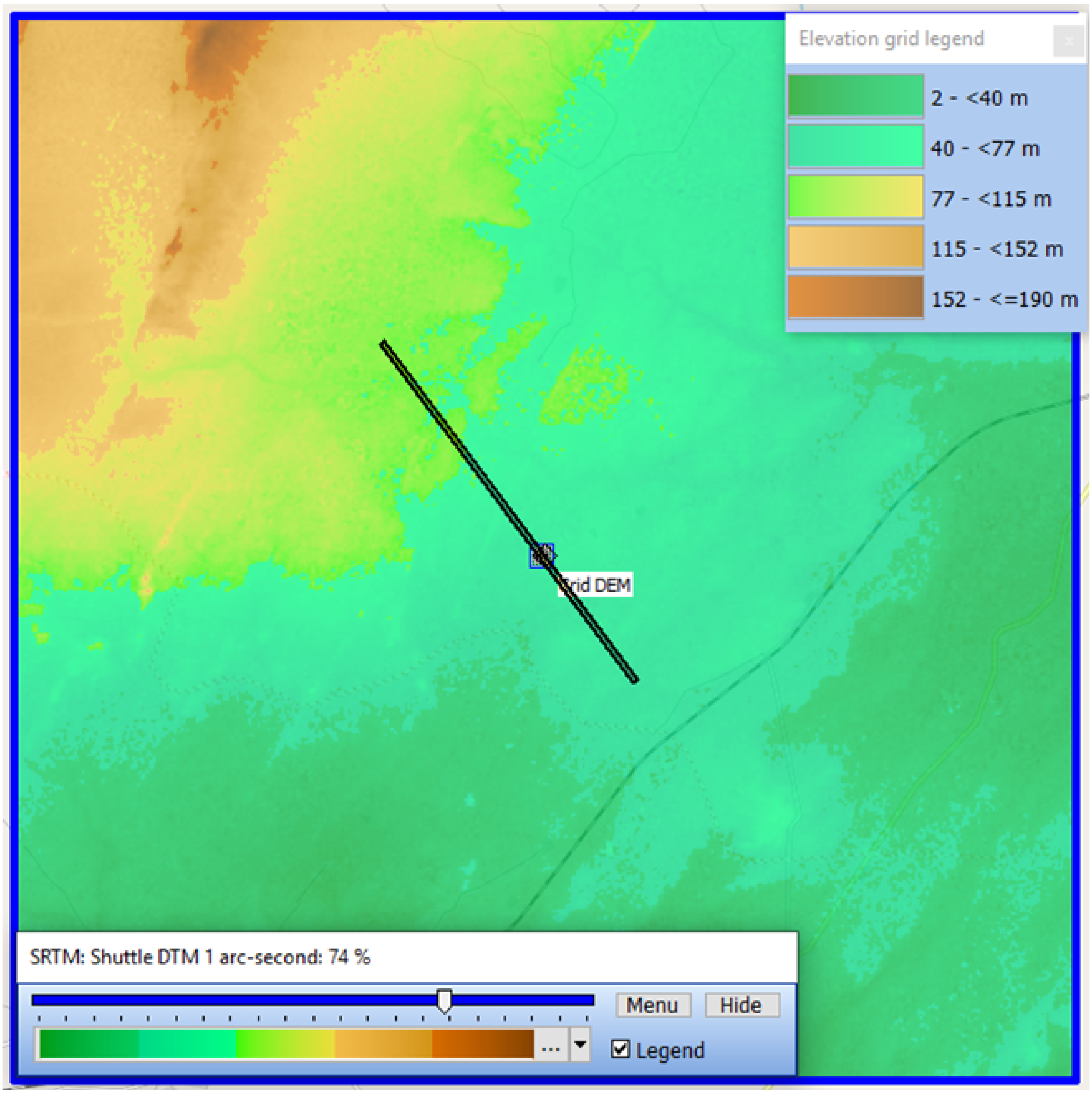

Figure 8: DEM and plot

Roughness model

A roughness model has been created based on satellite data, please refer to Figure 9. The roughness model covers a square of approx. 60 km side, thus characterizing the roughness conditions 20 km around each corner of the plot area.

There are the typical scattered bushes in the region. Accordingly the site can be characterized as low roughness area. The background roughness was evaluated as roughness class 0.9 equivalent to roughness length of z0 = 0.0182.

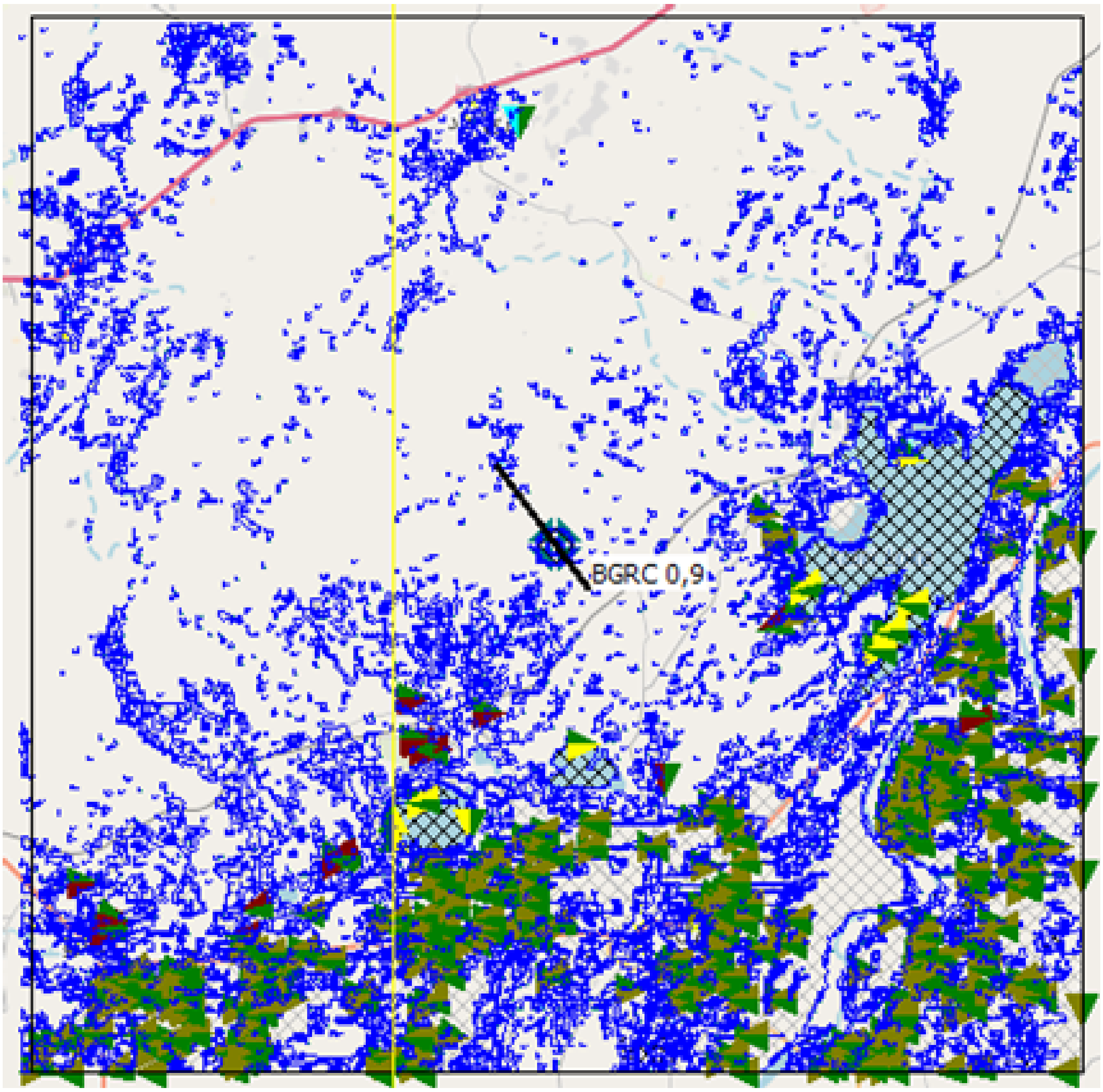

Figure 9: Roughness model and plot area

3.1.7 Model calibration

The common process of flow model calibration consist in adjusting the roughness length of the roughness model until the flow model simulates wind speed vertical profile with acceptable matching of the measured wind speed profile at the local measurement mast position.

Figure 10 shows the measured wind speed profile (purple power law line based on long-term representative wind speeds at 80 m, 100 m and 120 m a.g.l.) vs wind profile simulated by the WAsP model (red line). It can be noticed that WAsP flow model does not fit well the measured wind profile.

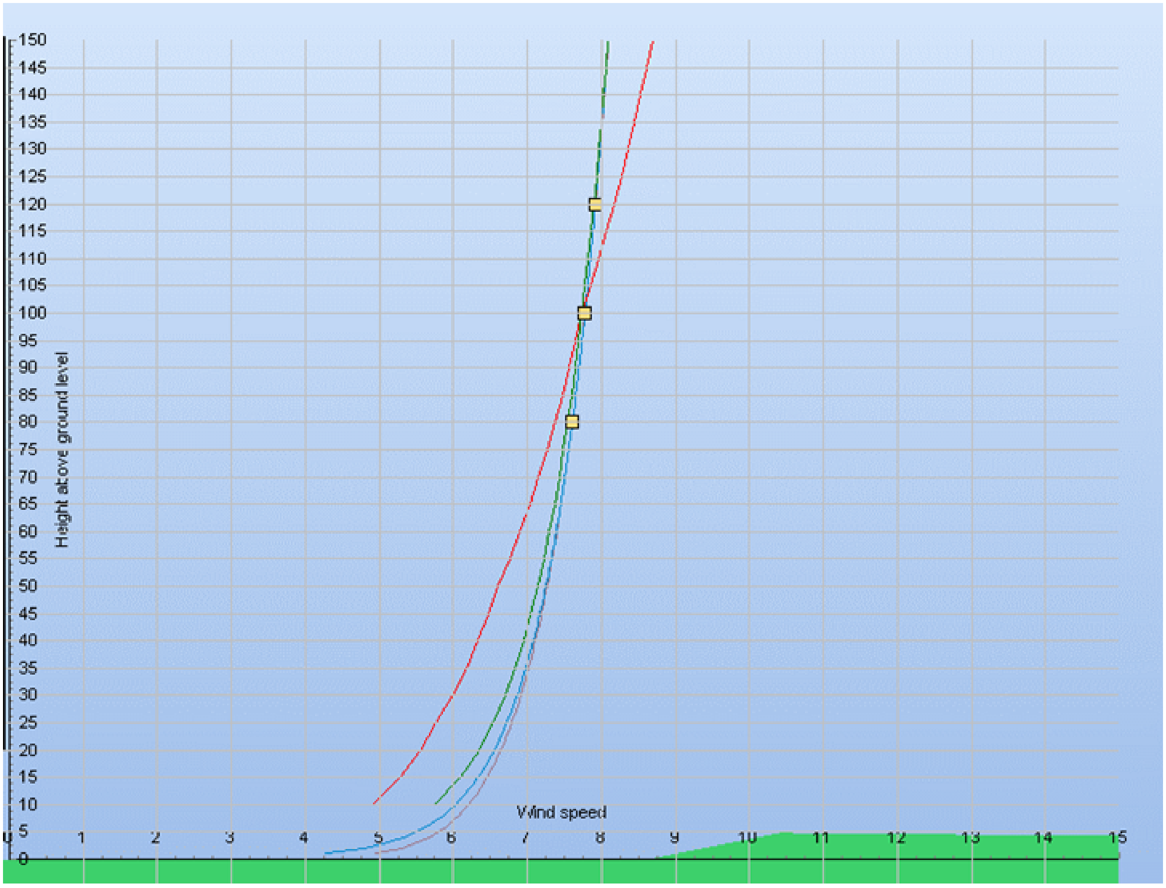

Figure 10: Measured wind profile vs simulated wind profile before model calibration

After numerous iterations changing the roughness heights of the roughness model, it was observed the flow model was not responding to changes in the roughness and therefore an adjustment of the WAsP parameters was assessed. Changing the offset heat flux over land (classic) from -40 (slightly stable heat flux parameter) to 100 (more unstable conditions), still within the minimum and maximum range (-200 to +200), the fit of the flow model was successfully achieved, please see Figure 11.

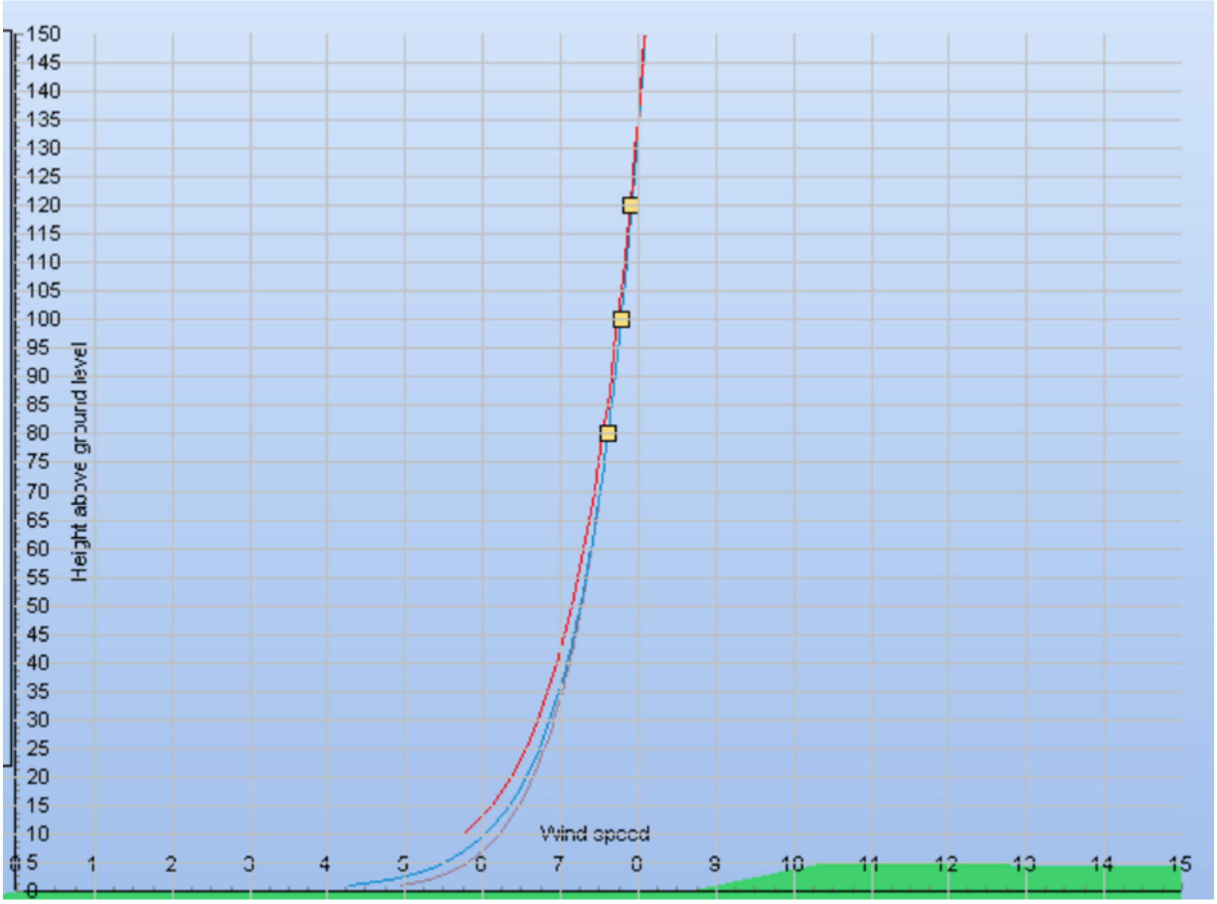

Figure 11: Measured wind profile vs simulated wind profile after model calibration

At this stage, the wind flow model is considered calibrated and ready for calculation of local wind resource maps, micro-siting and energy yield calculations.

Based on the processed data, which were long-term corrected using 30 years ERA-5 reanalysis data from 1991-2021, a wind resource map was calculated with WAsP-model for the areas under consideration.

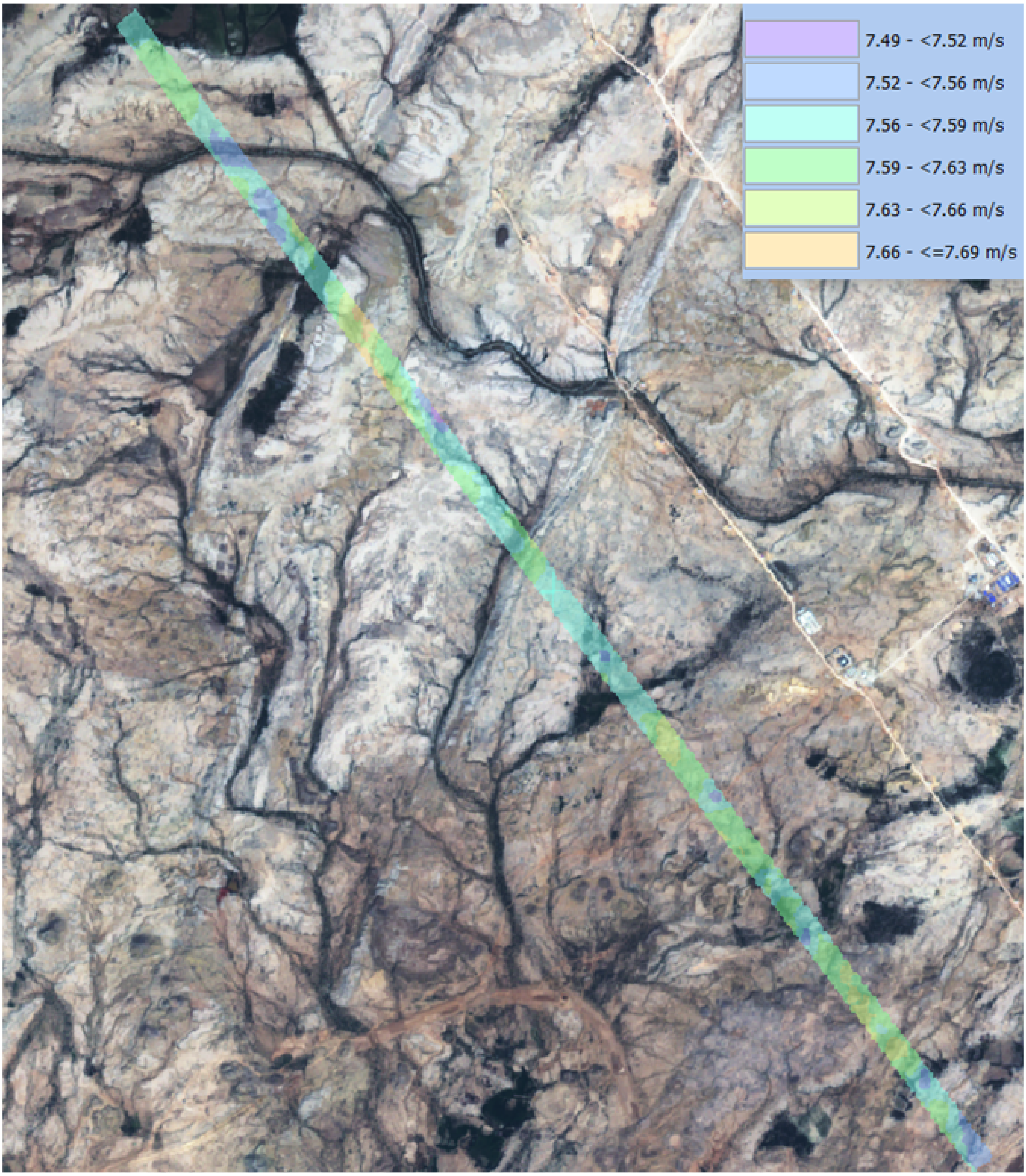

Figure 12: Wind resource map at 90 m a.g.l.

Figure 12 shows the mean wind speed in a height of 90 m above ground. Furthermore it is obvious, that the mean wind speed is not varying much through the site, what can be expected, as the terrain is not complex and rather homogenous.

3.2 Solar

The aim of the solar resource analysis is to provide an estimation of the solar energy the surface of the earth receives throughout a typical year. The solar resource is usually given as a series of hourly values for the irradiance and temperature, for a period of one year. Often, wind speed and humidity are included as well. These series are called Typical Meteorological Year (TMY) as they reflect the typical conditions over one year. Having emphasised "typical", it is clear that differences occur from specific year to specific year, but the TMY tries to mitigate this effect.

3.2.1 Horizon Profile

The horizon profile reflects the condition onsite and include (far) shading objects into the consideration. Hills, mountains, and skyscrapers or high buildings may impact the horizon. These physical obstructions will block the beam component of the irradiance during some periods of the day and will have an impact on the diffuse component as well. Therefore, it might happen that horizon directly shades elements of the photovoltaic plant.

The horizon line has an average elevation of 0.6° and a maximum elevation of 1.5°. Throughout the year, the Sun will be blocked by the horizon line for a total of about 51 hours. The data source for the horizon line was the PVGIS 5 database.

The blocked elevations over the complete azimuth range are shown Figure 13.

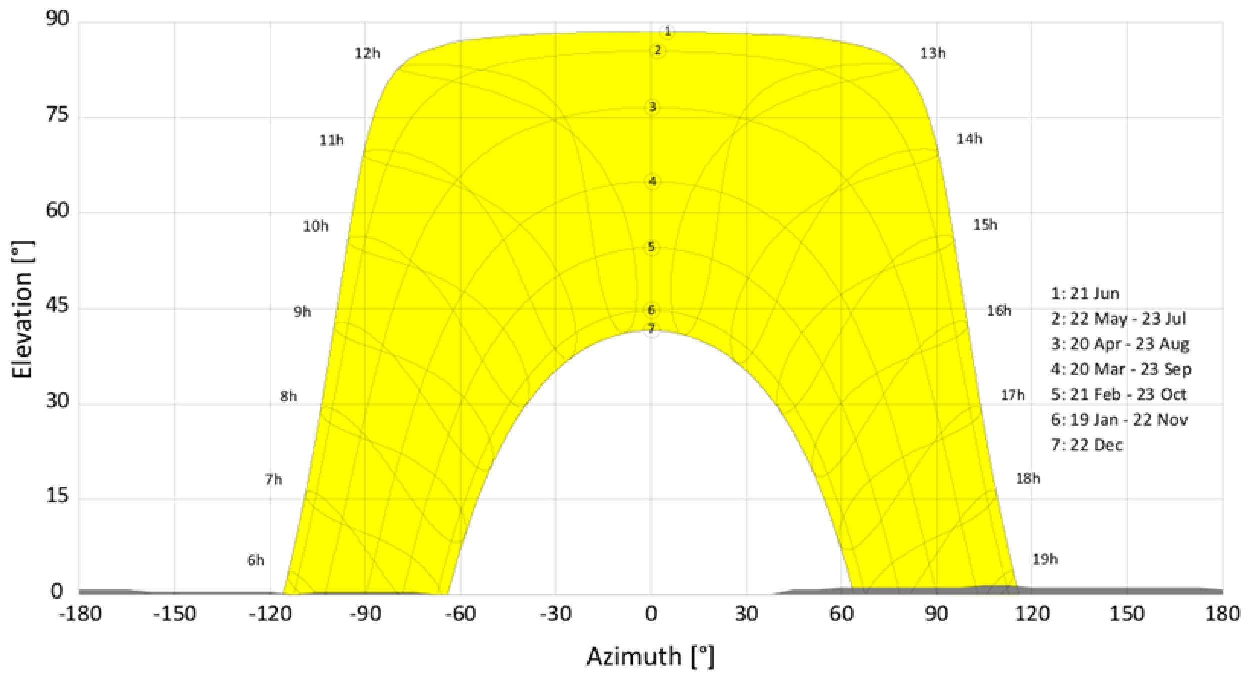

Figure 13: Horizon profile at project site (Source: PVGIS 5)

3.2.2 Typical Meteorological Year

As discussed in the intro in Chapter 3, the TMY is a set of representative values of any given meteorological parameter, for the given location. TMY is prepared in hourly resolution (being 8760 lines per year) and is derived from long-term meteorological data. This data set has been used to prepare an overview, showing a monthly summary of the TMY data (Table 5). A chart representing the data of Table 5 is shown in Figure 14.

Analysing the hourly temperature values in detail following parameters have been detected:

- Minimum temperature: 7.69 °C.
- Maximum temperature: 42.91 °C.
- Average temperature: 26.82 °C

Table 5: TMY monthly irradiation and temperature

Month	Global horizontal irradiation [kwh/m²]	Horizontal diffuse irradiation [kwh/m²]	Ambient Temperature [C°]
January	123.6	45.5	18.27
February	132.1	54.8	21.30
March	176.3	73.7	26.28
April	189.8	82.5	29.37
May	201.9	98.6	31.88
June	183.0	104.7	31.96
July	150.3	105.0	30.94
August	142.8	95.6	29.43
September	160.8	80.3	29.11
October	154.0	68.0	29.04
November	127.4	49.3	24.29
December	114.0	44.4	19.70
Year	1855.9	902.4	26.82

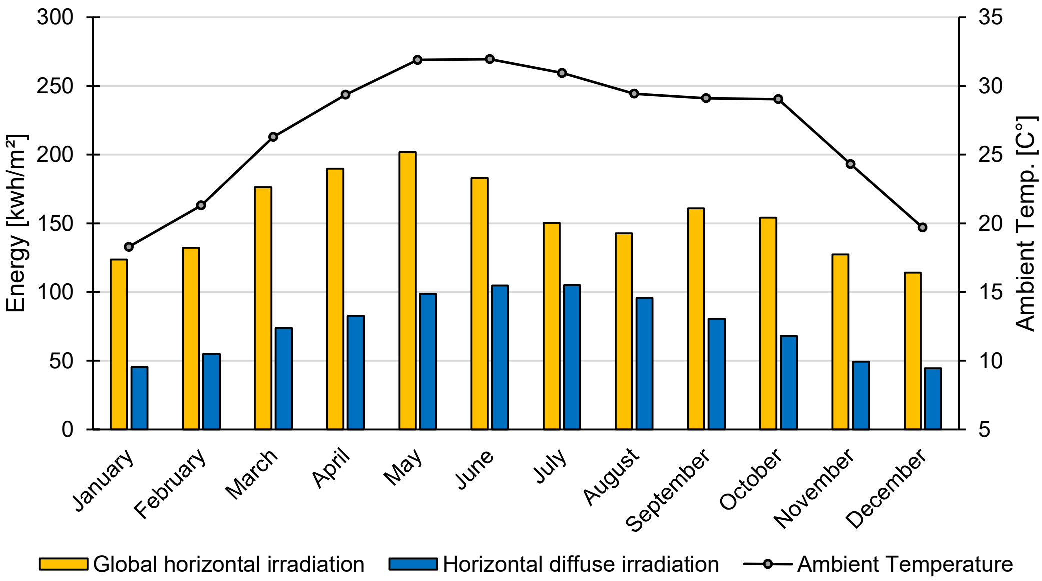

Figure 14: Solar resource chart

4. Component Layout

4.1 Wind

4.1.1 Selection of WTG

It was agreed, that a turbine of rated power about 2.5 MW and maximum tip height of approx. 150 m would be considered for this study.

The Consultant evaluated several alternatives of wind turbine generators (WTGs):

- Siemens Gamesa 2.1-114 2.1 MW 93 m hub height,
- Siemens Gamesa 3.4-132 3.4 MW 84 m hub height,
- GE 2.5-100 2.5 MW 100 m hub height,
- Goldwind GW 121 2.5 MW 90 m hub height.

Generally the choice of the right WTG for a wind farm site depends strongly on the site characteristics and transportation constraints. Within site characteristics, wind conditions are the main criteria when selecting a wind turbine (optimum energy yield and structural suitability) to mitigate the risk of failure during operation keeping high availability of operation.

The Consultant evaluated diligently turbulence and wind speed parameters (Weibull distribution, maximum records). It was observed that measured ambient turbulence intensity at the site are low and, for the histogram of turbulence intensities calculated following the procedure defined in the IEC 61400-1 (ed. 2 and also ed.3), the resulting combination of mean value and standard deviation of turbulence intensity remain below the lowest turbulence categories defined by the IEC for the standard classification of WTGs.

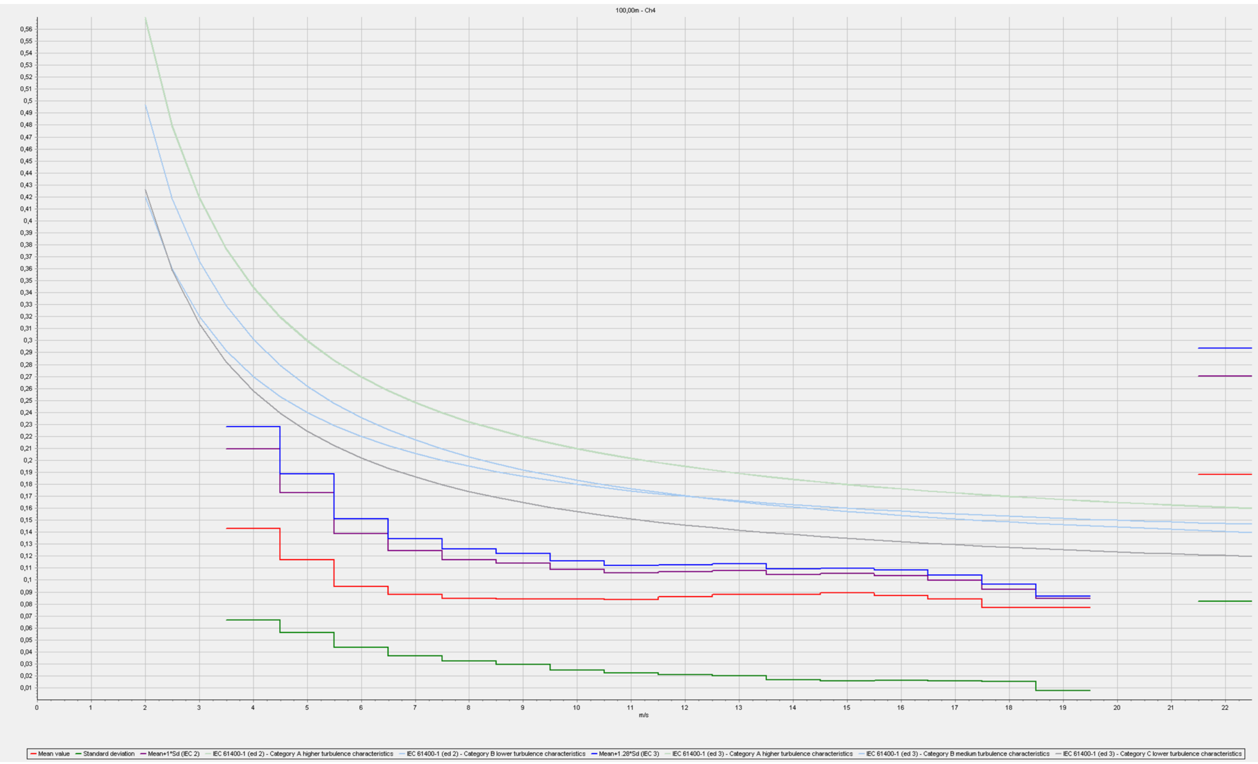

Figure 15: Histogram of turbulence intensities vs categories defined by IEC standards

WTG models turbulence category C (IEC 61400-1 ed.3) or B (IEC 61400-1 ed 2) would be suitable for the site.

The long-term representative wind statistic at 100 m height shows the following Weibull distribution fit to the histogram of wind speeds. Weibull parameters A= 8.8 m/s and k=2.51, with a mean wind speed of 7.8 m/s characterize the expected long-term representative wind potential of the site. The shape of the Weibull distribution (k = 2.51) tends to a symmetrical bell distribution, with a very short tale (distribution of probability of high wind speeds events). Without doing a site suitability assessment, we strongly believe WTG models IEC Class III would be suitable for the site because of the very low probability of wind speed events higher than 22 m/s (in more than 3.5 years of measurements at 100 m a.g.l. only two wind speed values were higher: 22.49m/s and 22.21 m/s).

Table 6: Basic parameters for wind turbine classes (IEC 61400-1 Ed.3).

Wind turbine class		I	II	III	S
V_{ref}	(m/s)	50	42,5	37,5	Values
A	I_{ref} (-)	0,16			specified
B	I_{ref} (-)	0,14			by the
C	I_{ref} (-)	0,12			designer

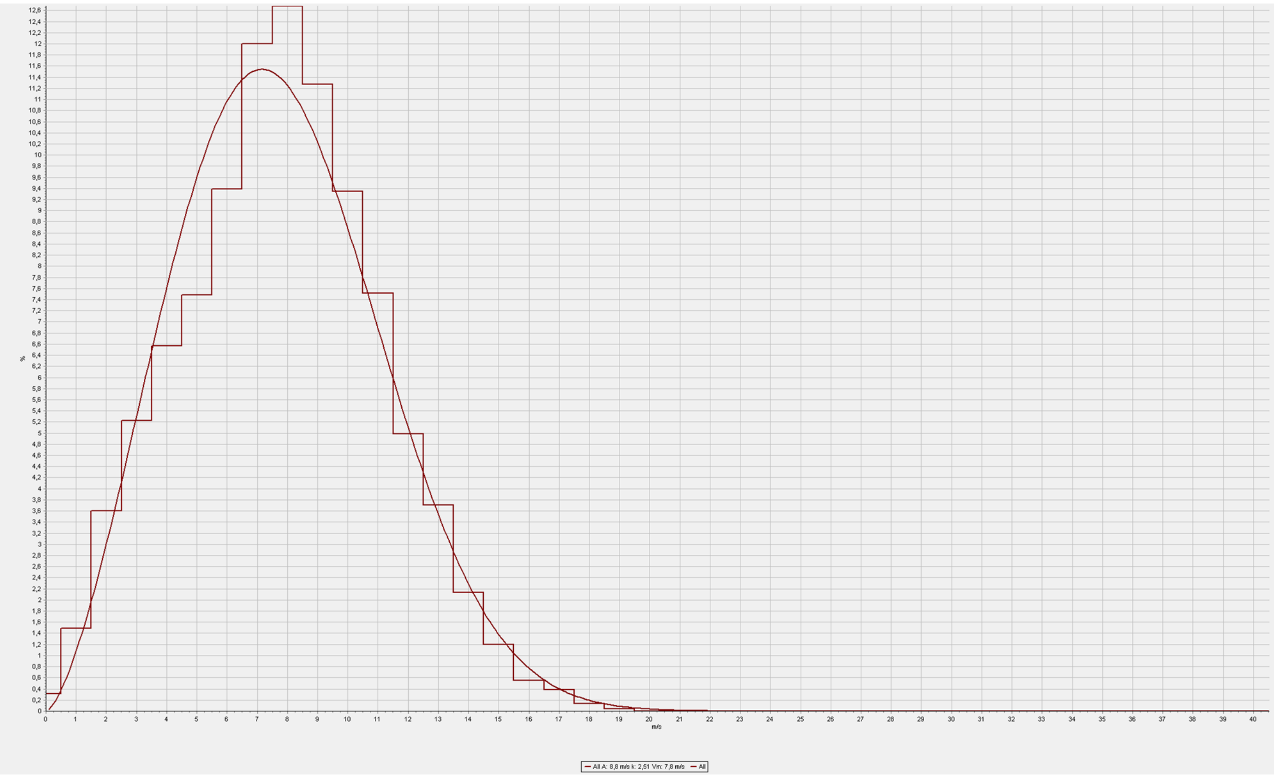

Figure 16: Weibull fit of the histogram of local measured wind speeds at 100 m a.g.l.

On the basis of this diligent assessment, the Consultant selected the WTG GW121-2.5 MW with 90 m hub height for the preparation of the wind farm layout and estimation of the expected annual energy yield of a 50 MW wind farm project. Next table show the main characteristics of the selected wind turbine. The power curve of this WTG is included in chapter 7 Appendix A.

Table 7: Main parameters of the wind turbine considered in this assessment

Item	Unit	Goldwind G121
Manufacturer		**Goldwind**
Turbine Model		GW121 2.5 MW
IEC Class		III B
Rotor diameter	m	121
Rated power	MW	2.5
Hub height	m	90
Cut in / Cut out wind speed	m/s	3.0 / 22.0

4.1.2 Layout Wind farm

The Consultant prepared the micro-siting considering the selected wind turbine model and the wind resource map calculated for the plot area on the basis of the long-term representative wind potential evaluated in chapter 3.1.5. A minimum distance of 2.5 rotor diameters (2.5 D) has been considered between wind turbines in the plot area. Topographic features such as slopes, protected vegetation, non-perennial stream beds, have been considered in the micro-siting as far as noticeable with public available map systems like Google Earth and the like.

The micro-siting is an iterative process. After several iterations (7 iterations), a wind farm layout was defined. **Error! Reference source not found.** shows the optimized wind farm layout over the calculated wind resource map. Wind turbine positions are designated with cardinal numbers ordered incrementally from NW to SE.

Table 8: Hybrid wind turbine coordinates and altitudes

Pos	WTG label	Hub height [m]	Longitude	Latitude	Altitude [a.s.l] [m]
1	1	90	67.814273°	24.983330°	80.0
2	2	90	67.816455°	24.980801°	79.3
3	3	90	67.819700°	24.976436°	78.8
4	4	90	67.823003°	24.973430°	79.1
5	5	90	67.826303°	24.969324°	78.9
6	6	90	67.827795°	24.966788°	78.3
7	7	90	67.829732°	24.964566°	74.8
8	8	90	67.831685°	24.962125°	70.0
9	9	90	67.833481°	24.959867°	70.0
10	10	90	67.837985°	24.955461°	65.0
11	11	90	67.840644°	24.951697°	58.6
12	12	90	67.845360°	24.945822°	60.0
13	13	90	67.847309°	24.943771°	57.3
14	14	90	67.849070°	24.941548°	55.0
15	15	90	67.850787°	24.939143°	54.8
16	16	90	67.853246°	24.935970°	50.0
17	17	90	67.856478°	24.932794°	55.0
18	18	90	67.858090°	24.930441°	55.0
19	19	90	67.859982°	24.928347°	54.3
20	20	90	67.862226°	24.924992°	50.0

The layout displayed in Figure 17: Optimized wind farm layout over the resource map at 90 m height a.g.l.Figure 17 has been considered in the calculations of the Consultant.

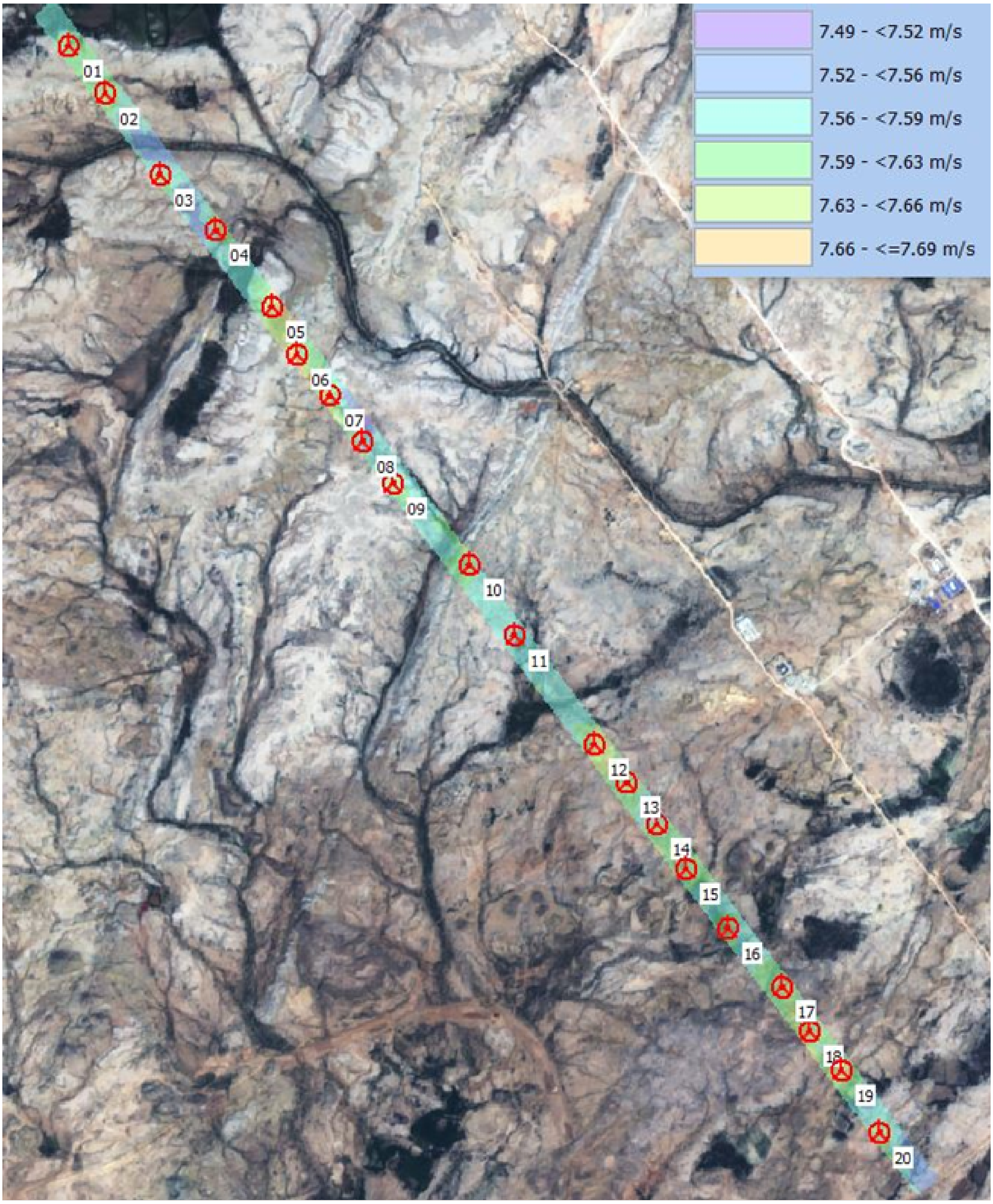

Figure 17: Optimized wind farm layout over the resource map at 90 m height a.g.l.

4.1.3 Internal Roads and Crane Pads

For the implementation of a wind farm, an internal road infrastructure of sufficient structural capacity shall be constructed. The design of the internal road has to fit to the local topography as much as practicable in order to minimize the impact on the natural terrain, while meeting requirements for safety and serviceability.

Primary aspects considered in the design of internal roads were:

- Maintain the original hydrological regime;
- Roads to be designed to minimize habitat loss and utilise existing tracks;
- Limit requirements for regular maintenance;
- Safe transportation of major WTG components and access for cranes;
- Long-term access for the O&M teams during the operational phase of the wind farm.

The preliminary design was done for the level of detail expected for a feasibility study (geometrical design considering minimum internal radius of horizontal curves of 45 m, minimum road width of 5 m, minimum radius of vertical curves of 600 m.

During the construction of the wind farm, there is sufficient space available for the erecting of turbines. After the construction of the wind farm it is sufficient to keep, an undeveloped area around the WTG (40x30m) and next to the internal road (62x16m) in order to allow eventual major corrective maintenance tasks such as replacement of rotor blades. When erecting PV modules, these areas are left out. The remaining space will not be large enough to allow the operation of main and auxiliary cranes to dismantle blades, for example.

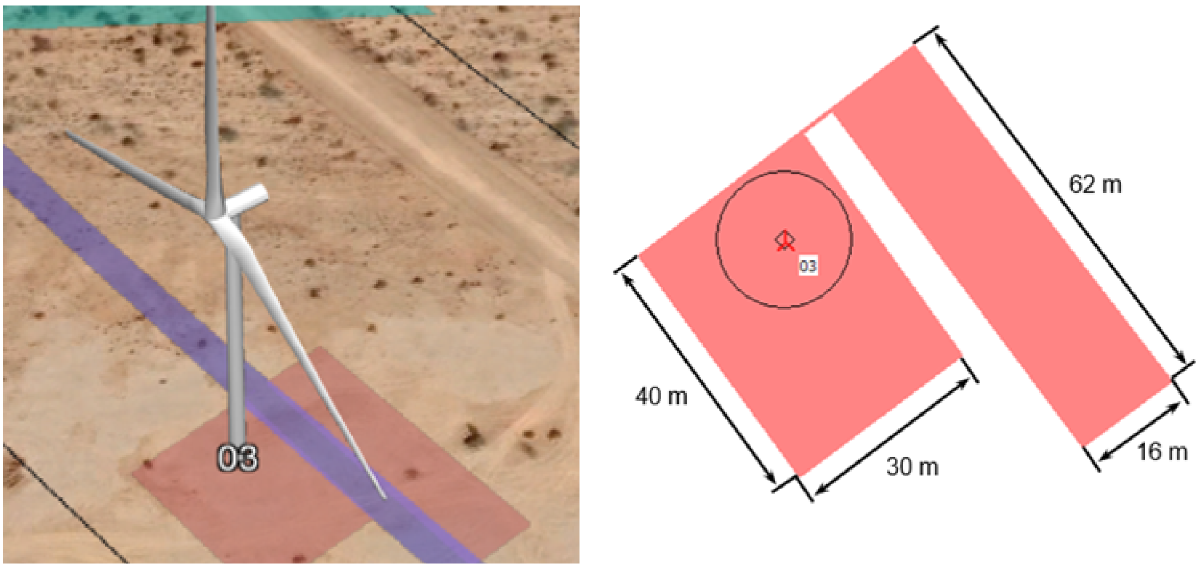

Figure 18: Crane pads with storage area

4.2 Solar PV

4.2.1 Exclusion areas

The area, where the PV plant is to be built, consists of an available area with a total surface area of 128.03 ha. For the specific analysis of available space to install PV modules, the Consultant defined a number of areas, which cannot be used. Areas mentioned in Chapter 4.1.3 are strictly to be kept open and are to be excluded from module covering. When analysing the conditions for Chapter 4.1.3, it is transparent that a road along the whole plot needs to be implemented. The described approach of defining crane pads and lay-down areas next to each turbine does not follow the well know approach of today's operating wind parks in the area. The described approach is dedicated to the fact that there will be a solar plant on the same site. This means that for refurbishments and replacements areas needs to be kept-open, avoiding additional challenges when intensive repair of the turbine generators is requested. This is why the Consultant defines a crane pad and a lay-down area for the blades of every turbine. This shall be understood as a "just in case" procedure and the protected area around each wind turbine might be too small to deinstall and replace the tower without additional effort like storage of elements on the roads. But, for a "just in case" approach, it should be avoided to spare out too much spaces for unlikely events of tower replacements. .

Additionally the substation plus the camp side have been excluded for obvious reasons.

Finally, a review of the site conditions with regard to possible environmental impact has been executed. Engineers have performed this execution and no environmental expert has been involved. Thus, the results can be understood to be preliminary, and having in mind the character of the site (exemplary chosen) and the regional reference of all environmental impact regarding graben, gradation and cutting of trees and bushes, this is an applicable approach here.

The Consultant finally defined a total of 56 restricted areas to be not suitable for the installation of PV modules. The final available area covers a surface of 97.74 ha.

The following Figure 19 shows the final result of the analyses of the available area. It is difficult to go into detail in this report as the size of the plot in narrow and long. Exclusion areas are shown in (transparent) red in the mentioned figure and it can be seen that there are areas around each turbine. These areas are exemplary shown in Figure 18 above. One road ensuring access to the site itself and to each turbine is part of the exclusion area. Also, areas of the substation and the camp site are excluded. A number of (transparent) red areas are covering sensitive environmental areas as discussed above.

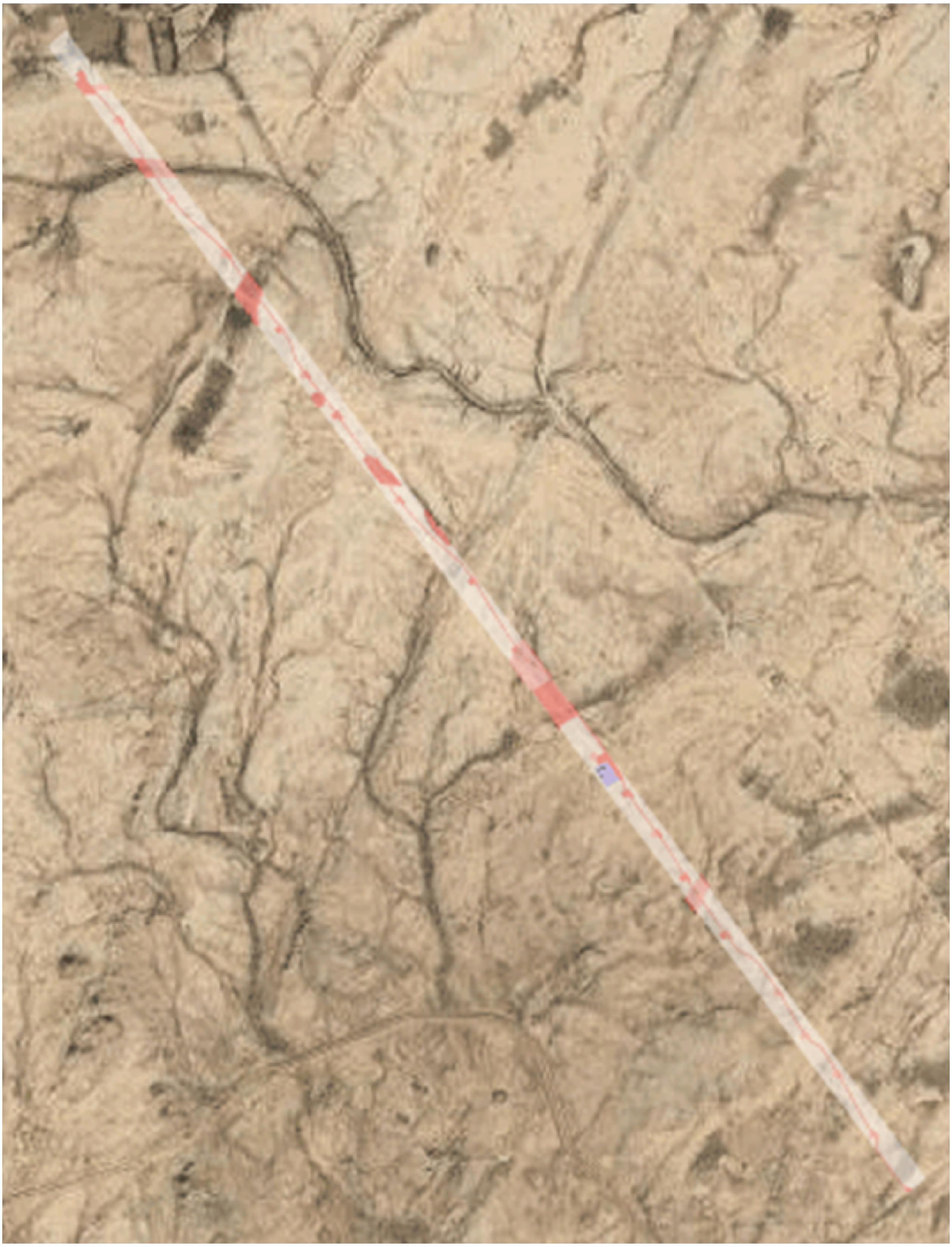

Figure 19: Excluded areas within the plot

4.2.2 Photovoltaic Modules

In order to provide a realistic design of the grid-connected PV plant, the Consultant chose a module, which is considered common international market standard, but not cutting edge. This is appropriate for an energy yield assessment at this project stage. Instead of maximising the module efficiency, focus was set on good standard and handling of the modules. Dimensions and weight make it easy to perform installation works even under harsh conditions. Changing the parameters and opting for a bigger sized module with higher weights would have marginal effect on the design and energy yield. Also, the bifacial technology is not considered in this study. Despite the on-site conditions, which seem to show considerable Albedo factors, this is due to the fact that this study shall not limit future IPPs to a specific technology. The set of chosen products reflect the standards we see installed in the world.

The photovoltaic module selected is the CS3W-440MS 1500V model, manufactured by Canadian Solar Inc.. It has a peak power of 440.0 W, and the technology of the cells is Si-mono.

The features of the photovoltaic module are shown in Table 9.

Table 9: Characteristics Photovoltaic module CS3W-440MS 1500V

Main characteristics	
Module model	CS3W-440MS 1500V
Manufacturer	Canadian Solar Inc.
Technology	Si-mono
Type of module	Monofacial
Maximum voltage	1500 V
Standard test conditions (STC)	
Peak power	440.0 W
Efficiency	19.9 %
MPP voltage	40.7 V
MPP current	10.82 A
Open circuit voltage	48.7 V
Short circuit current	11.48 A
Temperature coefficients	
Power coefficient	-0.350 %/°C
Voltage coefficient	-0.270 %/°C
Current coefficient	0.050 %/°C
Mechanical characteristics	
Length	2108.0 mm
Width	1048.0 mm
Thickness	0.40 mm
Weight	24.9 kg

4.2.3 Fixed Structure

Fixed module structure is considered for this study. It might be possible to gain more results by applying one axis tracked system, but the Consultant kept in mind that the installation might be first of its kind in Pakistan.

The modules will be mounted on a fixed structure. The structure will establish the orientation and inclination of the modules, as well as the separation between the rows.

The structure will be composed of the following elements:

- Mounting structure formed by different types of metallic profiles.
- Foundation elements for anchoring the structure to the ground.
- Clamping elements and screws to assemble the structure and for mounting the modules on the structure.
- Structural reinforcement elements.

An example of a fixed mounting structure is shown in Figure 20.

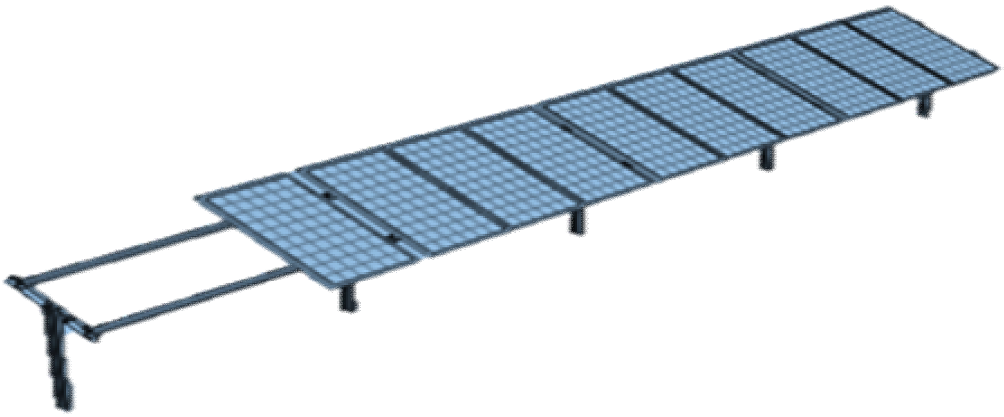

Figure 20: Example of a fixed mounting structure (1V)

The main features of the fixed mounting structure are shown in Table 10.

Table 10: Main features of the fixed mounting structure

Fixed structure characteristics	
Structure type	1V
Tilt angle	21.0 °
Poles type	Mono pole
Pitch distance	3.0 m
Designed for	MONOFACIAL modules
Minimum ground clearance	0.5 m

4.2.4 String Combiner Box

The string boxes collect the power generated by the DC array, connect the strings in parallel to the inverter, and provide electrical protection to the PV field. To match the number of inputs of the inverters, several parallel strings will be concentrated to function as a single circuit. Junction boxes shall be installed with a fuse per string to protect each array. Overvoltage DC dischargers will be installed, and one DC switch will be situated in the output line. Additionally, a communication system may be installed to monitor the string current and voltage.

An example of a string box is shown in Figure 21.

Figure 21: Example of a string box (Schneider Electric)

The string boxes will be installed in a shaded position and shall be easily accessible to facilitate maintenance works. They will be placed behind the PV modules and if possible, will use existing structure poles, so that they remain shaded and to prevent damage caused by rainwater or other meteorological phenomena is prevented.

4.2.5 Central Inverter

The decision to be felt here is between a string inverter concept and a central inverter concept. Both technologies carry advantages with them, but central inverter concepts are using slightly more space for a) the inverter itself, and b) with regard to the string length, which is used to define the table size. By this means the central inverter represents the solution to be focused on. The inverter converts the direct current produced by the photovoltaic modules to alternating current. It is composed of the following elements:

- One or several DC-to-AC power conversion stages, each equipped with a maximum power point tracking system (MPPT). The MPPT will vary the voltage of the DC array to maximize the production depending on the operating conditions.
- Protection components against high working temperatures, over or under voltage, over or under-frequencies, minimum operating current, mains failure of transformer, anti-island protection, behavior against voltage gaps, etc. In addition these features serve also for the safety of the operation and maintenance staff.
- A monitoring system, which has the function of relaying data regarding the inverter operation to the owner (current, voltage, power, etc.) and external data from monitoring of the strings in the DC array (if a string monitoring system is present).

The main characteristics of the selected inverter are shown in Table 11.

Table 11: Inverter characteristics

Main characteristics	
Inverter model	ULTRA-1500.0-TL
Inverter type	CENTRAL
Manufacturer	ABB
Maximum DC to AC conversion efficiency	98.04 %
Input side (DC)	
MPPT search range	470 - 850 V
Maximum input voltage	1000 V
Output side (AC)	
Rated power	1560.0 kVA
Power at 30 C (datasheet)	1560.0 kVA
Power at 50 C (datasheet)	1560.0 kVA
Output voltage	690 V
Output frequency	50 Hz

4.2.6 Power Station

The power stations or transformer stations are indoor buildings or containers. The voltage of the energy collected from the solar field is increased to a higher level to facilitate the evacuation of the generated energy. The inverters and power transformers will be housed in the power station.

An example of an indoor power station is shown in Figure 22.

Figure 22: Example of an Indoors power station

The power station shall be supplied with medium voltage switchgears that include one transformer protection unit, one direct incoming feeder unit, one direct outcoming feeder unit and electrical boards. Particularly, for the first power station of each MV line, a direct incoming unit will not be installed.

4.2.7 Layout PV Plant

Based on the above mentioned exemplary chosen products, the Consultant prepared a more general layout for the PV part of the hybrid plant. "General" here means, that, without changing the manufacturers and technologies of basic elements, an easy adaption of the PV field size by adapting the number of elements can be performed. This allows for installation of a range of a differently sized PV part of the hybrid plant. All park layouts are simulated with a worldwide accepted PV simulation tool, named PVSyst.

The maximum installable AC power of the PV Plant is 65.5 MWac and the DC Power is 78.6 MWdc, which results in a DC/AC ratio of 1.20. The present description of the project could be subject to changes in the next stages of project development.

The main equipment used to convert the solar energy to electricity is the following:

- Photovoltaic modules, which convert the solar radiation into direct current;
- Fixed mounting structure, which supports the PV modules;
- String combiner boxes, which consolidate the output of the strings of photovoltaic modules before reaching the inverter;
- Central inverters, which convert DC from solar field to AC;
- Power transformers, which raise the voltage level from low to medium voltage;
- Power stations, which hold inverters and transformers;

The simplified electrical configuration of the PV plant can be seen in Figure 23.

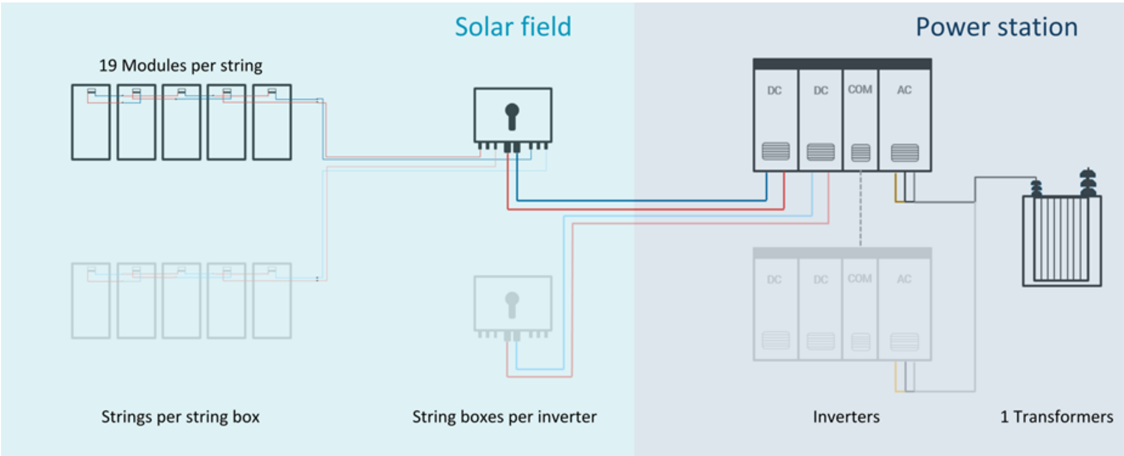

Figure 23: Simplified electrical configuration diagram

Seven different layouts with different performance were calculated for the site. The general layout remains the same (Figure 24). Only the number of modules and consequently the number of inverters, tables, boxes, etc. has been changed.

The seven layouts cover the range of the installations the Consultant considers useful. An eighth variant would simply reflect the current status, considering a "wind park only" set-up and leading to a PV part of 0 MW. Variant 1 displays the smallest PV part installation, reaching about 10 MW_{ac}. Then, in steps of about 10 MW, the variants go up to some 65 MW. The Consultant is aware that for Variant 6 and Variant 7 the installed capacity exceeds the evacuation capacity, even without any power delivered from the wind part. These two cases will show the impact of dimensioning higher than the limits remaining from public grid. The different variants are shown in Table 12:

Table 12: Layout PV Plant - Variants

Variant	Rated Power [MWac]	Peak power [MWdc]	Strings [-]	Nb. of inverters [-]	P_{nom} ratio [-]	Nb. of Modules [-]
1	9.36	11.23	1,344	6	1.2	25,536
2	18.72	22.46	2,686	12	1.2	51,034
3	28.08	33.70	4,030	18	1.2	76,570
4	37.44	44.93	5,375	24	1.2	102,125
5	46.80	56.16	6,715	30	1.2	127,585
6	56.16	67.39	8,060	36	1.2	153,140
7	65.52	78.62	9,405	42	1.2	178,695

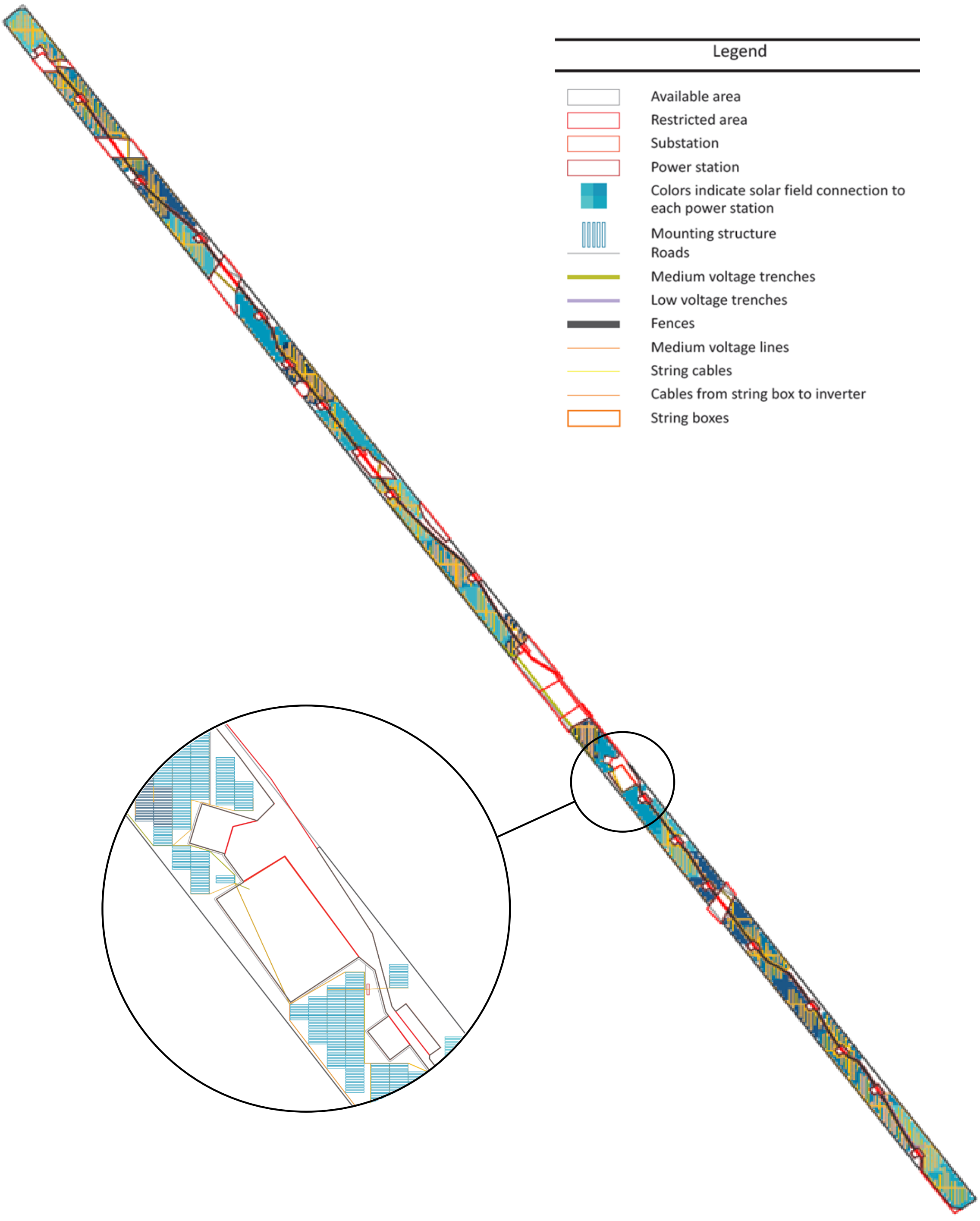

Figure 24: General Layout PV Plant

4.2.8 Calculation Methodology

The methodology to compute the energy yield requires the following inputs:

- The typical meteorological year,
- The parameters of the electrical equipment to be used,
- The electrical configuration of the photovoltaic plant,
- Simulation parameters such as losses or calculation settings.

The Consultant utilized the commercially available solar farm layout software “PVSyst” to calculate energy yield. PVSyst is a tool that allows accurately analysing different configurations and corresponding energy yield assessment and to evaluate the results and identify the best solution. With the above inputs, PVSyst sequentially performs the following steps to compute the final value of the energy yield:

- design of the PV array (number of PV modules in series and parallel), given the chosen plant components;
- analysis of fine effects like thermal behaviour, wiring, module quality, mismatch and incidence angle losses, horizon (far shading), or partial shadings of near objects on the array, and others;
- calculation of the energy yield of the photovoltaic modules, considering all associated losses for both scenarios – P50 and P90.

4.3 Wind/solar PV Hybrid

The challenge in hybridising PV and wind is, in addition to the difficult energy yield forecast, the mutual optimization of the both systems. In the first step, the area was planned like an ordinary wind farm. The turbine locations were optimized according to the AEP, taking into account the exclusion areas. In the next step, the park internal infrastructure, like roads, was planned. The third step was to place PV modules on the remaining area to subsequently execute an energy yield optimization. In the last step, the two technologies, especially the PV Plant in this hybrid project, is adapted. Figure 25 displays a part of the site, not considering northern direction of the map. It shows the approach when considering exclusion areas.

Further optimization can be made depending on the requirements. One example could be an adjustment of the PV-Layout-Orientation. A deviation of the PV from the south, and thus the maximum yield in addition to an east-west orientation, could reduce the curtailment around solar noon. Depending on the size of the PV field, the areas north, north-east and north-west in the vicinity of the WTG can be excluded in order to reduce shading losses.

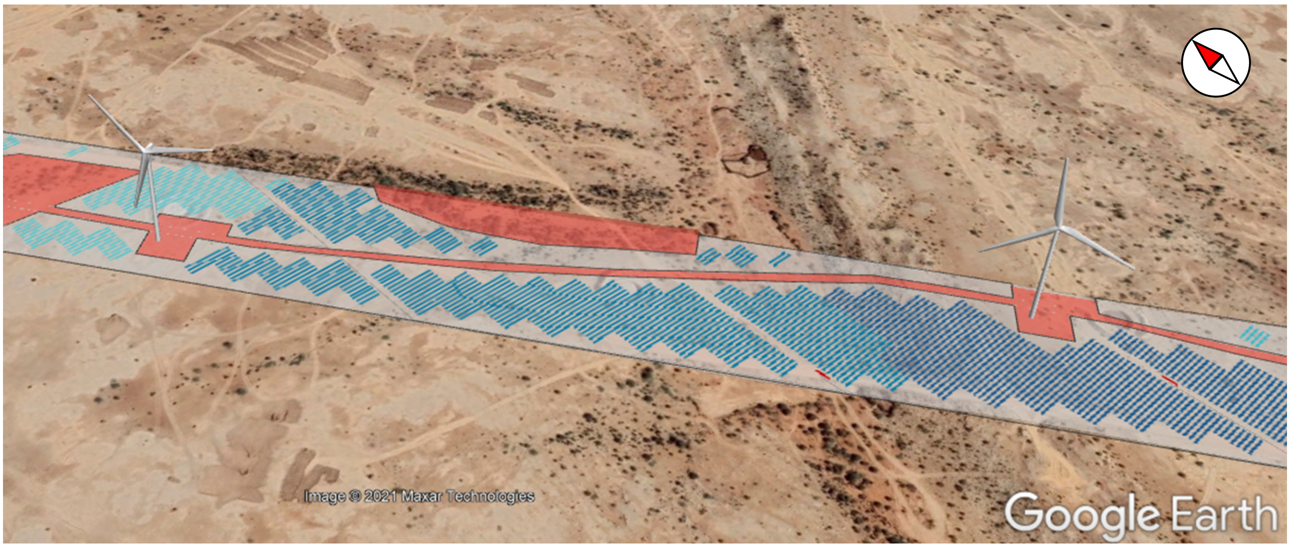

Figure 25: Exemplary hybrid scene with exclusion areas

4.3.1 Shading Caused by WTG

Hybridising wind parks with PV systems might cause internal shades from WTGs onto PV modules, negatively impacting the irradiance received by the modules. On the one hand, the tower of the WTG casts a shadow on the PV field, which is determined by the position of the sun over the course of the day and the year. Additionally the shadow of the nacelle and the rotor are also influenced by the wind direction and wind speed, resulting in a certain frequency of the rotor. Depending on the depth of review, the shading analysis turns out to become arbitrarily complex. In order to be able to approximate the shading losses that occur, the hybrid park layout described below was calculated using the shading simulation tool included in the PVSyst software. Having seen the many different fields of impact and to handle this extensive task, following simplifications have been made for the simulation (Figure 26):

- The wind direction is always from the southwest;
- The rotor stands still and with a rotor blade as an extension of the tower in order to achieve maximum shading height;
- The PV field in the designated area is densely built up;
- The topography is flat;
- The shape of the WTG is simplified.

With the results gained from this simplified model the Consultant is aware that, depending on the result and importance of the shading impact, it might be necessary to reduce the number of simplifications.

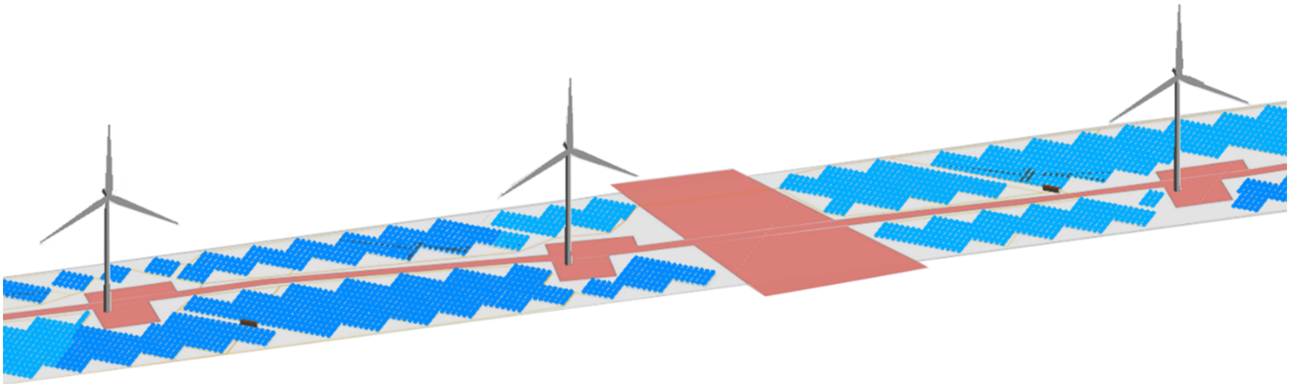

Figure 26: Simulation of Shadow effects with PVsyst

For the shading simulation, the entire available area for possible installations of PV modules of approx. 98 ha is occupied with 500 Wp PV modules with a tilt of 21° and a south orientation mounted on a fixed structure. With a pitch distance of 4 m, the ground coverage ratio (GCR) amounts to 51.04%. The considered PV plant has a rated power of 54.6 MW_{ac} and a peak power of 65.5 MW_{dc}. In total 131,040 PV modules and 35 inverters were installed on the site in this simulation design. Detailed of the described design are displayed in Figure 27. As seen in the shown layout, available space has been used completely. The Consultant assumes that there is no need to install a PV part for hybrid plant being bigger than the mentioned almost 55 MW_{ac}. This means that a result taken from this layout might be understood to reflect the maximum of shading losses. When reducing the installed capacity and by this reducing the PV covered area, the shading impact can only be lower than with the layout introduced in Figure 27.

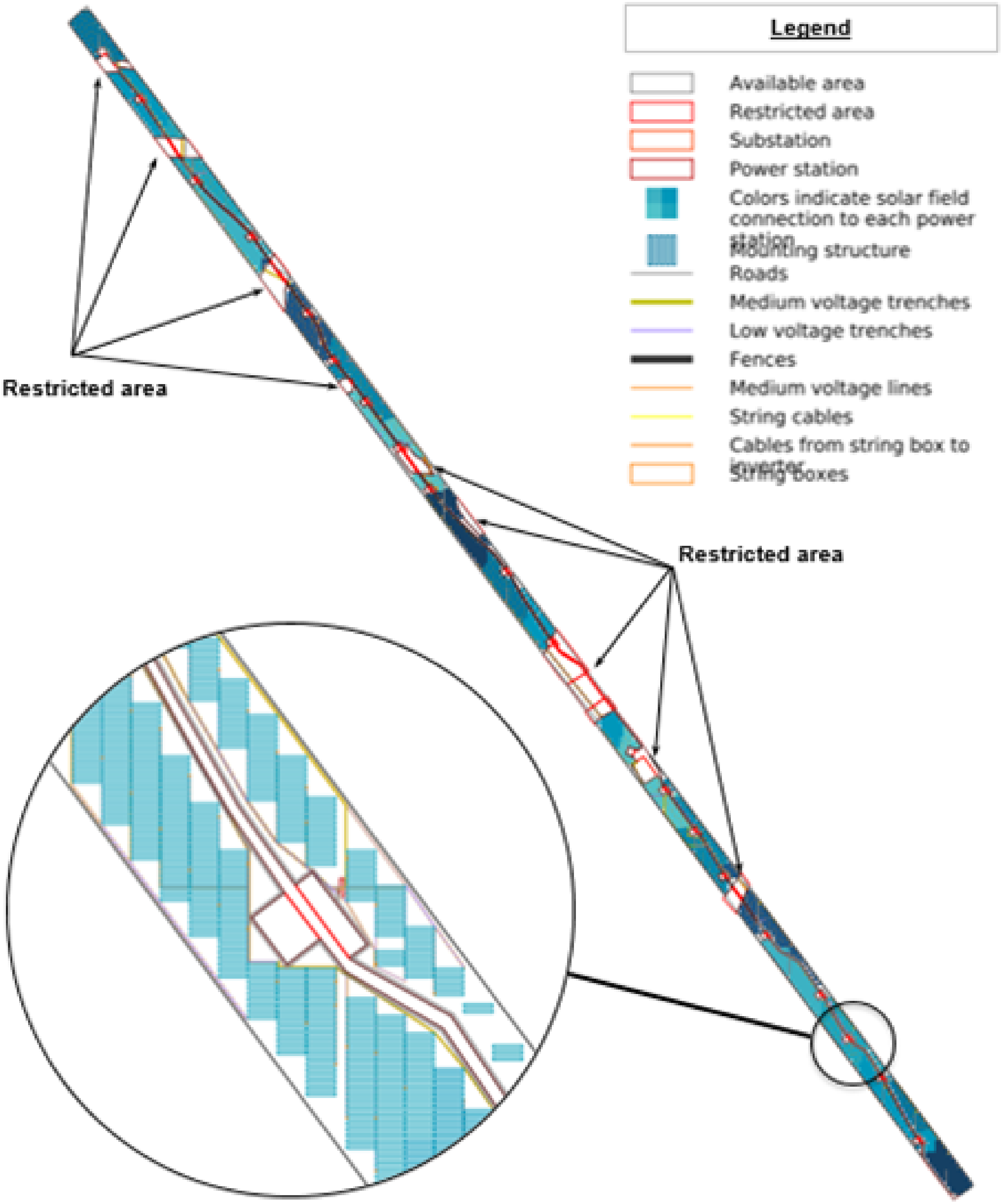

Figure 27: Hybrid layout for the Shadow simulation

The most important characteristics about the PV Plant are listed in the Table 13.

Table 13: Characteristics of the PV Plant (Shadow simulation)

Main characteristics	
Location	Pakistan, Sindh
Rated power (AC)	54.6 MWac
Peak power (DC)	65.5 MWdc
Ratio DC/AC	1.20
Civil characteristics	
Suitable plot area	97.74 ha
Ground coverage ratio (GCR)	51.04 %
Structure type	Fixed structure – 1V
Tilt angle	21.0 °
Pitch distance	4.0 m
Minimum ground clearance	0.5 m
Electrical characteristics	
PV Modules (500.0 Wp)	131040
Power station (up to 3120.0 kW)	18
Number of inverters (up to 1560.0 kVA)	35

Simulations have been run with the layout introduced above including the WTGs causing shading. Not all shading indicated by PVSyst is to be understood as a result of the WTG shading, PVSyst also considers further sources for internal shading, such as inverter buildings and shading caused from row to row in certain specific cases along the day. To identify these shadings the same model has been run in PVSyst without wind turbines. The results of both simulations (with and without WTGs) have been compared. The results per month of a typical year are shown in Figure 28 and the numbers on top of each bar reflect the additional losses caused by the WTGs.

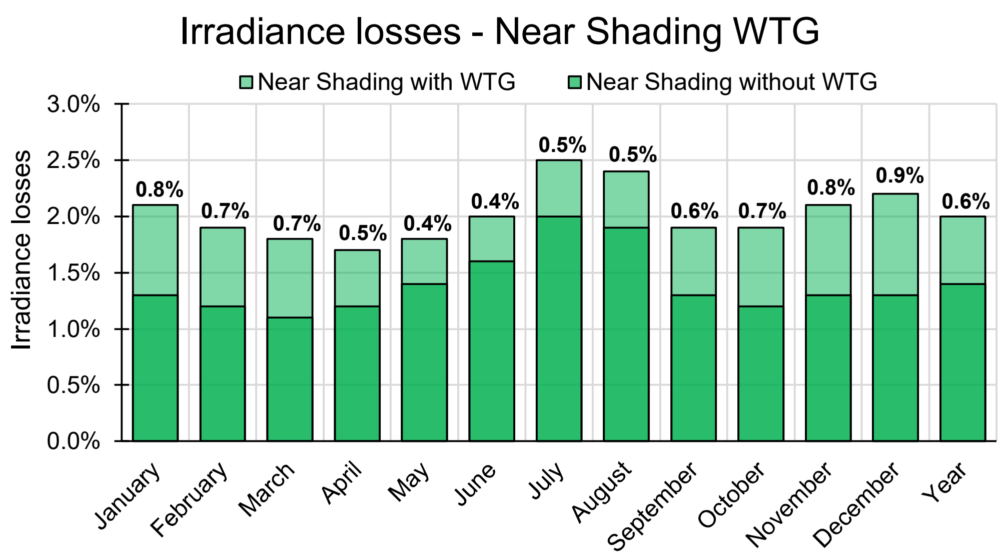

Figure 28: Results of Irradiance losses due WTG Shading

The annual impact of WTGs sums up to of 2 % of the total yield. Without WTGs the same models refers to 1.4 % of losses. Comparing this data the impact caused by the WTGs can be calculated to be 0.6% only. These additional losses are to be classified as low and the Consultant will not consider these losses further on within this study.

Figure 29 and Figure 30 show the horizon profiles with and without shading losses caused by WTGs, supporting the impression of low impact resulting from the WTGs.

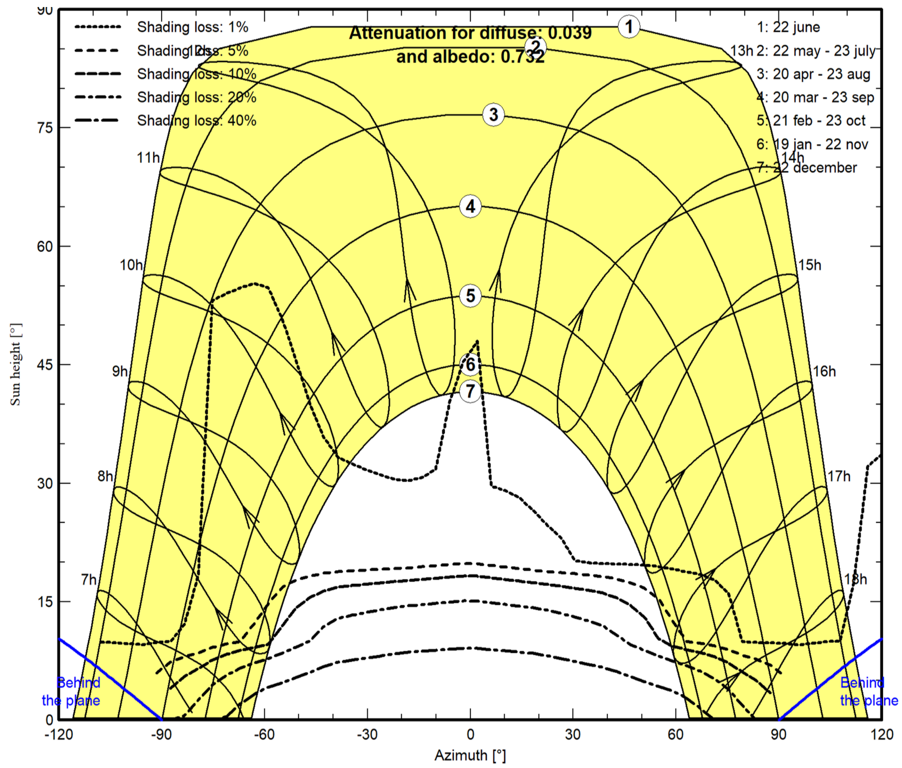

Figure 29: Horizon Profile and Shading loss with WTG

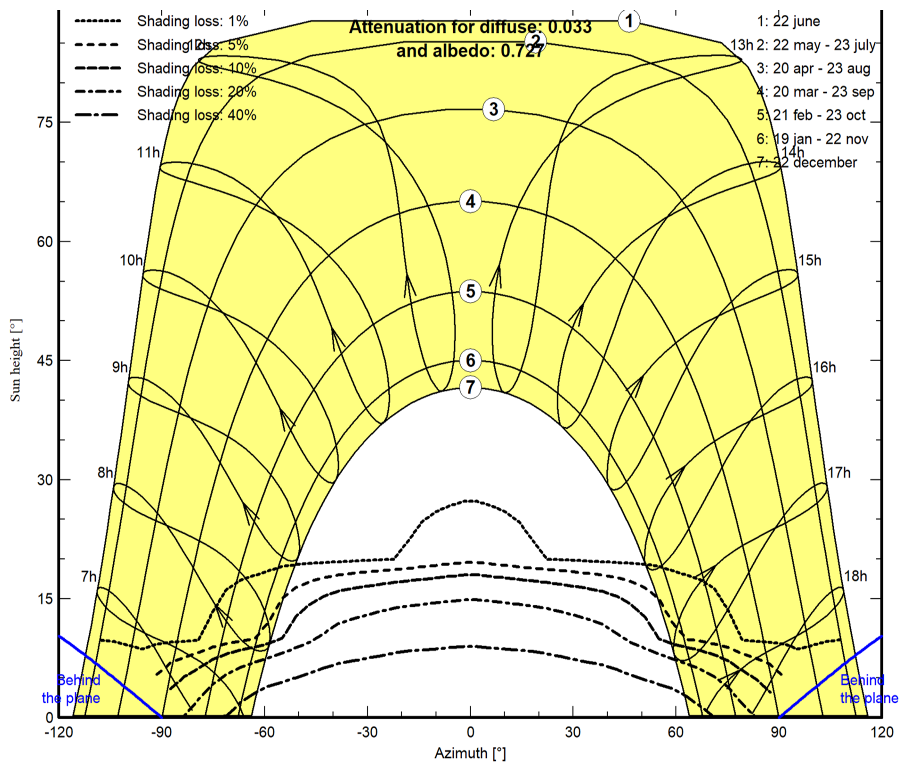

Figure 30: Horizon Profile and Shading loss without WTG

To complete the shading analysis, the following Figure 31 shows the shades caused by WTGs on 21st of December. This date represents the day with lowest inclination of the sun moving along the Tropic of Capricorn at different time stamps. At this day, the shading is the longest over the year, but it occurs at the days with the shortest period of daylight and by thus low solar yield results.

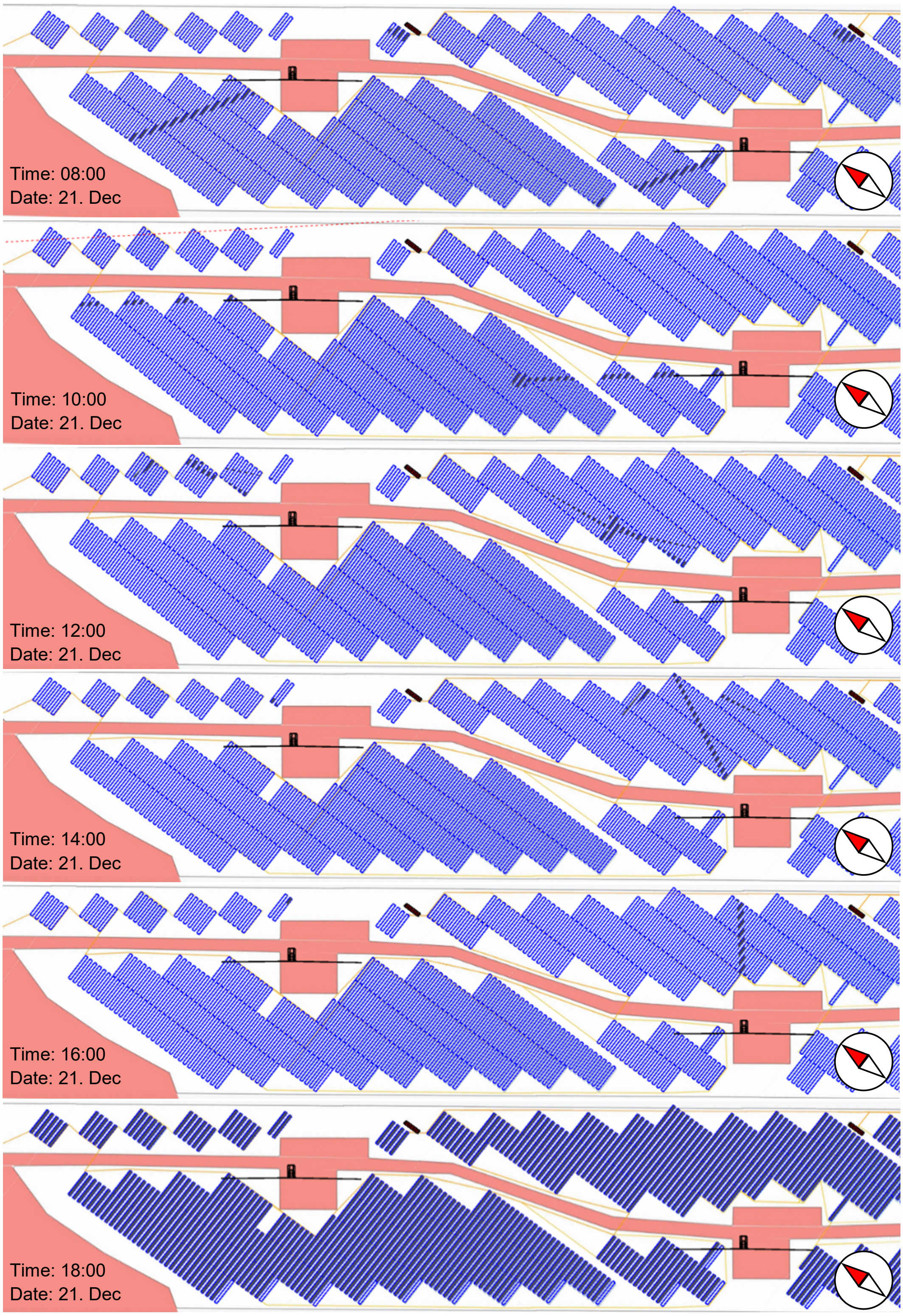

Figure 31: Shadow simulation of the 21. December at different time stamps

5. Expected Annual Yield and Hourly Resolution

Annual yield calculation based on given plant layouts are shown in this chapter. The calculation of the probability of exceedance values (P50; P75 and P90) are executed for all three types of power plant configuration, for wind alone, solar PV alone and wind / solar hybrid systems. The later mentioned values (P75 and P90) are often used to financially evaluate the robustness of the models and layouts as these values consider yield being same or more per year in either 75% (P75) or 90% (P90) of the cases. The likelihood for a financing institute of investing into a sound project is checked mainly with such values.

The task to analyse the probability of exceedance in different scale has been included into Consultant's task list for this part of the project. It is well understood that the consideration of the hourly resolution of the yields for wind alone, solar alone and wind / solar hybrid is important to understand the advantages of hybrid solutions but as well the resulting need for curtailment of the combined plant to avoid evacuation capacities of more than 50MW. Such comparison is done based on the consideration of the P50 values of each single plant and of the combination into a wind / solar hybrid system. Results of these analyses are given hereunder, mainly displayed in graphs and figures. This allows to understand detailed results of this huge amount of data quickly and without stepping into number crunching systems and needing preparation of extensive explanations.

The general approach to include P75 and/ or P90 analyses into an hourly breakdown of generation values will lead to an increase of the values. As one simply can understand, a forecasted value for one specific hour of the year, hosts huge uncertainties. It turns out that breaking down the probability of exceedance onto a shorter timeframe (than a year) will cause a tremendous increase for the mentioned P75 or P90 values. Also, the main interest for such values is with financing institutions and these are not interested in hourly values but in annual values.

This is the reason for not evaluating P75 and P90 values for hourly resolution analysis in the following pages.

5.1 Wind

Annual energy production (AEP) for the wind farm site was calculated based on the specific wind conditions, the specific power curve of the wind turbine and the thrust coefficient curve.

All results of an energy forecast are subject to fluctuations, losses and uncertainties Energy losses and uncertainties has to be assessed, in order to give an estimate of the expected net annual energy production (Net AEP) for a prediction horizon as well as the corresponding level of exceedance.

5.1.1 Technical Losses

The gross energy yield produced by the wind turbines is reduced by losses. An assessment of losses is conducted for the planned wind farm. Each identified source of loss is calculated relatively to the total energy output.

Losses are occurring along the whole energetic transformation chain from the rotor (kinetic energy) to the substation's delivery point (metered electrical energy). Individual losses are added up in the determination of the expected net energy yield by means of their diminished efficiency factors. The following sources of technical losses have been assumed or calculated respectively.

A. Array losses (wake losses)

After passing a wind turbine, the speed of the wind flow decreases due to the kinetic energy absorbed by the rotor and due to an increased turbulence caused by the rotation. While the speed difference to undisturbed flow is not equalized, the result is a lower energy yield for downwind-located turbines. The park efficiency is calculated with the N.O. Jensen (RISO/EMD) wake model. The wake losses are caused from the neighbouring wind turbines within the wind farm and highly depend on the wind direction.

The Consultant has considered wake losses due to new (red symbols corresponding to the hybrid wind turbines) and existing WTGs (blue symbols from the hybrid turbines) and future WTGs (blue symbols W from the hybrid turbines) as well (Figure 32).

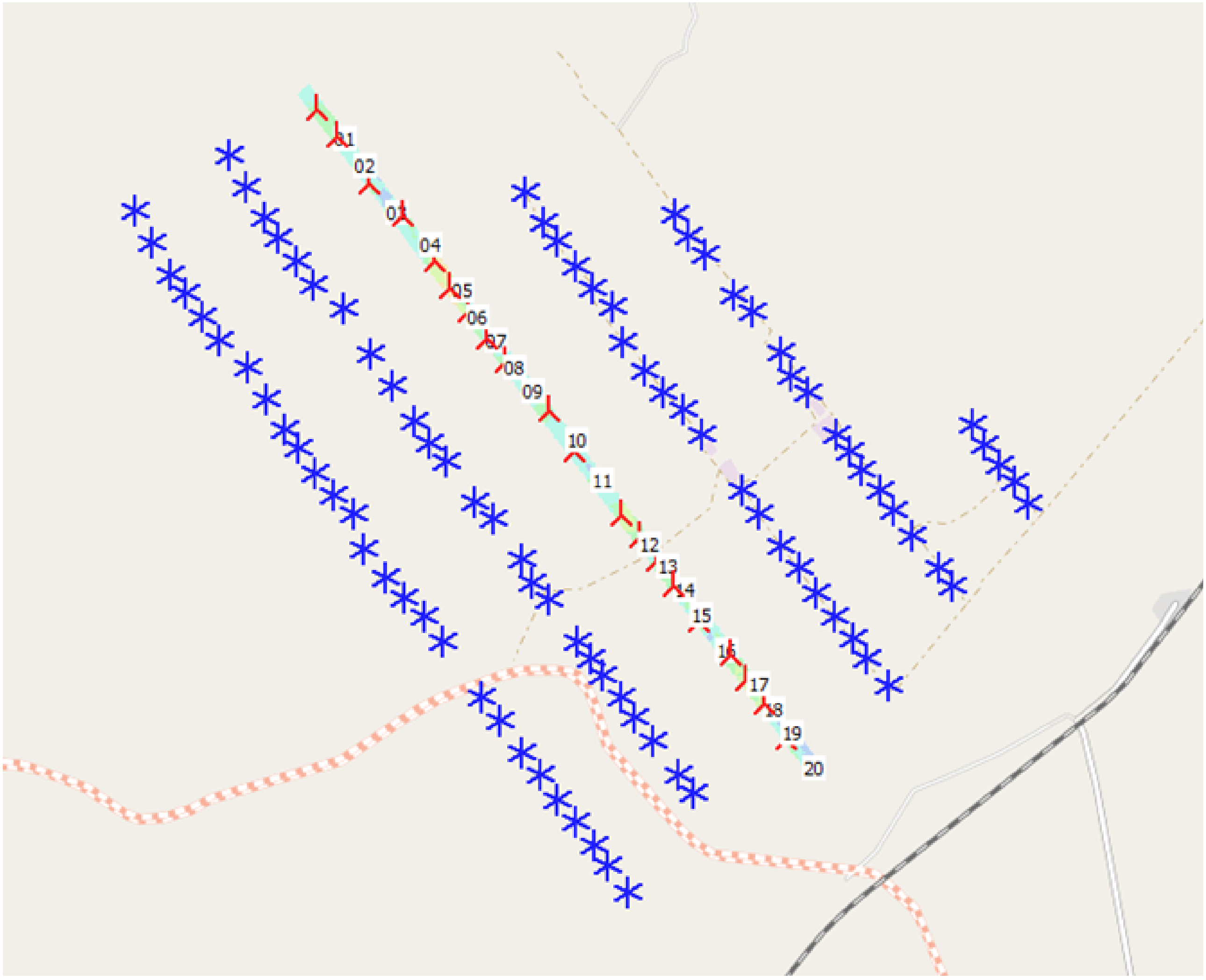

Figure 32: Layout of New and existing WTG wake losses

New and existing WTG wake losses amount to 2.8%. Future wake losses amount to 9.3%. Combined, wake losses achieve 11.8%.

B. Availability
The availability describes the percentage of time per year, when the turbine is actually operational and ready for production. It is noted that some turbine downtimes have contractually the status "available" (e.g. scheduled turbine maintenance) but no energy can be produced in the respective time period. The time-based availability is equalized with energy-based availability. An average long-term availability of 97.0% is considered as representative for the actual turbine availability, resulting in a loss figure of 3.0%. This figure assumes regular maintenance of the turbines, adequate reaction times of the service teams as well as adequate lead times for spare parts.

Further losses accounting for substation unavailability as well as grid unavailability are considered. Therefore 3.6% of losses in total due to unavailability is assumed adequate for the wind farm.

C. Turbine performance
Losses due to the turbine performance generally apply to the power curve not producing to its reference level. Reasons could be suboptimal turbine control settings, site-specific conditions, high wind speed hysteresis, wind flow inclination, high turbulence, dust and shear.

The site conditions are not complex resulting in minor flow inclinations and varying wind directions. However, there are strong influences on the wind flow due to wake effects so a loss factor for this category is determined to be 0.5% for the wind flow.

An average total loss factor for the turbine performance is determined to be 0.5%.

D. Electrical losses
Electrical losses occur during transformation between voltage levels and during transportation from the WTG to the metering point. Since there were no detailed information provided regarding the electrical design, generic losses from the turbine generator to the metering point are applied with 2.5% of the generated electricity. The metering point is considered located at the site substation.

E. Environmental
The environmental losses are referred to losses due to performance degradation from climatic and ambient conditions such as contamination and abrasion of blades, extreme temperature, force majeure events (e.g., site access), tree growth, etc.

A total loss factor for the environmental category is determined to be 0.5%.

F. Curtailments (regulatory and operational restrictions)
Losses can be caused by curtailments due to restricted operational conditions such as power restrictions, wind sector management, shadow flicker mitigation, noise issue, animal protection, etc. Wind sector management is not considered for this study. For the present case, the Consultant was not informed of any grid restriction or wild life protection mitigation measures (usually bats and migrating birds).

A total loss factor for the Curtailments is determined to be 0.0%.

G. Total losses

As mentioned before the given losses (except wake losses) are based on estimations and generic values. Detailed losses shall be determined in the further project development and detailed engineering phases (such as electrical design and contractual conditions for e.g., availability).

The total losses are calculated not by adding the single losses, but by multiplying the efficiencies (defined as one minus the loss). The total loss is given by:

$$L_{total} = 100\,\% - (100\,\% - L_1) \cdot (100\,\% - L_2) \cdot (100\,\% - L_3) \cdots$$

where the values L_n are the individual losses in percent.

The following table presents the net annual energy yield for the hybrid wind farm layout applying the losses as described above.

Table 14: Gross free-flow and Net AEP

Goldwind G121	Value
Gross (free-flow) AEP P50 [MWh/a]	**239,499**
Wake Effects	11.8 %
Availability	3.6 %
Turbine Performance	0.5 %
Electrical	2.5 %
Environmental	0.5 %
Curtailment	0.0 %
Energy Losses	17.9 %
Net AEP P50 [MWh/a]	196,624

5.1.2 Uncertainty Assessment and NET AEP

Throughout the report, calculations are made based on models, which describe the reality or predictions out of past data to future occurrences. Even though the data and calculation are in line with real world occurrences and with good quality, they are still linked to uncertainties. Each step, starting with the wind measurement campaign setup up to the calculated energy output of the whole project, is afflicted with a particular uncertainty. To assess the overall uncertainty (U_{total}), the single uncertainties are considered as stochastically independent and calculated as the root of the squared sum, whereas U_i is the single uncertainty.

$$U_{total} = \sqrt{U_1^2 + U_2^2 + U_3^2 + \cdots}$$

To determine these uncertainties, it is reasonable to split the uncertainty evaluation into a wind and an energy related field. The quantified values for each uncertainty is estimated according to international standard practice in the wind industry or based on the experience of the Consultant.

A. Wind speed related uncertainty

I. Measurement uncertainty

These uncertainties cover deviations of the mast setup from the recommended practice in cup anemometry and the IEC standard as well as influences to the measurements from the mast itself, from the booms and mounting clamps. The uncertainty of measured wind data depends on measurement system equipment, its quality standard, sensor calibration and mast configuration.

II. Wind Speed (Cup-Anemometer)

This uncertainty parameter covers amongst others the abrasion, the technical characteristics and the calibration procedure of sensors. Offset as well as slope parameters were adopted for logger setup. The Project site is considered as simple terrain accordingly only a minor degree of flow distortion to the sensor measurements is considered.

Correspondingly, a total uncertainty of 2.9% is estimated for the wind speed measurement.

III. Wind Direction (Wind Vanes)

On the measuring masts, three wind vanes were installed each at different heights. However, there was no information about the correct installation and calibration of the north marking.

Accordingly, an increased uncertainty of 1.5% is estimated for the wind direction measurement.

IV. Mounting

The uncertainty category mounting covers the deviations of the mast setup from the IEC standard as well as the influences to the measurement from the mast itself, booms and mounting clamps.

The uncertainty of the measurement due to mounting in total is estimated to 2.2%.

B. Data processing

I. Data Integrity

The wind data has been delivered to the Consultant in logger raw data and as processed data. Since the documentation of the measurement campaign is scarce, the data integrity uncertainty is relatively high (3.0%).

II. Data Analysis

Data analysis covers the uncertainty in the data processing and is applied for parameters such as duration of the measurement campaign, data coverage, measurement consistency, data processing and methodology in fitting the actual wind frequency distribution to Weibull distribution.

A total uncertainty of 3.5% for the category data analysis has been estimated.

III. Long-Term Correlation

The uncertainty of the long-term assessment considers quality, consistency and representativeness of the reference data, the correlation between site data and reference data as well as the uncertainty of the applied methodology. The long-term assessment is referenced to a representative period of the past of 30 years using ERA 5 data, that is sufficiently correlating with the on-site wind measurement.

An uncertainty of 2.0% is estimated and applied to this category.

C. Prediction Horizon

The prediction horizon describes the fluctuation of the annual average wind speed. For any period of interest, the wind speed fluctuates in the long-term. The uncertainty in terms of standard deviation of this fluctuation around the long-term annual average wind speed is determined to be 5.3% for a 1-year period and about 1.68% for a 10-year period on basis of the applied long-term reference data set.

D. Energy related uncertainty

The predicted energy yield is based on the results of wind flow modelling, which represents the wind conditions at turbine positions at hub height. Uncertainties of this modelling as well as uncertainties of the applied power curve and the determined losses are directly related to the energy level.

I. Transfer wind speed related uncertainties to energy related uncertainties

The interpretation of uncertainty in energy yield arising from the total uncertainty in wind speed is not straightforward. The theoretical cubic relation of wind speed and energy does not give a correct description of the phenomena. Hence, a sensitivity analysis is carried out using the following approach:

The calculated total wind speed related uncertainty is considered as a reduction to the wind speed. To transfer this reduced wind speed into the energy level, a likewise adapted wind speed frequency distribution is applied to the considered power curves. The difference between the calculated energy production derived from this distribution and the energy yield of the original distribution represents the energy related uncertainty which is displayed in the “Energy related” column in the following tables below.

II. Modelling

The uncertainty in the wind flow modelling includes uncertainties in surface roughness, orography (topographical description), the horizontal and vertical wind speed extrapolation from the meteorological mast to the wind turbine locations, as well as limitations of the model. The planned wind turbines are deployed on flat step area not influenced by any significant obstacles.

A total uncertainty for modelling is estimated to 4.4%.

III. Power Curve

The energy yield calculation has been done with calculated power curves. The uncertainty value of 5.0 % has been applied.

IV. Losses (Uncertainty of loss estimation)

Although the losses have been mostly approximated and/or generic values have been used, each loss position is subject to an uncertainty in its assessment. The uncertainty estimated for the determination of losses is 4.4% as shown in the following summary tables of uncertainties.

Table 15: Summary of uncertainties considered in the assessment of wind energy production

Summary of uncertainties		
Wind Speed (cup anemometer)	2,9%	
Wind Direction (wind vane)	1,5%	
Mounting	2,2%	
Subtotal (measurement)	3,9%	
Data Processing		
Data Integrity	3,0%	
Data Analysis	3,5%	
Long-term correlation	2,0%	
Subtotal (data processing)	5,0%	
Total (wind speed related)	6,4%	
		GW121 2.5MW
Transfer of Wind Speed To Energy		12,7%
Prediction horizon [years]	10	
1-year wind deviation	5,3%	8,4%
10-year wind deviation	1,68%	2,6%
Modelling		4,4%
Power curve		5,0%
Losses (uncertainty of loss estimations)		4,4%
Total Uncertainty on Net Production 1 year [%]		17,2%
Total Uncertainty on Net Production10 year [%]		15,2%

5.1.3 Expected Annual Energy Yield

The probability of occurrence of higher or lower energy generation compared to that level determined by prediction (the P50) can be obtained from the standard uncertainty, i.e., standard deviation, assuming a normal distribution according to the following probability density function:

$$f(x) = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{1}{2}\left(\frac{x-\mu}{\sigma}\right)^2}$$

where: σ = standard deviation [MWh]
μ = calculated energy yield [MWh]

Probability of Exceedance (PoE)

The gross energy production is reduced by all identified losses to achieve the net value of the energy production (P50 Net), which means that this energy yield is probable in 50% of all years. P50 means that there is a similar probability (50%) of exceeding the given value or of falling short.

In the field of wind energy this value serves as the base case scenario, i.e. “best estimate”. However, in order to determine a higher confidence level of the calculated results, the results are connected with uncertainties and presented for different Probability of Exceedance (PoE) levels. The most frequently used PoE levels are 50%, 75% and 90%, i.e., P50, P75 and P90. A given AEP as P75 or P90, respectively, has a 75% or 90% probability of being exceeded and only a 25% or 10% probability of not being achieved (shortfall).

Applying a Gaussian distribution for the statistical analysis, the calculated AEP P50 can be understood as the mean annual energy yield having the highest rate of probability of all single results. The calculated total uncertainty is understood as standard deviation of the expected results around the most probable event. The deviations of the P75 and P90 from the base case scenario (P50) are closely related to the uncertainties determined for the individual steps of the process, which are discussed in the previous section. The higher the uncertainties are, the larger the deviations downwards of the P75 and P90 from the base case P50.

Table 16 shows a summary of the estimated Net AEP figures for the wind farm layouts and the selected turbine models. Furthermore, all results are given for different confidence levels as well as for a 1-year and a 10-year prediction horizon.

Figure 33 gives an overview of the predicted Net AEP and the associated exceedance levels on the planned wind farm site.

Table 16: Predicted net annual energy production (AEP) - P50;P75:P90

Goldwind G121-2.5MW	P50	P75	P90
1 year - Net AEP [MWh/a]	196,624	172,249	150,310
10 year – Net [MWh/a]	196,624	176,221	157,857

The capacity factor[1] is a very good instrument to give a picture on the quality of a site. The number is calculated by dividing the production in MWh per year by the installed capacity and the total hours of the year. The result is then the cumulative theoretical amount of time during which the wind farm is running at full capacity (Table 17).

Table 17: Capacity Factor - P50;P75;P90

Goldwind G121-2.5MW	P50	P75	P90
1 year - Net [%]	44.9 %	39.3 %	34.3 %
10 year - Net [%]	44.9 %	40.2 %	36.0 %

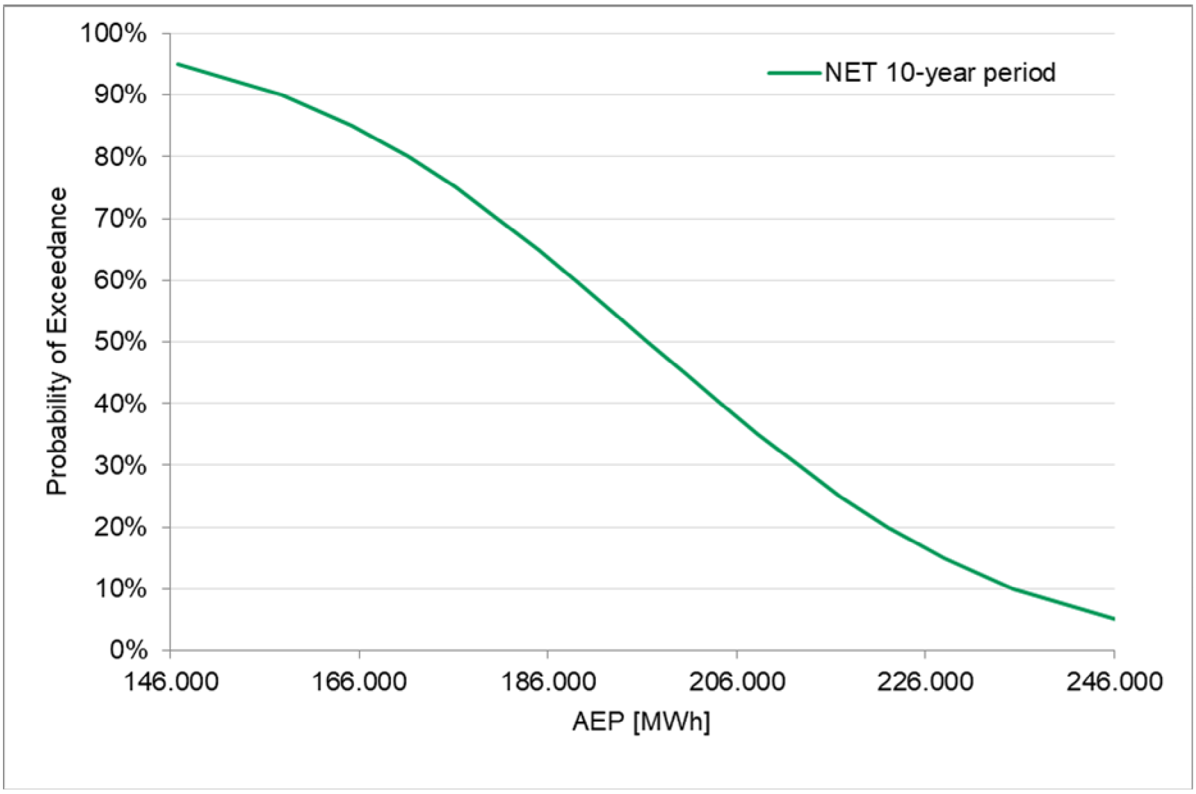

Figure 33: Probability of Exceedance for NET 10-year period – Goldwind G121-2.5MW

5.1.4 Expected Annual Hourly Generation

For the understanding of the analysis of the hourly resolution data it is necessary to have read the intro into this chapter, Chapter 5.

5.2 Solar PV

5.2.1 Losses

The irradiance seen by the plane of array is computed by transposition of the global horizontal irradiance to the tilted plane. Because of the tilt angle, the transposition results in an irradiance gain

[1] A capacity factor of almost 45% for wind only is unexpected high. Calculations with last years' turbine types led to a result of about 35% only. This verified the meteorological input data.

with respect to the irradiance, which would be received by a horizontal plane. This gain might be increased if the mounting structure is of the sun-tracking type.

Far Shading

The presence of obstacles in the horizon line (such as hills or buildings) will negatively influence the irradiance reaching the photovoltaic modules. This will occur in the times of day when the sun elevation is lower. An obstacle is usually considered to be part of the horizon profile if the size of its shade is more than ten times greater than the size of the photovoltaic plant. The far shading loss is computed against a hypothetical plant with no horizon obstacles. Considering Far Shading impact is automated in that way that the surrounding elements in the area are considered. PVSyst generates the impact itself.

Near Shading

Contiguous rows of photovoltaic modules will block the sunlight to nearby rows whenever the sun elevation is low. These shades will negatively influence the irradiance received by the photovoltaic modules.

The yearly loss due to the near shadings is ignored due to the possible wide distribution in most applicable variants. This loss is due to the reduced diffuse and albedo irradiance seen by the modules, and because of the shade cast by the fixed structures whenever the sun elevation is low. Losses caused by WTGs have been analysed separately for a densely covering PV part and are described in Chapter 4.3.1. The impact remaining from WTGs is very small and has not been considered in the calculation of the variants.

IAM Effect

A loss is incurred due to the non-zero angle of incidence of the sun rays on the plane of array, in addition to the cosine effect. A fraction of the light reaching the surface of the modules is reflected by the glass cover protecting them. This loss is computed using an Incidence Angle Modifier (IAM) coefficient, which is a function of the glass used.
The front face glass was modeled according to the manufacturer specifications, using a custom IAM profile found in the PAN file.

The losses due to the IAM effect were of -1.7 %.

Soiling

The deposition of dirt and dust on the surface of the module causes a direct loss of irradiance known as soiling loss. This impact is greater for oblique sun rays than for perpendicular rays. The soiling loss is easily minimized by regularly cleaning the photovoltaic modules. It also is reduced whenever the atmospheric conditions result in the removal of dirt from their surface (through rain or wind). However, in transient conditions of high pollution the loss may be as high as 8 %, e.g. in between cleaning operations. Other conditions which influence the soiling loss are the proximity of roads, the terrain characteristics, or the tilt angle of the modules.

The soiling loss is modelled as an average value constant throughout the whole year, with a value of -3.00 %.

Photovoltaic Module Degradation

An initial degradation of the module performance occurs in the first hours of exposure to sunlight, known as the Light Induced Degradation loss (LID). However, after this initial degradation, a more long-term process takes place which results in a yearly loss of performance. This degradation occurs due to corrosion of the conductors and a gradual failure of the back-sheet seal of the module. Atmospheric conditions such as high temperature swings, rain, ambient humidity, and salinity may accelerate the corrosion.

The value of the 10 year degradation -3.8 % was considered.

Irradiance Level
The loss due to the irradiance level refers to the lower production of the photovoltaic module whenever the irradiance is lower than 1000 W/m^2 (STC conditions).

The irradiance level loss was -0.2 %.

Temperature Loss
The production of photovoltaic cells is negatively affected by high operation temperatures. The loss is a consequence of the photovoltaic module characteristics. The cell temperature is always higher than the ambient temperature.

The yearly loss due to the module cell temperature was -7.7 %.

Photovoltaic Module Quality
The rated power of mass-produced photovoltaic modules varies on a module-to-module basis. This dispersion of the module performance is usually modeled as percentage of the variation against the rated power in STC conditions. The dispersion often results in a net gain, as the manufacturers usually aim for tighter tolerances with a bias towards a slightly higher than rated performance.

The gain due to module quality dispersion was of +0.60 %.

Electrical Mismatch
The mismatch loss occurs because of the variation of electrical characteristics between photovoltaic modules connected in series in an array. This means the modules are not always able to operate at their maximum power operating point.

The value of the loss was constant throughout the whole year, -3.9 %.

DC Cable Losses (DC Ohmic Losses)
There is a loss due to the Ohmic effect incurred in the electrical transmission of DC power. This loss occurs in the cables connecting the photovoltaic module strings to the string boxes and inverters (or directly to the inverters if the plant is designed using a DC bus system).

The value of the transmission losses depends on the cable cross sections and cable lengths, which are usually calculated by specifying a value for the voltage drop in STC conditions. A value of 1.0% for the DC ohmic losses and 0.8% for AC losses has been considered.

Inverter Loss
The main loss incurred in the electrical inverter is the conversion of DC to AC, usually known as the efficiency loss. Additional losses may occur if the sizing of the DC array with respect to the rated power of the inverter is not optimal (inverter operation window losses).

The combined losses in the inverter were -2.1 %. This value includes the efficiency loss, operation window losses and the auxiliary consumption loss.

Plant Unavailability

Unavailability occurs from scheduled maintenance operations, which may require the plant to be unproductive, and from unscheduled stops due to unforeseen circumstances. The loss value depends on the plant O&M contract and the performance of the O&M contractor. These parameters are unpredictable at this stage. Therefore, the PV plant's unavailability is estimated in this report to be -1.2%. However, random dates for maintenance were chosen for the calculation

The losses are graphically visualized in the loss diagram (Figure 34):

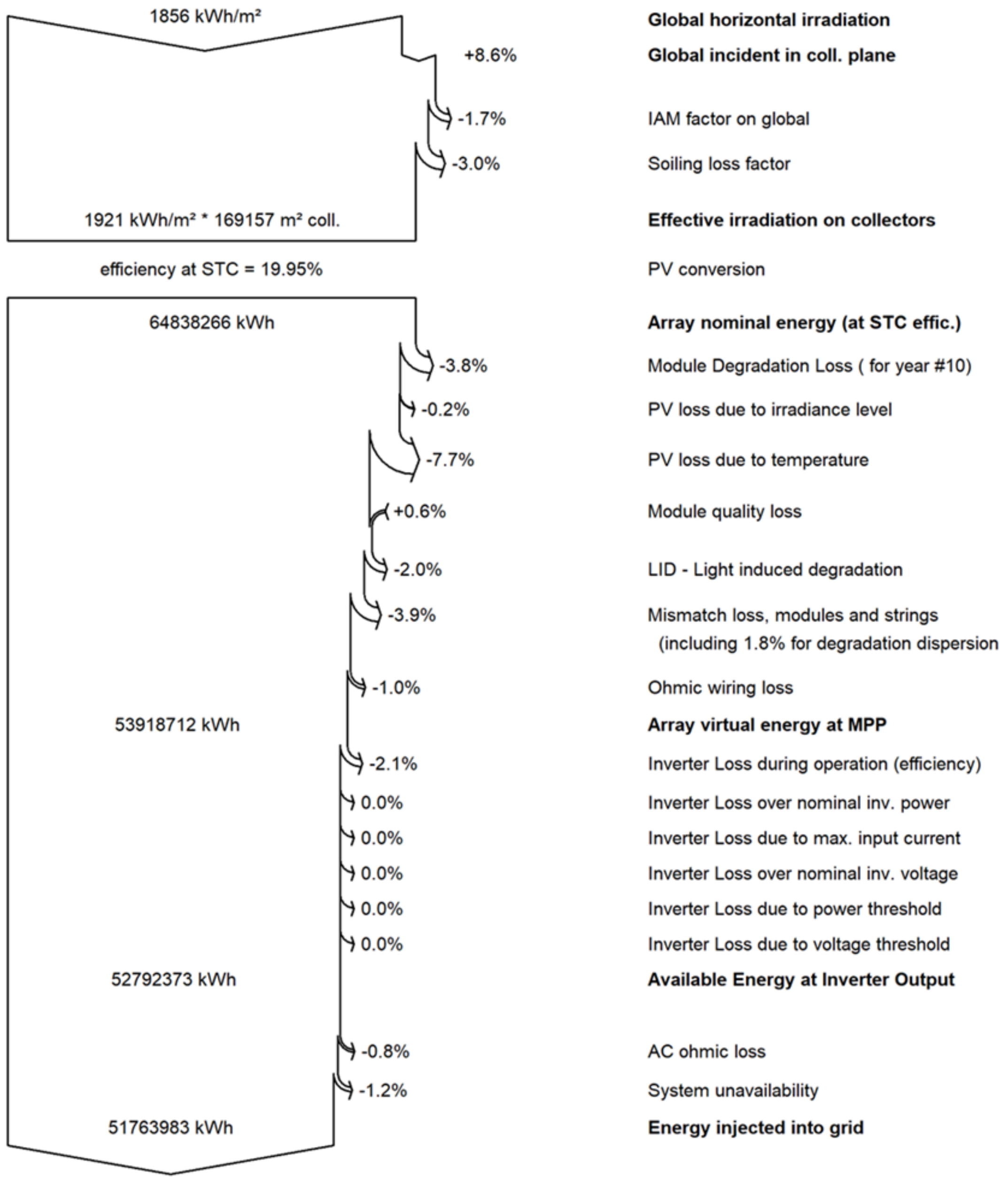

Figure 34: Energy Yield and Losses of Variant 3 (P50)

5.2.2 Expected Annual Energy Yield: P50; P75; P90

The annual yield has been calculated for the different PV variants and PoE reduction for P75 and P90 have been considered. A total uncertainty of 1.87 % was assumed for the calculation of the PoE values. Table 18 summarises the annual yield values.

Table 18: Expected Annual Energy for different Variants - P50;P75;P90

Variant	Rated Power [MWac]	P50 [MWh/a]	P75 [MWh/a]	P90 [MWh/a]
1	9.36	17,253	17,035	16,839
2	18.72	34,480	34,045	33,653
3	28.08	51,730	51,077	50,489
4	37.44	69,000	68,129	67,344
5	46.8	86,200	85,111	84,132
6	56.16	103,470	102,163	100,987
7	65.52	120,730	119,205.	117,833

For one of the variants, Variant 3 Figure 35 shows the probability distribution curve.

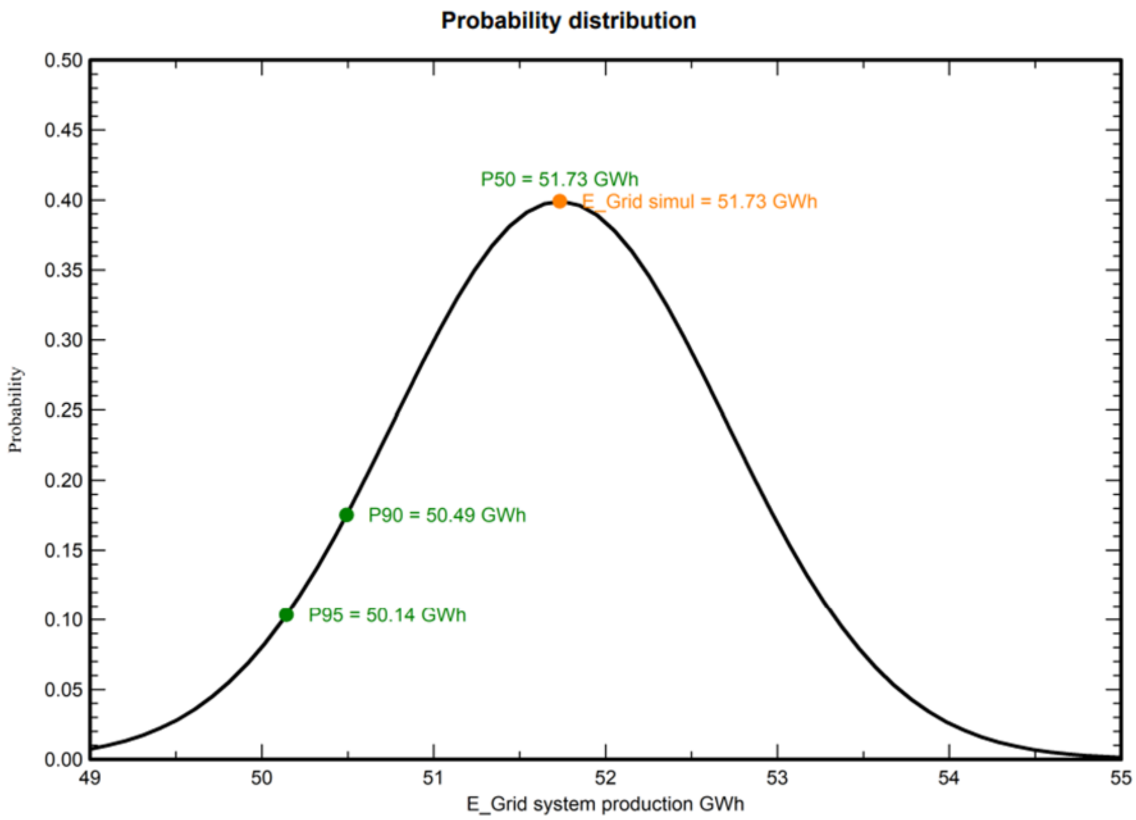

Figure 35: Variant 3 - Probability distribution - P50;P90;P95

5.2.3 Expected Annual Hourly Generation

For the understanding of the analysis of the hourly resolution data it is necessary to have read the intro into this chapter, Chapter 5.

5.3 Wind/solar PV Hybrid

The combination of two regenerative and fluctuating energy resources have some challenges for the model calculation of the energy yield, which can only be solved optimally to a limited extent. While the behaviour of the wind / solar hybrid can be well considered at night, some assumptions have to be made during the day due to the cumulating of the two energy yields. Rather, it is a question of the correlation between PV and wind yields. If the two energy yields correlate well, this is an disadvantageous for the hybrid park, as it neither makes a contribution to better use of the grid nor has an economic advantage. Only the land use speaks for this case. For an economically sensible use, the yields must correlate as little as possible. This allows the advantages of hybridization to be fully exploited. The advantage then lies in the higher capacity, the higher yield, the reduced variability of the generation as well as the maximized utilization of the infrastructure of the power plant.

In the studied hybrid park, the correlation of the yields varies according to the season. During the summer half-year, the yields correlate much better than in the winter months. This leads to increased curtailments in summer, depending on the design of the hybrid.

For an abstraction of the yields over the year for the wind park, the PV plant and the commutated yields for the hybrid park, the yields were averaged and displayed per month. This means, one typical day per month has been prepared in hourly resolution. The results for a 28.08 MWac rated power PV Part (Variant 3) combined with the wind park, the outputs are shown in the Figure 36. It is important that it is an abstraction, i.e. a simplification of the complex situation. By averaging the values, yield peaks and downturns are neglected. Figure 37 & Figure 38 show hybrid combinations with differing PV part sizes.

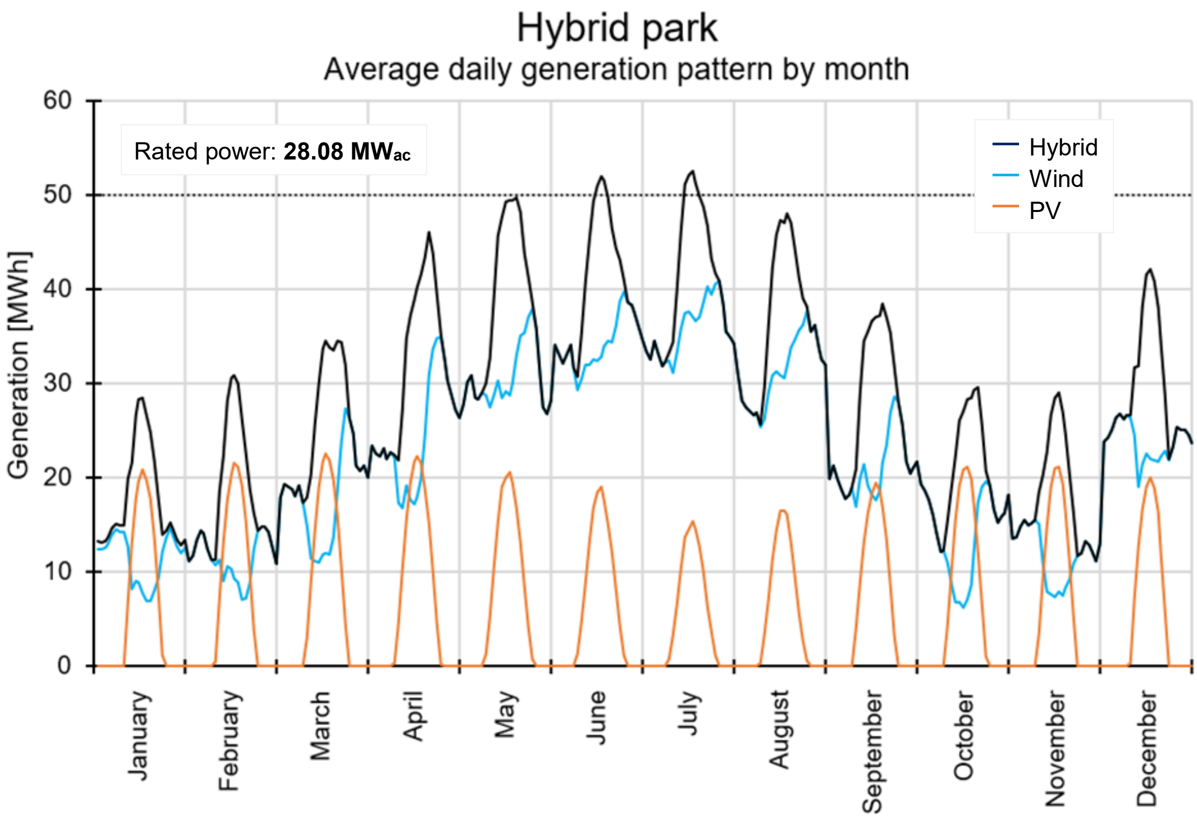

Figure 36: Hybrid park - Average daily generation by month - PV rated power 28.08 MWac

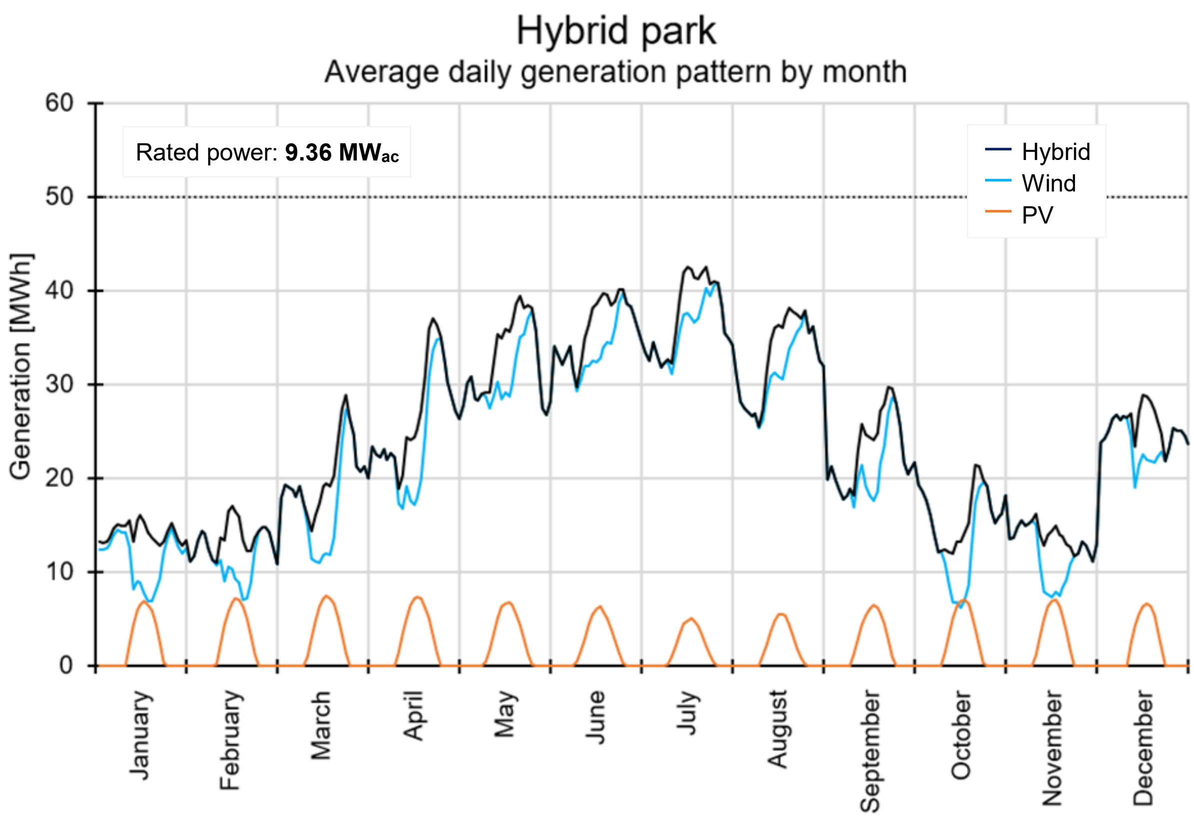

Figure 37: Hybrid park - Average daily generation by month - PV rated power 9.36 MWac

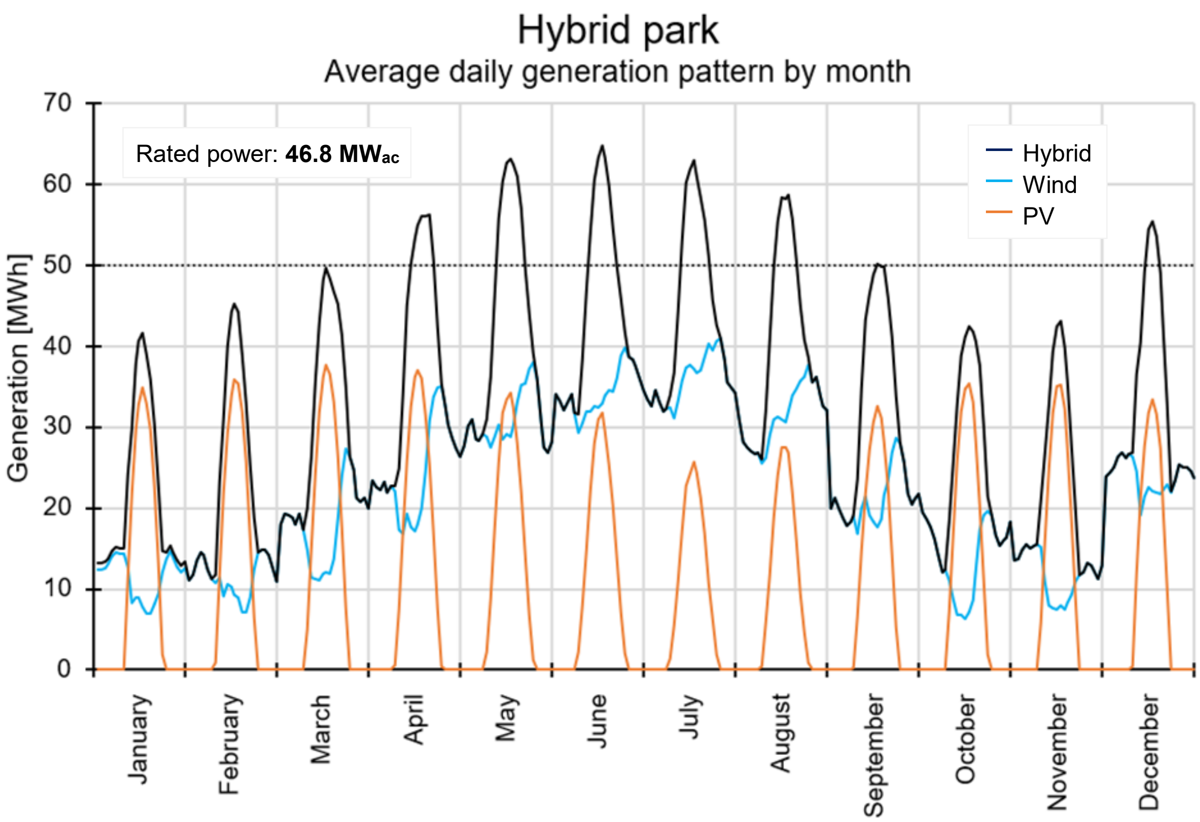

Figure 38: Hybrid park - Average daily generation by month - PV rated power 46.8 MWac

5.3.1 Calculation Model

In order to be able to calculate the hybrid yield, hourly P50 yield data of the PV and the wind farm are used and summarized. The hourly wind yield is calculated from the long-term corrected wind data. Future wake effects are already taken into account in the hourly energy yields. For every hour of the year, the yields from PV and wind are added up. Whenever (in hourly resolution) the sum exceeds the 50 MW value (better: the 50 MWh/h value, as only hourly averages are under discussion), the exceeding amount is considered curtailed. These curtailed amounts are summed over the year. According to this calculation model, the yield of the hybrid park and thus the capacity factor as well as the curtailments are determined. This approach involves a certain degree of uncertainty due the fluctuating effects of the resource, which cannot represented arbitrarily.

5.3.2 Expected Annual Energy Yield

For further assessments, seven PV Plant sizes were evaluated using the previously explained model. The different variants are explained in chapter 4.2.7.The influence of the PV size on the expected hybrid yield and curtailment is shown in Figure 39.

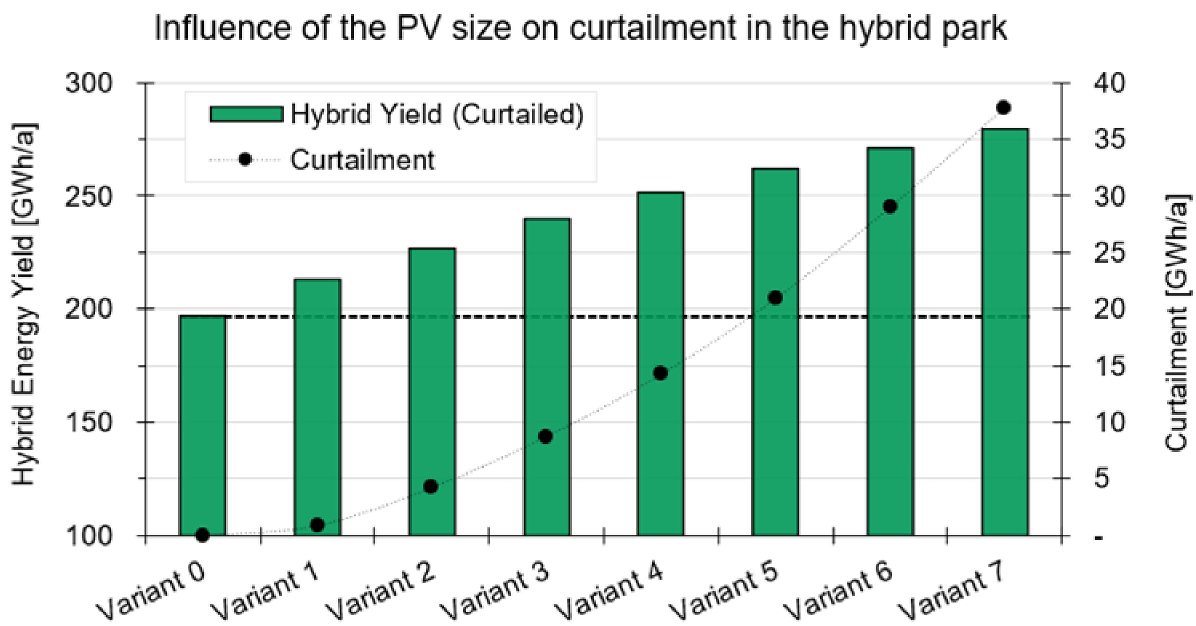

Figure 39: Influence of the PV size on curtailment in the hybrid park

From Figure 39, it can be seen that the curtailments increase when the size of the PV increases. However, the ratio of higher energy yield to curtailment decreases with increasing system size. Variant 3 enables a higher yield of 12.77 GWh/a compared to Variant 2, whereby between variants 5 and 6 it is only 9.18 GWh/a with the same increase in Rated Power.

The following Table 19 give an overview of the predicted energy yields of different hybrid park layouts.

Table 19: Predicted energy yield of the hybrid park - P50

Variant	PV Rated Power [MWac]	PV Yield [GWh/a]	Wind Yield [GWh/a]	Hybrid Yield [GWh/a]	Curtailment [GWh/a]	Capacity Factor [%]
1	9.36	17.25	196.62	212.97	0.904	48.6%
2	18.72	34.48	196.62	226.83	4.271	51.8%
3	28.08	51.73	196.62	239.61	8.751	54.7%
4	37.44	69.00	196.62	251.37	14.256	57.4%
5	46.8	86.20	196.62	261.92	20.909	59.8%
6	56.16	103.47	196.62	271.10	28.995	61.9%
7	65.52	120.73	196.62	279.59	37.763	63.8%

Figure 28 visualises the development of curtailment with increased PV part size. The diagram displays the total generated energy of the respected wind/ solar hybrid park. This is reflected by the total size of the bars, the green part of the bar represents the amount possible to deliver into the public grid under the condition the maximum evacuation power is 50 MWh/h. The red part shows the amount of curtailed energy. The black dash and the dotted line refer to the right side y-axes and display the capacity factor of each version. The capacity factor is calculated by the ratio of the energy delivered into the grid on the one hand and the maximum possible energy, calculated from the 50 MW connection capacity times 8760 hours/year. The diagram shows that the increase of the capacity factor is considerable high when applying wind/ solar hybrid systems, but the increase reduces from Variant 4 on, meaning that investments into higher solar capacity turns out to be less efficient.

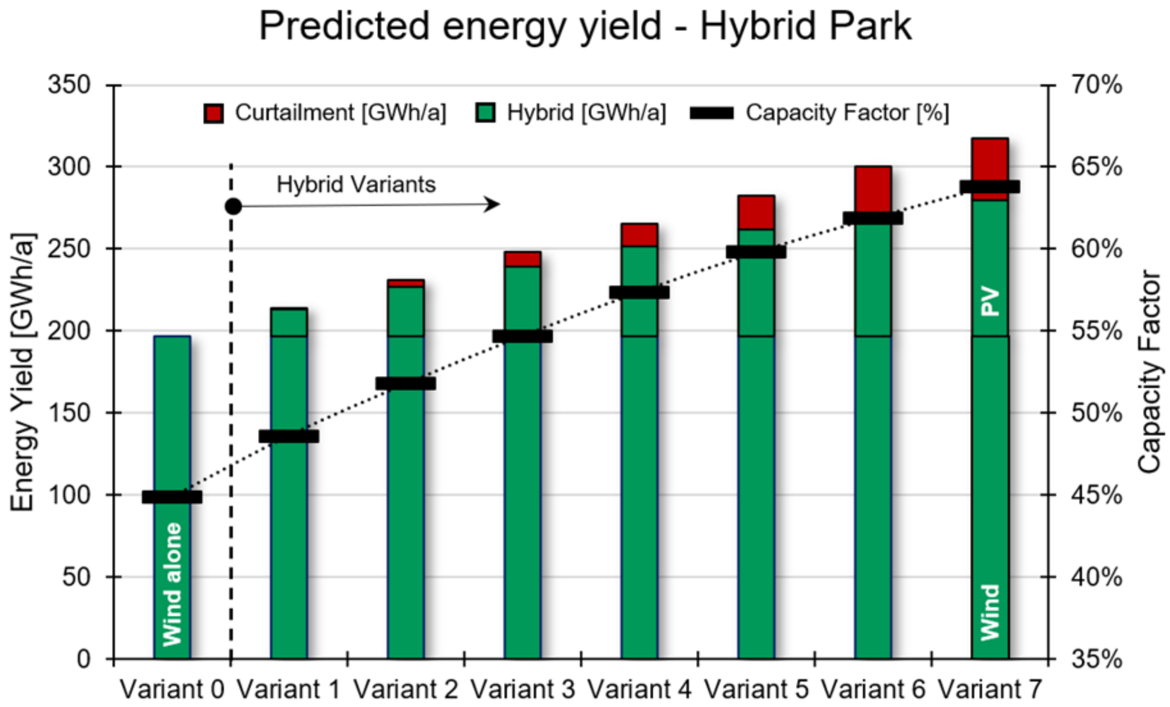

Figure 40: Predicted energy yield - Hybrid Park

5.3.3 Expected Annual Hourly Generation

For the understanding of the analysis of the hourly resolution data it is necessary to have read the intro into this chapter, Chapter 5.

6. Conclusion

The study shows some very important results:

- State of the art wind turbine types allow for increased annual yield (compared to current situation).
- Nevertheless, hybridisation still leaves room to increase the energy evacuation into the public grid.
- Shadow analysis for a densely packed park layout display the impact of shading caused by WTGs to be very low and insignificant. This is the reason for the Consultant not to follow up this review for further layouts.
- Adding solar power to the wind park causes the need for curtailment within the hybrid park. Only for wind only parks curtailment is zero.
- Accepting curtailment shows the option to increase the amount of evacuated power over the year. This is correct for almost all sizes of solar parks but at a certain installed solar capacity the increase becomes considerable less.
- The decision on which technology's output to be reduced when curtailment is necessary has not been touched as results of this discussion are not in the focus of this study. This decision shall be taken by every IPP / operator himself. It is likely that the decision will often lead to the main curtailment organised by shutting down turbines as the operational costs for the WTG can be considered higher than for the PV part.
- No financial analyses have be run for the task A as this is not part of the assignment. A technical limit cannot be seen. The Consultant assumes that such measure would show a clear optimum.
- Technologies chosen are not any cutting edge technologies. By this, IPPs might have room to increase the financial viability of the hybridisation.
- No consideration others than module being fixed mounted and facing south have been analysed. The curtailment curves seem to show good opportunities to either face a one axis tracked system or an East/ West installation (instead of south facing).
- The Consultant displayed that the approach of implementing a hybrid park in Sindh region shall be considered in the nearer future.

7. Appendix A

Power curve of the wind turbine Goldwind GW121-2.5 MW

GW 121/2500 Calculated Power Curve and Thrust Coefficient

Prepared by

GOLDWIND

Goldwind International Holding(HK) Limited

Contents

GW 121/2500 Calculated Power Curve and Thrust Coefficient

Turbine Type: GW121/2500 with Sinoma59.5 blade

Reference Standard: IEC61400-12-1-2005

1. Calculated GW121/2500 Power Curve – Standard Condition

Air Density: 1.225kg/m^3

Turbulence Intensity: 10% or below

Wind Speed at Hub Height (m/s)	Power Output (kW)	Wind Speed at Hub Height (m/s)	Power Output (kW)
3	63	14.5	2500
3.5	113	15	2500
4	188	15.5	2500
4.5	279	16	2500
5	384	16.5	2500
5.5	513	17	2500
6	666	17.5	2500
6.5	847	18	2500
7	1056	18.5	2500
7.5	1294	19	2500
8	1555	19.5	2500
8.5	1805	20	2500
9	2068	20.5	2500
9.5	2302	21	2500
10	2457	21.5	2500
10.5	2494	22	2500
11	2500		
11.5	2500		
12	2500		
12.5	2500		
13	2500		
13.5	2500		
14	2500		

2. Calculated GW121/2500 Thrust Coefficient – Standard Condition

Air Density: 1.225kg/m^3

Wind Speed at Hub Height (m/s)	Thrust Coefficient	Wind Speed at Hub Height (m/s)	Thrust Coefficient
3	0.9957	14.5	0.1463
3.5	0.8846	15	0.1323
4	0.7969	15.5	0.1201
4.5	0.7968	16	0.1094
5	0.7969	16.5	0.1001
5.5	0.7969	17	0.0919
6	0.7969	17.5	0.0846
6.5	0.797	18	0.0781
7	0.7969	18.5	0.0724
7.5	0.797	19	0.0672
8	0.797	19.5	0.0625
8.5	0.7907	20	0.0584
9	0.7504	20.5	0.0546
9.5	0.6248	21	0.0511
10	0.4981	21.5	0.048
10.5	0.414	22	0.0451
11	0.3513		
11.5	0.3024		
12	0.263		
12.5	0.2309		
13	0.2041		
13.5	0.1817		
14	0.1626		

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MEMBER OF GOPA CONSULTING GROUP

Feasibility Study to determine optimal capacity of hybrid wind/solar PV projects in Pakistan

Task B: BESS and LCoE Calculations

Study Report

October 2021

Study Report

Feasibility Study to determine optimal capacity of hybrid wind/solar PV projects in Pakistan

Renewable Energy and Energy Efficiency II - Pakistan

Task B: BESS and LCoE Calculations

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Executive Summary

The Task B report in hand is a follow-up of the Task A report dated September 2021. Whereas the Task A report was reflecting the technical details of opportunities for a Wind/PV hybrid system to be implemented in Sindh, Pakistan, the Task B report in hand displays opportunities for adding an electrical storage system plus analyses the economic impact by presenting the Levelized Cost of Energy (LCoE) for a number of combinations.

With all variants the grid connection parameters have been kept constant. This means that starting from a "wind only" plant with a grid connection of maximum 50 MW for evacuation no changes have been taken for further variants. It follows the usual way wind power plants in the area are currently connected. This quite strict approach has been set as a condition for the study. Consequently, when installing a 50 MW wind power plant and adding even a small PV power generator of less than 10 MWac, there will be certain times within a year where the generated power exceeds 50 MW and curtailment is needed due to the fact that the grid connection cannot absorb the whole power. Extending the on-site set-up with an electrical storage device (BESS) might help to store the exceedance for a while and to restore power into the grid whenever the power generation is below 50 MW.

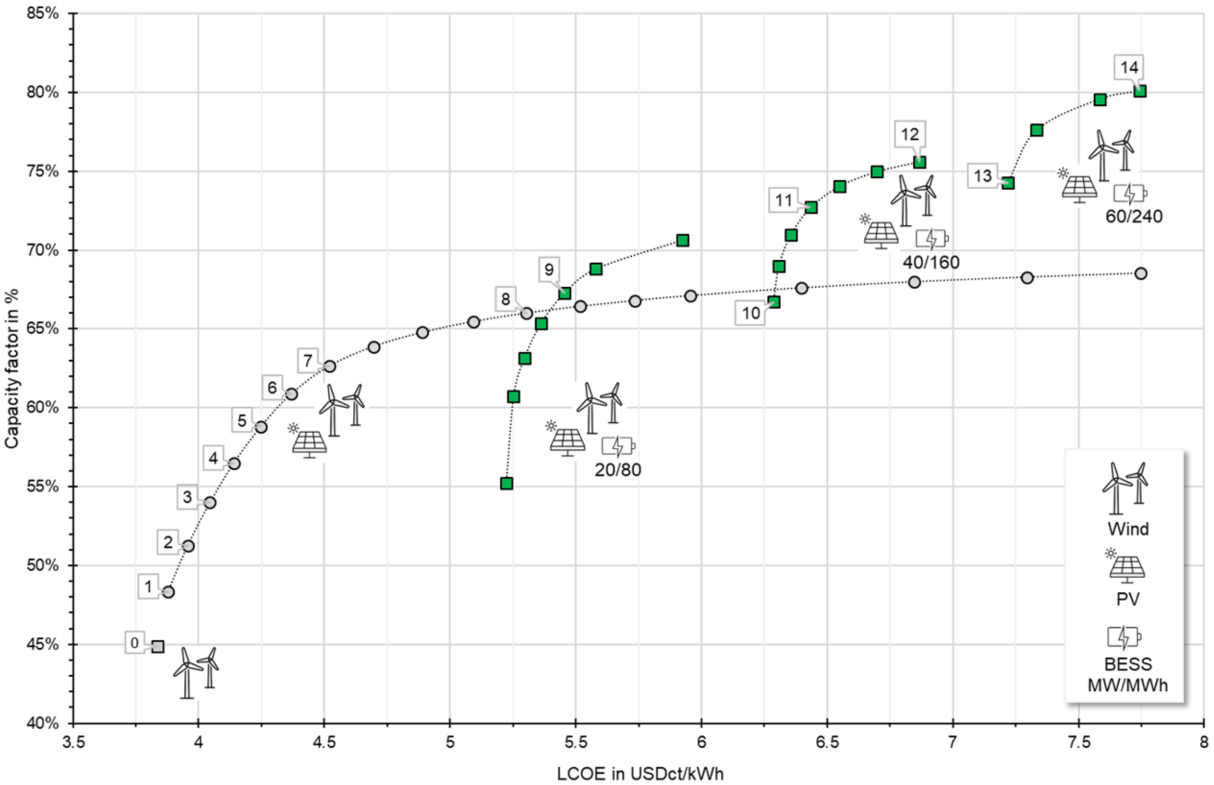
Two additional facts need to be mentioned before understanding the results:

- Currently operated wind power systems seem to show a Capacity Factor of around 35%. This means: If all power would be delivered in a rectangle shape (50 MW permanently), the grid connection is used in 35% of the hours of a year, being a bit more than 3000 hours per year. A layout with up-to-date WTGs increases the Capacity Factor to almost 45%.
- No adapted regulation for BESS systems are in place in Pakistan. This means: The price for the discharged power transferred into the grid is equal to the price of directly delivered (wind or PV) power from the plant. Considering the losses within the BESS and considering that shifting power to a time with huge demand or delivering of grid services is not payed for, BESS will be an economic hurdle for the complete set-up.

Economical calculations for wind/PV/BESS combinations are not possible in a linear way as the curtailment can mitigate the generation losses due to degradation over the years. This is why balances need to be prepared for all years and afterwards add into a common routine to calculate the LCoE.

The main result of the two reports (Task A and Task B report) is summarized into one single diagram, please see Figure 1. The diagram shows the LCoE on the x-axis whereas the y-axis displays the Capacity Factor of the grid connection. It is quite clear that under current conditions (means based on calculation with up-to-date WTGs) still the "wind only" plant is the configuration with the lowest LCoE. This result shows that the region in Sindh is not only labelled to be a "wind corridor" but also delivers such results. Going along on the a-axis the next point is quite close, but represents a bit higher LCoE. This grey and circular dot (labelled "1") represents a hybrid system including 50 MW wind power part plus a 9.36 MWac PV power part. As said, slightly higher LCoE is forecasted but at the same time a considerable higher Capacity Factor is calculated. Following this curve to somewhere between label no. 3 (Wind 50MW, PV 28.08 MWac) and no. 4 (Wind 50MW, PV 37.44 MWac) the gradient of the curve seems to turn to lower values. This is from whereon increase in Capacity Factor will cause higher increase in LCoE. All BESS solutions (shown in lines with green squares) are located far more to the right within the diagram. They represent higher LCoEs due to reasons explained above in the second bullet.

One can clearly understand that all green square dots being located beneath the line with the grey circles represent installation / combinations which are less effective with regard to the increase of the Capacity Factor while increasing the LCoE as well. These cases are not worth to consider because there are pure wind/Solar PV combinations being equal or more efficient but with lower LCoE. The lines with the green squares are crossing the line with the grey circles only at relatively high LCoEs.



Modalities:

Grid connection		**PV**		**BESS**	
Supply limit	50 MW	Degradation	0.607 %/a	Loss of charge	6 %
CAPEX	7 million USD	CAPEX	811.2 USD/kWac	Loss of discharge	6 %
OPEX	80,650 USD/a	OPEX	13.2 USD/kWac	Degradation	1.84 %/a
				Replacement	50 % after 13 Years
LCOE		**Wind**		CAPEX	190 USD/kW
Discount rate	6%	Degradation	0.000 %/a		290 USD/kWh
Plant-Lifetime	25 years	CAPEX	1,450 USD/kW	OPEX	7 USD/(kWh a)
Construction phase	1 year	OPEX	24.9 USD/kW	Include Salvage value of BESS	

Figure 1: LCoE and Capacity Factor of Wind/PV Hybrid and Hybrid + BESS

From a technical point of view a lot of combinations bring additional value into the system, but commercially assessed the selection of a preferred combination goes back to the discussion on the value of additional Capacity Factor. Increase here needs to be "bought" and the correct point for such additional LCoE values is subject to a decision of the responsible entities.

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List of Abbreviations

AC	Alternating Current
AEDB	Alternative Energy Development Board
BESS	Battery Energy Storage System
BoP	Balance of Plant
CAPEX	Capital Expenditure
DOD	Depth of Discharge
EES	Electrical Energy Storage
GWh	Giga Watt Hours (1,000 MWh)
LCoE	Levelized Costs of Energy
Li-ion	Lithium Ion Battery
MRA	Maintenance Reserve Account
msec	Millisecond
MTBF	Mean Time Between Failures
MW	Mega Watt
MWh	Mega Watt Hours
NaS	Sodium Sulphur Battery
NPV	Net Present Value
O&M	Operations and Maintenance
OPEX	Operational Expenditure
PbA	Lead Acid Battery
SOC	State of Charge
VRB	Vanadium Redox Battery
VRE	Variable Renewable Energy

1. Introduction

Variable renewable energy (VRE) is characterized by its intermittence, randomness and uncertainties. As the rate of VRE penetration continues to increase, high proportion VRE generation has become a global concern for the future energy system scenario. In this scenario, power system characteristics have changed dramatically, and large-scale VRE integration has posed increasing challenges to the safe and reliable operation of the power grid. To address this problem, energy storage technology has been widely studied as an effective means to mitigate the fluctuation of VRE generation. After the introduction of energy storage into the system operation, demand-side management can be performed effectively, the difference between peaks and valleys can be reduced, and the load can be smoothed.

One of the main advantages of energy storage technology is the possibility of ancillary services, such as adjust frequency and compensate for load fluctuations (e.g. redispatch). In contrast to that it has to be considered that an energy storage also consumes energy. Accordingly, the services of the battery must compensate for this additional cost factor.

This report builds on the previous report “Feasibility Study to determine optimal capacity of hybrid wind/solar PV projects in Pakistan" (Task A) and its results. This Task A report analysed opportunities for the hybridisation of the wind parks in the Sindh region in Pakistan. The general idea is to use the very good wind resources in the way currently done but to add a share of Solar PV power production to increase the production of the complete ensemble. The grid connection of the wind power plants offers a capacity of maximum 50 MW and this shall not be changed. Task A report showed that the combination of wind power projects with PV power generation (hybridisation) will help to increase the capacity factor of the grid connection. Task A covered this fact from a technical point of view.

The objective of this Task B is to technically discuss the extension of a Wind/ Solar PV Hybrid system with an electrical storage device, a Battery Energy Storage System (BESS). Therefore, an introduction into the BESS technologies is given in Chapter 2. The most suitable BESS layout for the Wind/ Solar PV Hybrid Park will be identified. Selection criteria will be the best possible minimised curtailments and an increase of the capacity factor of the grid connection. A number of suitable solutions and their calculations will be introduced in Chapter 3. Commercial aspects of the different set-ups of Wind/ Solar PV Hybrid systems including BESS variants will be analysed by applying the LCoE method (Chapter 4). For all combinations of Wind/ Solar PV Hybrid systems introduced in the Task A report plus the variants with BESS from this report an estimate of CAPEX and OPEX will be given. Parameters for LCoE calculations will be defined and the energy balance will be analysed in hourly resolution for a 25 years' lifetime for each combination. A good understanding on the conditions will be gained via diagrams displaying the commercial and technical results. After identifying the challenges of commercial viabilities the Chapter 5 will display opportunities to use ancillary services for the grid. Chapter 6 addresses the conclusions taken from the analysis of this report and will combine the most important diagrams to introduce the questions to be answered before deducing final future targets.

2. BESS Design Specifications

2.1 Energy Storage System

Electrical power networks face great challenges in transmission and distribution to meet demand with less predictable daily and seasonal variations. Adding VREs into the generation for such systems might cause an additional impact onto the power networks and their operation. Electrical Energy Storage (EES) is recognized as underpinning technology to enable great potential in meeting these challenges. Energy might be stored by applying different physical methods and is extracted when needed. Maybe a conversion of the stored energy to electrical energy is necessary before delivered into an electrical network.

Generally, energy storage devices can be classified according to their technology. It is needed to differ into electrical, mechanical, chemical, electrochemical or thermal energies for storage. An overview over different storage opportunities is given in Figure 2.

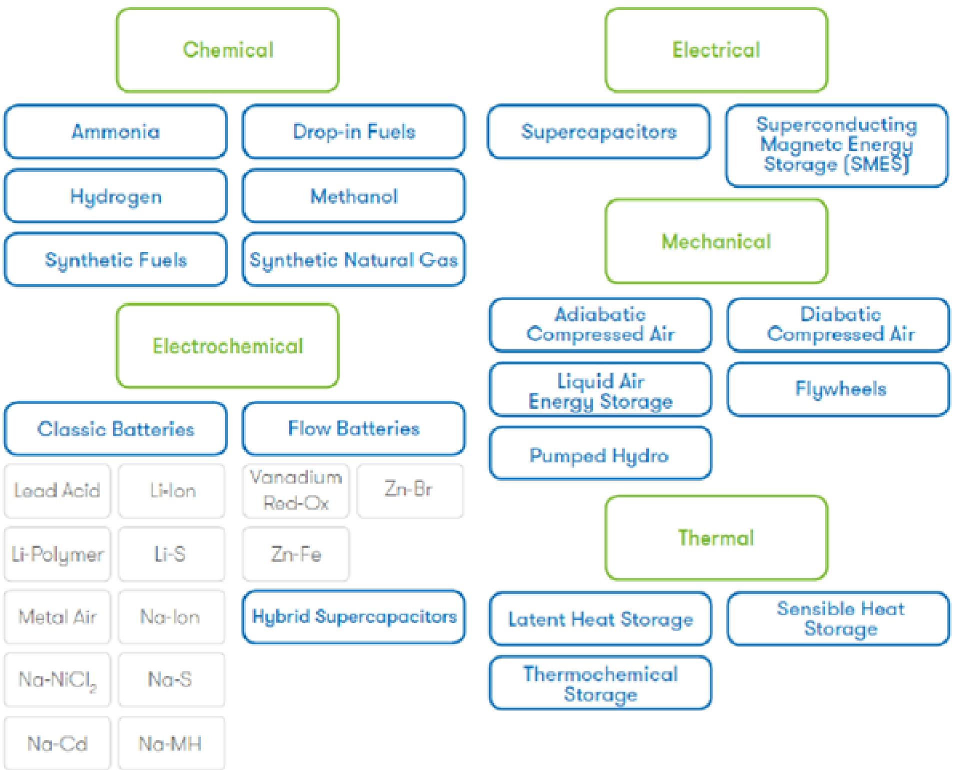


Figure 2: Classification of Energy Storage Systems. Source: EASE [1]

EES can have multiple functions to power network operations and load balancing, such as:

- Helping in meeting peak electrical load demands;
- Providing time shifting energy management;
- Lightening the intermittence of renewable source power generation;
- Improving power quality/reliability;
- Meeting remote and vehicle load needs;
- Supporting the deployment of smart grids;
- Helping with the management of distributed/standby power generation;
- Reducing electrical energy import during peak demand periods.

Even though the potential benefits of EES installation to power system operation have been widely recognized, some significant challenges in the deployment of EES systems exist, mainly in:

- How to choose the suitable EES technology to match the power system application requirements, and
- How to accurately evaluate the actual values of deployed EES facilities including technical and economic benefits.

Focusing on the first challenge, ESS usually are qualitatively classified according to the power versus discharge duration to identify their suitability for different applications that are also grouped according to the level in the energy system (generation, T&D networks, end-users) and their power and energy requirements:

- Energy management, concerning the supply of power to loads independently of the time of generation which includes applications such as load levelling, spinning reserve, energy transfer (peak shaving/valley filling), contingency service, and area control;
- Bridging power, to ensure continuity of power supply over a period of minutes including peak shaving, investment deferral, load following, demand side management, loss reduction, contingency service, black start, and area control;
- Power quality, for short periods of time and rapid cycling energy needs, to maintain voltage and current within the required limits, including also intermittency mitigation, end-use applications, and black start.

A general overview over available ESS technologies and processes is shown in Figure 2 above. For the Task B report in hand the target is to identify a storage technology to apply:

- In areas without any geographical or topographical specifics;
- For a medium amount of energy to be storage;
- For a quick response and change between charge and discharge status;
- For an installation in green fields considering possible environmental impacts.

Within Figure 2 only the part of electrochemical storage seems to be able to address these topics. This is why the report in hand uses the abbreviation BESS, meaning Battery Energy Storage System and being part of the electrochemical storage group.

Additionally, the analysis shall focus on commercialised and matured technologies. This again reduces the number of option displayed in Figure 2. The report is focussed on four types of electrochemical storage systems, namely on:

- Lead Acid Battery (PbA);
- Lithium Ion Battery (Li-Ion);
- Vanadium Redox Flow Battery (VRB); and
- Sodium Sulphur Battery (NaS).

These four technologies are introduced in the following section.

2.2 BESS Technology and Size Recommendations

As previously mentioned different electrochemical energy storage technologies are considered matured and available. All seems to be able to transfer electrical power into another time of the day. However, none of them holds all advantages. Therefore, depending on the target application, some BESS technologies are more adequate than others. In this study, the target applications are the best possible avoidance/reduction of curtailments and the increase of the Capacity Factor of the wind/PV Hybrid grid access.

2.2.1 Selection of BESS technology

To select the proper technology for a given purpose, the main technical requirements of the service in terms of power, energy or response time should be identified. Further aspects like potential restrictions (operational, environmental, etc.), shall be considered.

Assuming that technical specifications for the corresponding application are fulfilled, other main aspects to take into account when selecting the most suitable BESS technology are costs and lifetime. Efficiency, reliability, commercial availability and maturity level are important to be considered for the assessment as well.

- **Battery Energy Storage System**

Based on the maturity level, a preselection of the BESS technology is proposed and this study focuses on Lead-Acid batteries (PbA), Lithium ion batteries (Li-ion), Vanadium Redox batteries (VRB) and Sodium Sulphur batteries (NaS). The maturity level can be best understood from market observations and mentioned technologies are the most available and applied once.

All the technologies have similar characteristics regarding capacity, efficiency or durability in terms of years. Main differences are related to energy density, cycling life and costs. However, generally for stationary applications, energy density is not a major handicap as the issue of area needed for installation does not show restrictions. Therefore, this is not a decisive parameter in this Task B report.

There are other important aspects for utility services such as reliability and/or availability but those are difficult to evaluate since for most of the technologies, the operation experience is limited and there are not still available performance data.

Lead Acid battery

Among BESS, this is the most matured technology and widely used, especially with the experience gathered from decades of use in the vehicle industry. The cathode is made of PbO_2, the anode is made of Pb, and the electrolyte is sulfuric acid. Lead–acid batteries have fast response times, small daily self-discharge rates (< 0.3%), relatively high cycle efficiencies (75-85%) and low capital costs. The disadvantages are the poor low-temperature performance (a thermal management system is normally required), low durability (years and cycles) and environmental concerns due to the use of lead and sulfuric acid as a liquid hazard.

Lead–acid batteries can be used in a large variety of applications such as:
- Stationary stand-by & UPS (telephone and computer centers);
- Energy management applications (grid-connected energy storage, off-grid household or residential electric power systems);
- Motive power applications (e.g. in forklifts, hybrid or full electric vehicles);
- Starter batteries (e.g. starting, lighting, ignition (SLI)) requiring high power at low temperatures.

Currently, the research and development of lead–acid batteries focuses on:
- Innovating materials for performance improvement, such as improving the specific power, extending cycling times and enhancing the deep discharge capability;
- New “Advanced Lead-Acid” concepts are being developed to improve the power capability, to increase the energy density (lead-carbon batteries) and to address the performance related to acid stratification.

Li-ion battery

Highly deployed in the market for small appliances, the implementation of Li-ion batteries in the stationary field has significantly increased since 2010. Additionally, experience has been gained in the development of batteries for electric and hybrid vehicles, leading to magnificent quality increase.

These batteries have a very high efficiency (75 - 90%) and reliability, a good energy density (120–250 Wh/kg) and a slow self-discharge rate (<1 %/day). However, they are still expensive for medium- and large-scale, the cycle DOD (depth of discharge) can affect the Li-ion battery’s lifetime. The battery pack usually requires and includes an on-board computer to manage its operation, which increases its overall cost.

The Li-ion battery is considered as a good candidate for applications where short response time (milliseconds) and small dimension / weights of equipment are important. Due to their high scalability and flexibility in power and energy, Li-Ion batteries are used in a large variety of applications:
- Residential and commercial buildings: time shifting and self-consumption of locally produced PV energy;
- Distribution grids: voltage, capacity and contingency support of smart grids;
- Transmission grids: Ancillary services, namely frequency regulation;
- Renewable generation: smoothing and shaping functions associated with voltage and frequency sup-port to ensure better integration of large renewable plants into the electricity system.

The current research focuses on:
- Increasing battery power capability with the use of nanoscale materials;
- Increasing cycle and calendar life;
- Enhancing battery specific energy by developing advanced electrode materials and electrolyte solutions;
- Reducing the system costs; and
- Implementing recycling processes.

Vanadium redox battery

The VRB is one of the most mature flow battery systems, though its use in privately financed commercial application is still limited. The VRB stores energy by using vanadium redox couples (V^{2+}/V^{3+} and V^{4+}/V^{5+}) in two electrolyte external tanks. VRBs exploit the vanadium in these four oxidation states which makes the flow battery have only one active element in both anolyte and catholyte. During the charge/discharge cycles, H^+ ions are exchanged through the ion-selective membrane. The energy capacity of the system is determined by the size of the electrolyte tanks, while the system power is determined by the size of the cell stacks, allowing independent scaling of power and energy capacities.

VRBs have good responses (some msec), symmetrical charge and discharge, quick cycle inversion and can operate for more than 13,000 cycles. The efficiencies seems to be low compared with other technologies. It might reach up to 75% with capacity to provide continuous power for more than 24 hours. However, the low electrolyte stability and solubility leading to low quality of energy density is a drawback as well as the toxicity of some materials used and the relatively high operating cost.

VRBs can be used in a large number of applications, mainly including enhancing power quality used for stationary applications and UPS devices, improving load levelling and power security, supporting the intermittent nature of renewable energy-based power generation.

Current research focuses on further cost reduction mainly by developing cost-effective new membranes as well as by increasing energy density. Further innovation will help to increase the power density of the cell, which will also help to reduce stack size and costs.

Sodium Sulphur battery

NaS is a high-temperature battery, which uses molten sodium and molten sulphur as the two electrodes, and employs β-alumina as the solid electrolyte. The working temperature is in the region of 300 ºC to ensure the electrodes are in liquid states, which leads to a high reactivity.

Its advantages include quick reversibility between charging and discharging, efficient operation, relatively high energy densities (100 – 120 Wh/kg), almost zero daily self-discharge, higher rated capacity (>250 MWh) and high pulse power capability, low maintenance, quite long life, and good scale production potential. Also, the battery uses inexpensive, non-toxic materials leading to high recyclability (~99%). However, maintaining a high operating temperature is mandatory, leading to high operating cost (80 $/kW/year) and the need for an extra system to ensure its operating temperature. Also, some corrosion problems that may impair its reliability have been stated.

The research and development focuses mainly on enhancing the cell performance indices and decreasing/eliminating the high temperature operating constrains. Additionally, fire protection measures are being implemented.

Summary of chosen BESS technologies

A summary of the important details of the different BESS technologies is given in Table 1. This offers a quick overview over the mentioned technologies. The table furthermore allows for comparison of the technologies.

Table 1: Characteristics of BESS technologies for stationary applications [1], [2], [3], [4].

Parameter / Technology	PbA	Li-ion	VRB	NaS
Power Rating (MW)	0.01 – 50	0.01 – > 50	0.005 –> 50	0.5 – < 50
Gravimetric energy density (Wh/kg)	30 – 50	120 – 250	10 – 75	100 – 120
Volumetric energy density (Wh/L)	50 – 80	200 – 600	15 – 35	150 – 250
Power density (W/kg)	75 – 300	100 – 5,000	~ 170	150 – 230
Efficiency (%)	75 – 85	75 – 90	70 – 75	75 – 90
Durability (years)	5 – 15 (~ 10)	7 – 15	10 – 20	< 15
Durability (cycles)	500 – 3,000	2,000 – 10,000	> 13,000	2,000 – 5,000
Response time	msec.	msec.	Some msec	Some msec. if hot

- **Technical and economic considerations**

When assessing the feasibility of a BESS project in general, various technical and economic considerations should be faced. Following main aspects to be taken into account for making decisions are described as well as their impact in the projects viability.

Cycling duration

The charge/discharge cycles of BESS depend on the application. This could lead to the need for BESS to charge and discharge rapidly and to go through many cycles in a day. For the renewable energy time shifting case, the BESS goes through only one charge/discharge cycle per day. The amount of energy used for charging and generated when discharging is significant, typically requiring long duration energy support from 4~8 hours in one block. Depending on the charge/discharge cycle, applications can be classified as short, medium and long duration applications. Discharge time is a key parameter and if the BESS is used for frequency regulation in the electrical grid, discharge time ranges from minutes to 1 hour depending on the grid codes requirements.

2.2.2 Recommendations

There are diverse aspects to take into consideration when selecting and sizing BESS for a specific purpose. Taking into account the characteristics of the BESS and the parameters described previously and having in mind commercially available BESS, Li-ion batteries are the most suitable technologies to provide the renewable energy time shifting case. For the Task B report in hand all calculations considering a BESS have been based on the condition of applying Li-ion battery systems.

3. Energy Yield model for a Wind/ Solar PV Hybrid + BESS

3.1 Capacity Factor

Throughout the report in hand the terminus "Capacity Factor" is mentioned several times. This terminus is purely related to the grid connection conditions. Having a strict limitation of 50 MW for the power evacuated from the site, a simple multiplication with all hours of a year (usually 8760 hours/a) give the 100 % value for the maximum of energy evacuated through the grid connection. This multiplication leads to 438 GWh/a as the maximum possible value.

Whenever a reference to or a value for the Capacity Factor is given, this is related to the above given definition. Shares, usually give in percentage, can be transformed into absolute figure by multiplying with 438 GWh.

3.2 Calculation methodology

This chapter describes the calculation method used. Due to hybridization, or better due to the curtailment activities combined with hybridization, the yield calculation for each year of operation must be calculated individually. This is necessary because parameters such as degradation cause a special influence on the energy yield estimate but are (partly) mitigated when considering the maximum load into the national grid. The usual procedure to apply a constant or linear degradation factor to calculate the annual yield of the combined system over 25 years cannot be applied. The possible energy yields from the use of the BESS are based on the energy yield calculation of the hybrid. In this project the grid ancillary services (e.g. frequency regulation) provided by BESS, will neither be taken into account for the selection of the system nor for LCoE calculations. Possible ancillary services and their requirements are listed in Chapter 5. In the calculation model used, the BESS is used to operate renewable power shifting and thus reduce the amount of curtailments. Curtailments are energy yield losses due to the hybridization of wind with PV and the associated oversizing of power. When limiting the yield to the possible evacuation (limited power with 50 MW) at certain hours per year, curtailment will occur.

In the first step, the long-term corrected time series of wind and PV are added for each hour of the year to a theoretically hybrid energy yield (without curtailments). This value corresponds to the theoretical total energy in hourly resolution. Because of the existing 50 MW grid supply limit, not all of the energy generated can be evacuated. These energy losses, the curtailments, are the sum of the theoretically available energy yield above the grid supply limit. Based on the assumptions made, three variables can be determined: The hybrid yield, the theoretically hybrid yield (without curtailments) and the curtailments.

This procedure needs repetition for each year, taking into account the constant degradation of the PV. For each year, the half-year degradation percentage is applied to the entire time series, i.e. for each individual hourly output. This means that increased degradation is calculated in the first half of the year and decreased in the second. This assumption is considered sufficiently accurate and serves to simplify the calculations. Finally, an energy yield has been calculated for each year, as already mentioned above. The influence of degradation on energy yield and curtailments are described in the chapters 3.5 and 3.6.

In the next step, the hybrid park will be extended by a BESS. This requires further assumptions and performance parameters for energy yield simulation. These include the possible charging and discharging performance of the battery, the battery state of charge (SOC), the battery losses and the Hybrid + BESS energy yield. In the model used, it is now checked for every hour whether curtailments would occur due to grid restrictions as already described above. As soon as the hourly value exceeds 50 MWh, power is available for charging the battery. However, the battery cannot be charged arbitrarily. Loading is only possible up to the maximum charging performance. If more power is available, it cannot be used and needs to be counted as curtailment. The battery-specific parameters are also usable values. This means that the specified values can be retrieved under all conditions. Therefore, the maximum charging power corresponds to that charging performance divided by a loss factor due to charging losses (e.g. 20 MW BESS complies 20MW/(1 - Charging loss)). If less power is available, the possible charging power is reduced by the charging losses. Furthermore, the BESS can only be charged to the maximum battery energy capacity. As soon as the BESS is considered charged, all possible entries are counted to the curtailments.

If the grid supply limit allows the BESS to discharge, it feeds up to its possible performance into the grid. In the model used, the charging and discharge performance are the same. Therefore, the equivalent framework conditions apply to discharging. The BESS is discharged until it is empty or the grid allows not longer to feed in.

The losses during discharge are much more important than those during charging, as there is usually enough charging power available. For the simulation, an annual evaluation of the energy yields is necessary due to the degradation of the BESS. Consequently, the same routine to determine annual increase in the degradation of the BESS as in the case of PV has been applied. Further losses such as the self-discharge rate and stand-by losses are not considered.

3.3 Degradation

Degradation is an abstract for diverse ageing processes, which are not or hardly influenceable under operating conditions. Because of degradation, the energy yield is decreasing over the lifetime of the power plant. As a result of the noticeable difference between each technology, distinctions must be made here. In this report the degradation of wind parks are not considered, because this is not a standard in the industry. For the PV plants, a yearly degradation of 0.607 %/a are assumed over the whole 25 years. This value includes the annual degradation stipulated by the manufacturer of the modules plus effects considered for the whole plant. It is taken from the simulation tool and distributed linearly over the 25 years lifetime.

BESS degradation processes are complex and there are diverse parameters that contribute to degrade the cells that configure the battery packs. Parameters are interdependent making it difficult to determine a perfect degradation factor (corrosion, electrochemical passivity, loss of active material, etc.). As the frequency response of batteries is strongly dependent on the stochastic nature of the real contingencies which can occur on the grid, the estimation of the battery lifetime becomes a complex issue.

However, the BESS lifetime depends on diverse parameters, mostly DOD, SOC and temperature. These are linked to the operation mode and the grid service profile (duty cycle). Both aspects (operation mode and duty cycle) impact the BESS sizing and design since a compromise between grid benefits and BESS lifetime must be achieved to assure the system profitability.

Especially the degradation of the BESS (assumption: Capacity of the BESS reaches 80% after 13 years of operation, leading to 1.84 %/a) is an important factor, therefore the energy yield is calculated for every year for all time series. The influence of degradation on a Wind/PV Hybrid + BESS for exemplary and non-representative three days is shown in Figure 3 for operation year one and twenty-five. The main modalities are shown below the graph.

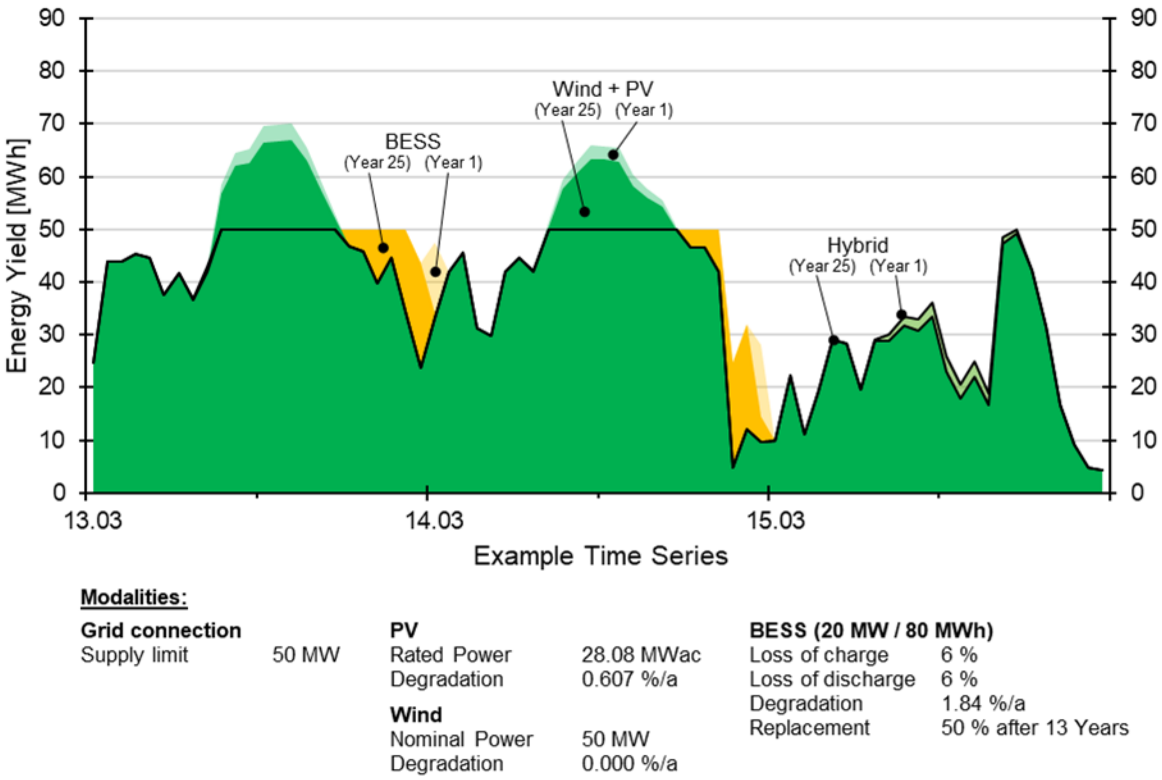


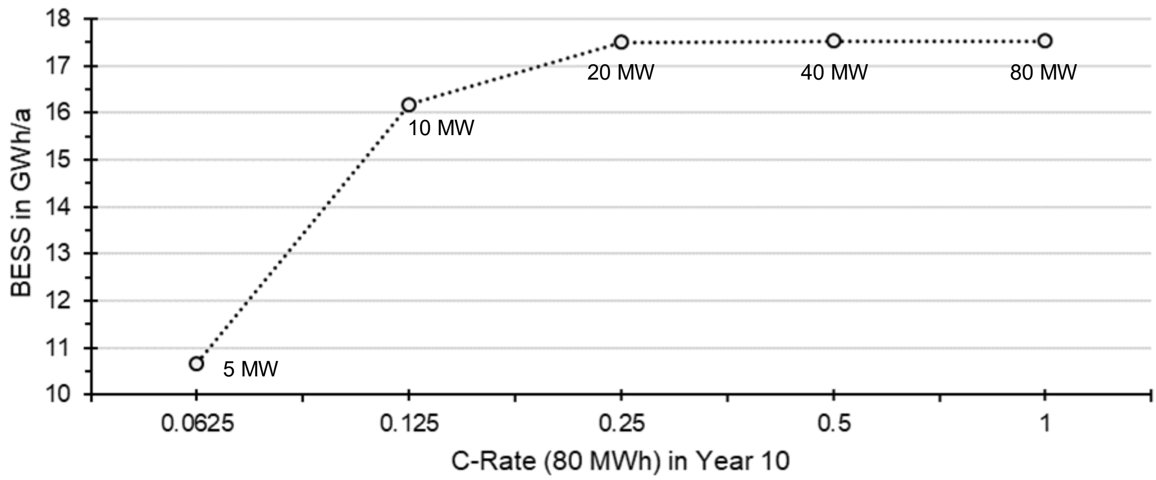
Figure 3: Degradation of a Wind/PV Hybrid + BESS

A close look at the line of the graph reveals that the hybrid energy yield without BESS is almost the same as in the first year. In the model used for energy yield, the degradation of PV of about 13.6% after 25 operation years affects the hybrid yield by less than 5 %. One reason for this is the exceeding of the grid supply limit, which is expressed in the amount of curtailments. For the hybrid park used in the Figure 3 the ratio of curtailments between year twenty-five and year one first is 78 %. This effect can be seen in the figure above in the range over the 50 MWh, marked by “Wind + PV” and “Hybrid”. The situation with the BESS and the degradation is quite different, because the ageing reduces the usable energy capacity and thus the possible energy shift (Figure 3) by the BESS. It has to be considered that a replacement of 50 % of the BESS after 13 years was assumed.

3.4 C-Rate and Capacity

C-Rate or charge rate describes the possible charge/discharge power in ratio to the battery energy capacity. The variation of the C-Rate is limited within certain boundaries. A value of 1 (means, the power of the battery is equal to its storage capacity) is possible with some technologies, e.g. with the chosen Li-ion battery system. C-Rates beneath 1 are given in case the battery power is lower than storage capacity. The power to be applied for charging / discharging is one important factor to determine the total CAPEX of a BESS as the power needs to be handled by a power electronic component, always organising the optimum charge / discharge depending on boundary conditions. This electronic might cover an important part of the CAPEX for a BESS. For the Li-ion type a C-Rate range of 0.25 to 1 shall be considered as values beneath e 0.25 value are not usual in the market. Choosing these will stipulate additional costs for unusual solutions.

Furthermore such values beneath 0.25 do not bring additional results for the cases in hand. In the Figure 4 the influence of the C-Rate with the same storage capacity (80 MWh) is shown. The figure, shows that a C-Rate of more than 0.25 does not increase the energy yield. This ratio may differ in other storage conditions, but in the case analysed here the most important variable obviously it is the storage capacity. This is why the C-Rate 0.25 is used for the calculations.



Modalities:

Grid connection
Supply limit 50 MW

PV
Rated Power 74.88 MWac
Degradation 0.607 %/a

Wind
Nominal Power 50 MW
Degradation 0.000 %/a

BESS
Loss of charge 6 %
Loss of discharge 6 %
Degradation 1.84 %/a
Replacement 50 % after 13 Years

Figure 4: Different C-Rate for the same Battery Capacity in operating year 10

3.5 Energy Yield

The energy yield was calculated per year following the methodology explained in Chapter 3.1. This became necessary due to the degradation effect of the different technologies and the impact of the same onto the complete system. As outlined before, the degradation influences the energy yield and at the same time the associated curtailments are impacted. Figure 5 displays the effects on the energy yield over the plant lifetime of 25 years. The "wind only" case shows a constant energy yield over the 25 years. The degradation of the PV power part is clearly visible by the decline of the upper border of the "Hybrid (without curtailments)" field. This area reflects the theoretically energy yield presuming all produced energy can be fed in the grid without any curtailments. Over the 25 years of operation, a significant decline in yields is observed. In contrast, the energy yield of the "Hybrid" gives an almost constant level as the degradation of the PV part is mitigated by the curtailments. Combining Hybrid and BESS ("Hybrid + BESS") allows for partly using curtailed energies. The consequences are summarized and shown in the graph. The slight increase in the 14th year of operation, is caused by the replacement of 50 % of the BESS.

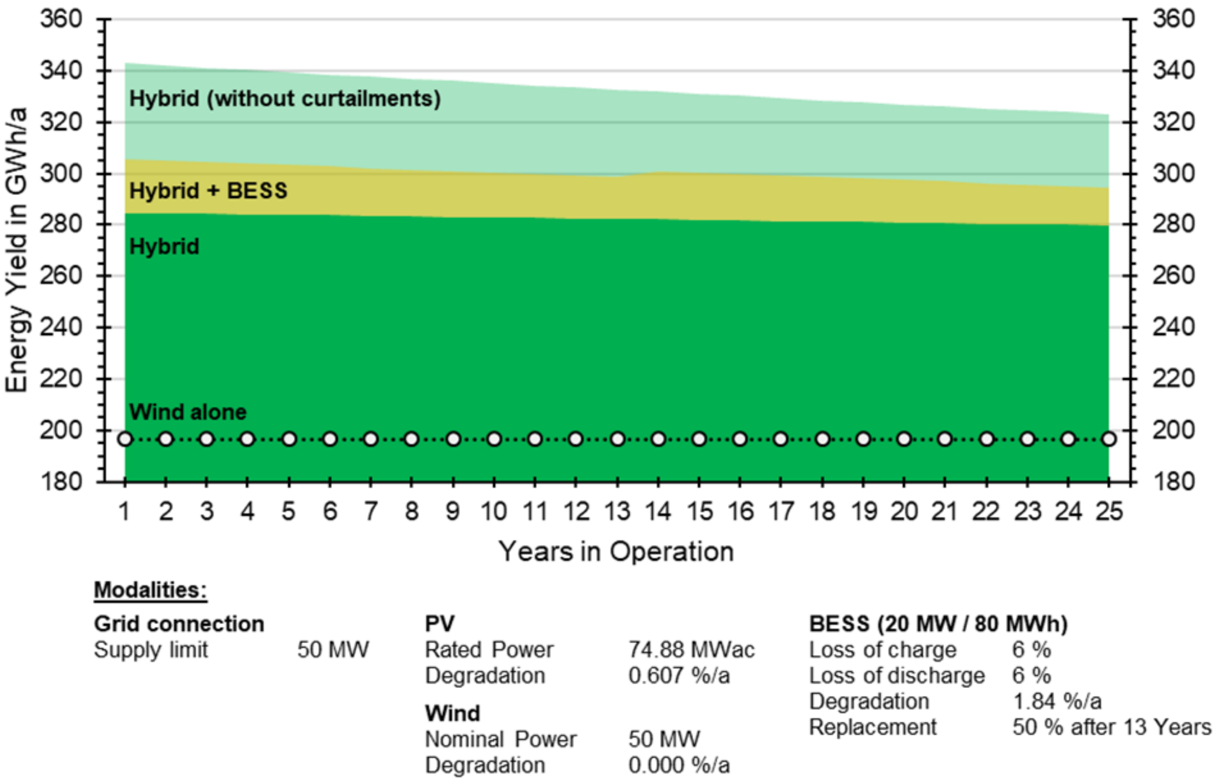


Figure 5: Energy Yields of a Hybrid concept over the years of operation

3.6 Curtailments

Due to the hybridization of wind with PV and the associated oversizing of power, the grid supply limit triggers unavoidable curtailments occurring during simultaneous energy production. By extending the Hybrid with a BESS, parts of the curtailment can be stored and released later, so that the grid related Capacity Factor increases.

In general, the curtailments are influenced by the selected additional PV part the simultaneous production of wind and PV energy and the degradation. Additionally, the implementing of a BESS impacts the curtailments. On its left-side y-axis, Figure 6 shows the annual curtailments in GWh of the wind/PV hybrid as well as the Hybrid + BESS for a specific case. It has been exemplary done for an added 74.88 MWac PV part and details describing the selected case can be found in the lower part of the figure. The x-axis displays the years of operation. Figure 6 shows the annual curtailments. Consequently, the economic efficiency increases with decreasing values. The dotted line reflects the ratio of the curtailments of two differing plant concepts. This ratio is displayed on the right y-axes. Generally, the ratio displays a break between operation year 13 and 14. This break is caused by the replacement of BESS parts. For smaller values of the ratio, the higher technical efficiency of the plant can be seen. This ratio changes over the years of operation and is mainly caused by superposing the degradation and curtailment effects.

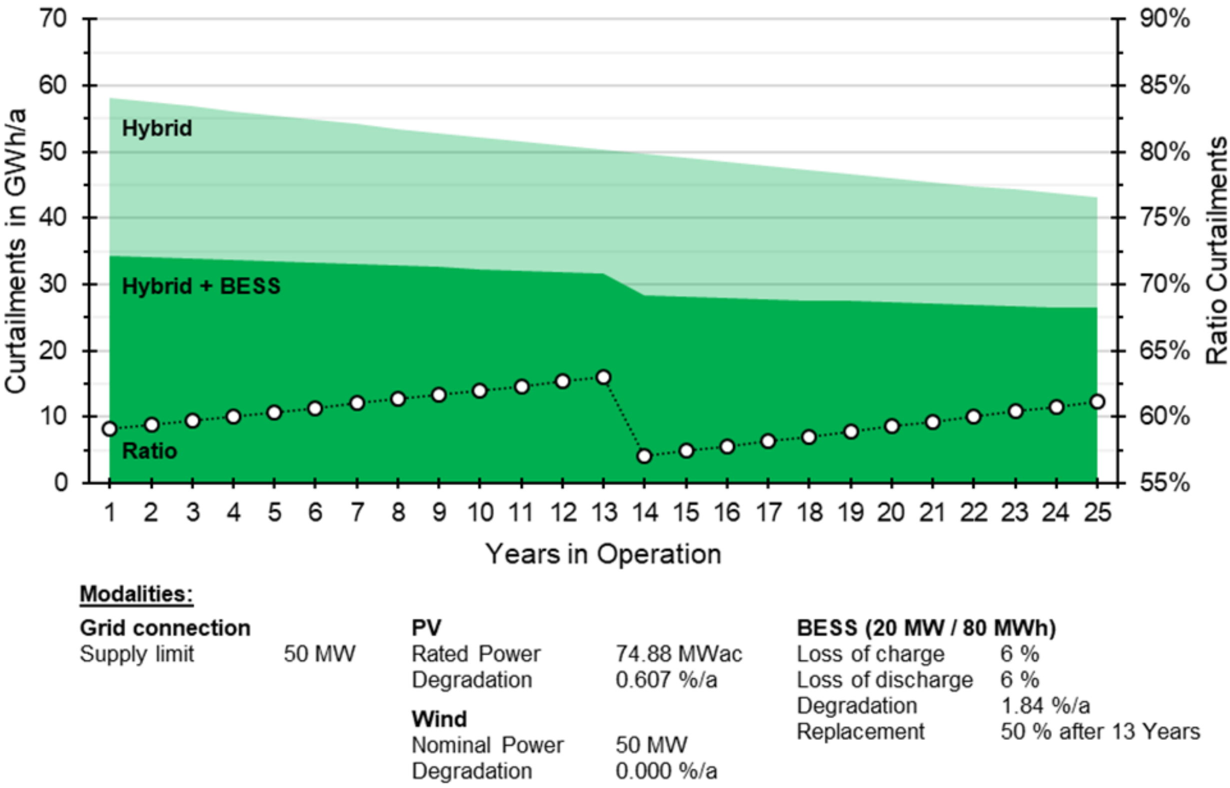


Figure 6: Curtailments of a Hybrid concept over the years of operation

Generally, the Figure 6 shows that by adding a BESS to a certain wind/PV hybrid system (details mentioned in the referred figure) the amount of curtailed energy over a 25 years lifetime can be reduced to 60.14%.

3.7 Effects of the BESS on the Hybrid Park

The idea of using a BESS in combination with a Wind/PV Hybrid Park with a grid supply limit is based on the shift from energy overload to low load. In addition to the BESS (C-Cate; capacity; etc.) the design of the Hybrid Park takes an essential role. The basic condition for the use of the BESS is the possibility to discharge the battery, charged during the day, in temporal proximity (e.g. night). The more cycles a BESS can perform, the better it can be adapted into the system. In Figure 7 the effect of a BESS on the energy yield of the Hybrid is exemplary illustrated. The illustration be viewed in a larger format in Chapter 8.

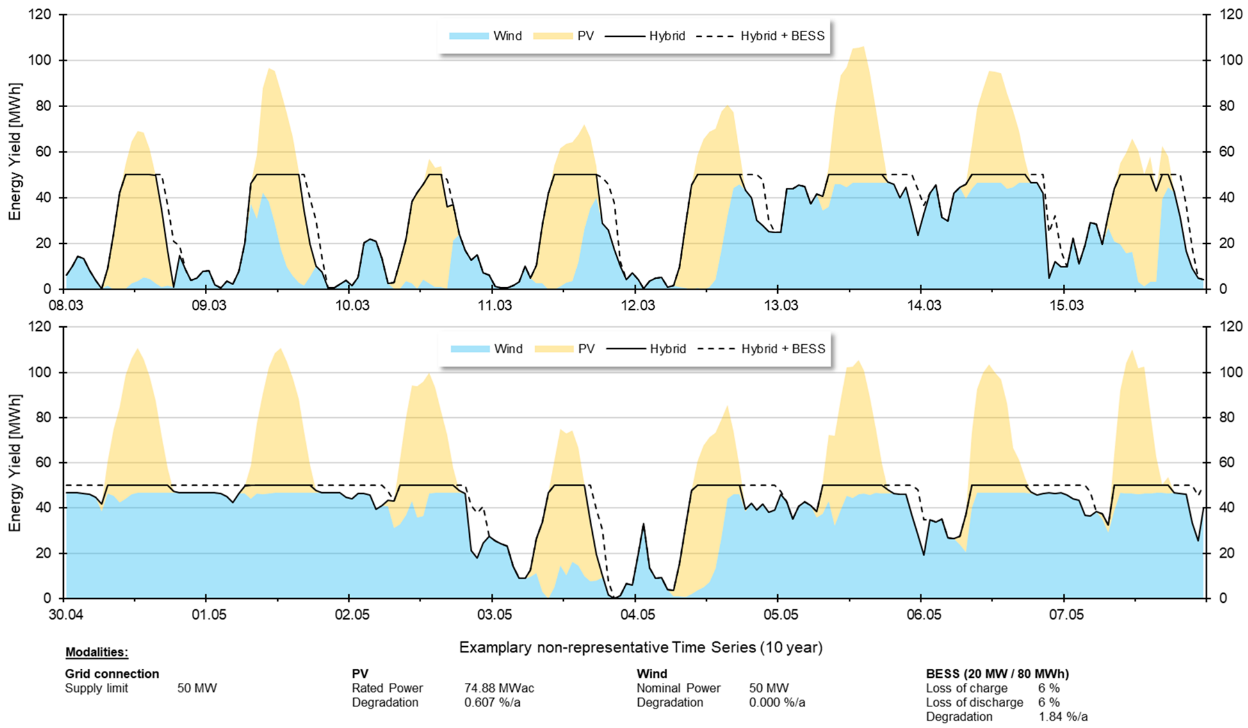


Figure 7: Exemplary non-representative Time Series for a Hybrid + BESS

The figure shows two exemplary non-representative time series for the 10th year of operation. In the upper part, the wind energy yield (blue) is low and the largest shares of energy yields from the PV (yellow) can fed directly into the grid. In contrast, the opposite example can be seen in the lower part: Most of the PV yield is curtailed, respectively used for charging if a BESS is provided. However, the curtailments can only be utilize by the BESS to a limited extent. Figure 7 displays a PV part with 74.88 MWac, a Wind park with 50 MW and a BESS with 20MW/ 80MWh. The hybrid energy yield over the time series is marked with a black line and the hybrid + BESS with a black dashed line. The areas between the dashed and the solid line reflect the energy yields which can be additionally fed into the grid by this BESS.

3.8 Introduction of Variants

For this Task B report a number of combinations of wind, PV and BESS has been considered. Not all of these introduced important results and the selection of variants shown in Table 2 reflect the once which are used for the preparation of this report. The column "No." includes the labelling and this label has been used throughout the report in hand.

The variants 0 to 7 have been included in the Task A report in detail and are here shown again. Variant 8 reflects a wind/PV hybrid set-up with an installed PV capacity of 102.96 MWac. The installation would request for extending the selected side for an additional area for PV only installation. This area should connect to the south/west and by defining a "solar only" purpose this would not impact the wind parks. From variant 9 to variant 14 BESS has been added to certain hybrid solutions.

Table 2 gives an overview over the significant technical parameters and the related energy yields and curtailments.

Table 2: Variants of wind/ PV / BESS combinations

No.	Wind MW	PV MWac	BESS MW/MWh	Gen. Yield (average) GWh/a	Curt. Yield (average) GWh/a	Curt.Yield (year1 / year 25)* GWh	Capacity factor %
0	50	0	-	196.6	196.6	-	44.9%
1	50	9.36	-	213.6	212.8	1.1 / 0.7	48.3%
2	50	18.72	-	230.6	226.5	4.8 / 3.6	51.3%
3	50	28.08	-	247.6	239.1	9.7 / 7.5	54.0%
4	50	37.44	-	264.6	250.7	15.7 / 12.3	56.5%
5	50	46.8	-	281.6	261.2	23.1 / 18.0	58.8%
6	50	56.16	-	298.6	270.3	32.3 / 25.7	60.9%
7	50	65.52	-	315.6	277.4	44.3 / 32.9	62.6%
8	50	102.96	-	383.7	290.7	105.5 / 81.3	66.0%
9	50	74.88	20/80	332.7	300.0	34.4 / 26.4	67.3%
10	50	65.52	40/160	315.6	298.5	16.0 / 12.6	66.7%
11	50	93.6	40/160	366.7	325.2	41.4 / 32.0	72.7%
12	50	121.68	40/160	417.7	336.5	85.7 / 65.7	75.6%
13	50	93.6	60/240	366.7	333.0	31.3 / 24.3	74.3%
14	50	140.4	60/240	451.7	357.3	97.3 / 75.37	80.1%

Table 3 details the situation for the variants including a BESS. For every system including BESS the discharged energy for operation year 1 and operation year 25 plus the average are given.

Table 3: Details for combination including BESS

No.	Wind MW	PV MWac	BESS MW/MWh	Discharge (Year 1) GWh/a	Discharge (Average) GWh/a	Discharge (Year 25) GWh/a
9	50	74.88	20/80	21.0	17.8	14.8
10	50	65.52	40/160	25.0	21.1	17.9
11	50	93.6	40/160	42.2	36.6	31.7
12	50	121.68	40/160	47.2	42.6	38.6
13	50	93.6	60/240	51.1	44.4	38.5
14	50	140.4	60/240	67.3	61.1	55.8

4. Commercial Analysis

The commercial analysis adds all technical details into a calculation scheme to determine the Levelized Costs of Energy (LCoE) per variant. For the calculation a number of information / inputs are needed, such as Capital Expenditure (CAPEX) and Operational Expenditure (OPEX) per variant, needs for re-investment, discount rate, project lifetime and construction period.

4.1 CAPEX and OPEX of Elements of a Wind/ Solar PV Hybrid Park + BESS

This subchapter explains the assumptions for CAPEX and OPEX for each part of the Hybrid + BESS. The costs are included mainly based on specific figures and it might be possible to slightly reduce the figures for very large scale application. As there is no clear measure available to include such reduction, the calculation is based on the mentioned figures without reduction. This procedure mirrors a calculation on the "save side". The specific figures are defined on the basis of company's experience from current offers after aligning with values taken from literature. The different components of the investment costs are broken down and summarized in one table for each technology.

4.1.1 Costs of Grid Connection

The grid connection has been defined with a capacity limit of 50 MW. This value is kept constant and is not depending on the installed capacity. The grid connection refers to the on-site substation where generated power can be transferred into the regional/ national grid. The substation is needed once and is identical for all (hybrid) variants. Based on this info the CAPEX and OPEX is reflected by values which can be considered typical for an on-site substation for power evacuation of the mentioned size including SCADA System. The assumptions are summarized in Table 4.

Table 4: Grid connection CAPEX & OPEX estimate

Component	Cost Installed	
On-site Substation incl. civil works - CAPEX	7,000,000	US$
OPEX	80,650	US$/a

4.1.2 Costs of Wind Power Part

The investment costs for the wind power part are given in form of specific values. As the wind park in all variants follows the same layout, it would have been an option to mention only one figure per CAPEX and per OPEX. The here chosen approach for specific figures offers some advantages, namely:

- Easy comparison with other sources;
- Transparent approach of calculation; and
- Option to adapt the size in case necessary in the future.

For the wind power part, these consist of the WTG (Wind Turbine Generator), the civil works, electrical works (Balance of Plant; BoP) and labour. The OPEX taken into account are divided into two parts. On the one hand, the OPEX of the current operational management including the manufacturer's costs plus the costs on-site for operation as well as the second part of the maintenance reserve account. The CAPEX and OPEX estimates are summarized in Table 5.

Table 5: Wind - CAPEX & OPEX estimate

Component	Costs	
WTG (elec. mech. Equipment)	840	US$/kW
BoP, civil works (roads, foundation, etc)	275	US$/kW
BoP electrical works (int. grid, capacitor, etc)	240	US$/kW
Labour	95	US$/kW
CAPEX	**1450**	US$/kW
OPEX (Part 1)	18.9	US$/kW
MRA: OPEX (Part 2)	6	US$/kW
Sum OPEX	**24.9**	US$/kW

For the wind part no degradation has been considered as the randomly expected costs for replacements are included in the OPEX (Maintenance Reserve Account, MRA, OPEX (Part 2)).

4.1.3 Costs of PV Power Part

For the PV power part, the investment costs are given based on specific values. The components of the CAPEX of the PV power part consist of the Inverters, Modules, Structure (BoQ), Electrical (BoQ), Labour and logistic costs. The CAPEX and OPEX figures are summarized in Table 6. Both, CAPEX and OPEX are shown twice in Table 6. The first mentioning is the "usual" displaying of costs per DC capacity (nameplate capacity) whereas the second mentioning shows these figures after converting into rated power (AC power) related sizes with the specific ratio considering the ratio between the DC and AC of the inverters (DC/AC ratio1.2) of the PV plant. For the PV no replacement was considered because the inverter prices contain already an extended warranty.

Table 6: PV - CAPEX & OPEX estimate

Component	Costs	
Inverters	45	US$/kWp
Modules	280	US$/kWp
Structure BoQ	120	US$/kWp
Electrical BoQ	100	US$/kWp
Labour	75	US$/kWp
Number of container	8	containers/MW
Logistics costs	7000	US$/container
CAPEX	676	US$/kWp
OPEX	11	US$/kWp
AC-CAPEX	**811.2**	US$/kWac
AC-OPEX	**13.2**	US$/kWac

The degradation of the PV part considers the degradation of the modules plus the system. It has been defined at 0.607 %/a, summing up to 13.6 % over the lifetime of 25 years.

4.1.4 Costs of BESS Part

In order to be able to compare different BESS performances and capacities, the costs are on performance-related basis. However, according to the Consultant experience, this estimation shall be applied in the range of a C-Rate of 1 to 0.25.

BESS generally consist of two cost components, the charging performance and the battery capacity. Two different figures are specified individually. With the OPEX, the costs are simply related to the capacity of the BESS. In Table 7 the components and the resulting CAPEX and OPEX are listed.

Table 7: BESS CAPEX & OPEX estimate

Component	Costs Installed	
Battery System (incl management system)	210	US$/kWh
Power Conversion System	110	US$/kW
BoP (connection to electrical systems)	80	US$/kW
Labour (Construction & Commissioning	80	US$/kWh
CAPEX	190	US$/kW
CAPEX	290	US$/kWh
OPEX	7	US$/kWh

A 50 % replacement after 13 years of operation has been considered. The degradation has been defined to 1.84 %/a, reflecting 80 % capacity after 13 years.

4.2 LCoE Calculation

The technical solution is evaluated by calculating the LCoE. For this no transfers within the country such as taxes and duties and no financing costs (credits and conditions) are considered. A discount rate of 6 % has been applied for the Pakistan case. The discount rate is applied to calculate the economic Net Present Value (NPV). The NPV is obtained by discounting at this constant discount rate and separately for each year the differences of all economic costs and benefits of the project to the present. The LCoE is calculated by dividing the present value of costs (net present cost) by the present value of produced electricity. The same discount rate as for NPV is applied.

$$\mathrm{LCoE} = \frac{\text{Present Value}_{\text{Costs}}}{\text{Present Value}_{\text{Energy}}}$$

$$\mathbf{LCoE} = \frac{\dfrac{\sum_{n+1}^{n} \mathbf{I_n} + \mathbf{Q\&M_n}}{(\mathbf{1}+\mathbf{i})^{\mathbf{n}}}}{\dfrac{\sum_{n=1}^{n} \mathbf{E_n}}{(\mathbf{1}+\mathbf{i})^{\mathbf{n}}}} \qquad \begin{array}{rl} \mathbf{I} & \equiv \textbf{Investment costs (CAPEX)} \\ \mathbf{O\&M} & \equiv \textbf{Operating and maintenance costs (OPEX)} \\ \mathbf{E} & \equiv \textbf{Energy generation at feed in point (P50)} \\ \mathbf{i} & \equiv \textbf{Discount rate} \end{array}$$

The LCoE calculations are done in constant prices. The division of the present value of costs by the present value of electricity production results in the LCoE. This value shows the expected unit costs of electricity produced by the plants at the feed-in point. It facilitates the cost comparison of the electricity produced by the new project with its different technical options. The development and construction period is assumed to be one year. After completion an operation time of 25 years have been considered and discounting of future values is done with a discount rate of 6 % as mention before. The input data are summarized in Table 8

Table 8: Input data LCoE

LCoE Paramater	Value
Discount rate	6 %
Construction Period	1 year
Assessment period	26 years
Lifetime of Hybrid equipment	25 years (no salvage value)
Lifetime of BESS equipment	13 years (with salvage value)

As a result of the operation time of 25 years, the replacement of 50 % of the BESS after 13 years and the lifetime of the BESS equipment of 13 years, the BESS installation asks for a salvage value. This value corresponds to the pro rata value of the replacement in relation to the remaining lifetime (e.g. 1 - (12 Years of Operation / 13 Years of equipment Lifetime) * Replacement costs).

Table 9 summarizes results of LCoE calculations for the expressly mentioned variants of plant combinations of the report. The specified capacity factor always refers to the 50 MW grid supply limit. The No. 0 stands for a "wind only" power plant. For this plant layout up-to-date WTGs have been considered and the Capacity Factor reaches almost 45%. The calculation leads to the lowest LCoE: With regard to the capacity factor this case also has the lowest figure. No. 1 to 8 are Wind/Solar PV hybrids, partly showing good results with regard to the Capacitor Factor increase. No. 9 to 14 reflect Wind/ Solar PV Hybrid + BESS combinations.

Table 9: LCoE for the different Wind/PV Hybrid + BESS No.

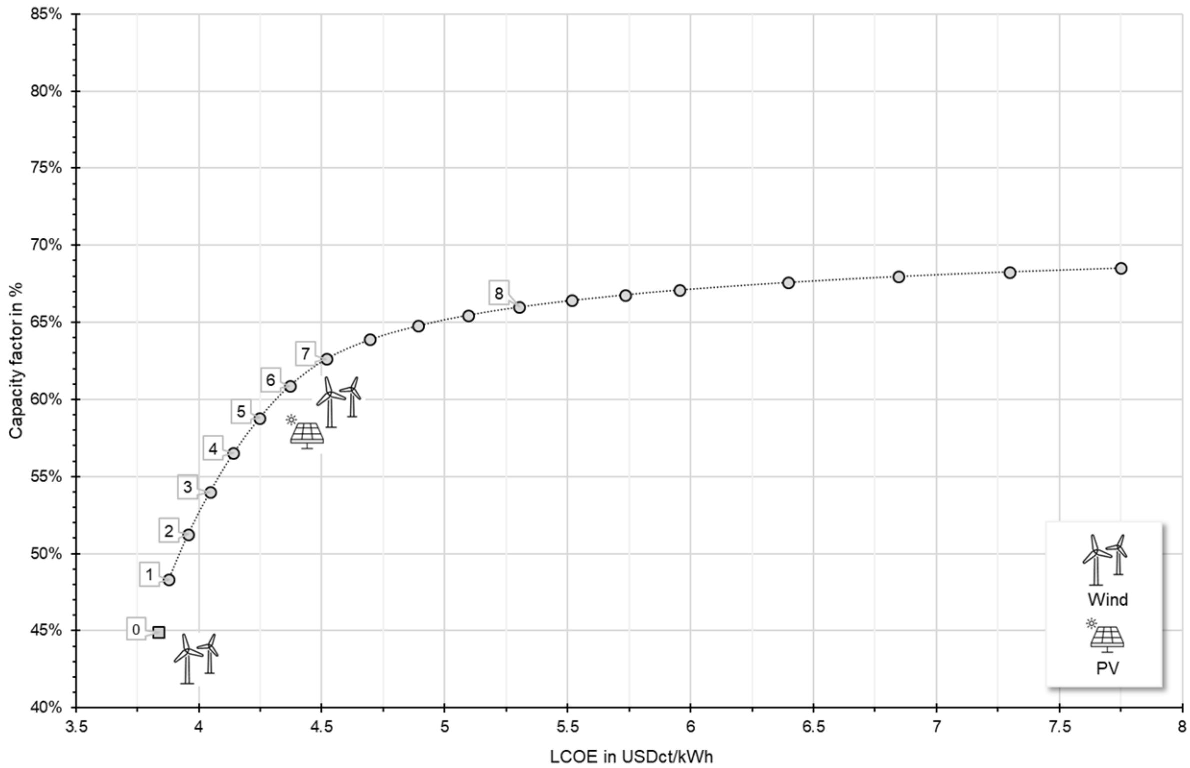
No.	Wind	PV	BESS		LCoE	Capacity factor
	MW	MWac	MW	MWh	USDct	%
0	50	0	0	0	3.84	44.9%
1	50	9.36	0	0	3.88	48.3%
2	50	18.72	0	0	3.96	51.3%
3	50	28.08	0	0	4.04	54.0%
4	50	37.44	0	0	4.14	56.5%
5	50	46.8	0	0	4.25	58.8%
6	50	56.16	0	0	4.37	60.9%
7	50	65.52	0	0	4.52	62.6%
8	50	102.96	0	0	5.30	66.0%
9	50	74.88	20	80	5.46	67.3%
10	50	65.52	40	160	6.29	66.7%
11	50	93.6	40	160	6.43	72.7%
12	50	121.68	40	160	6.87	75.6%
13	50	93.6	60	240	7.22	74.3%
14	50	140.4	60	240	7.74	80.1%

As a result of the technical and economic analysis a very huge amount of data and numbers have been prepared. To allow a quick and well based understanding, results have been reduced to the variants mentioned in Table 9. Furthermore, the most comprehensive way to display results has been identified in comparing two significant values per case: the LCoE and the Capacity Factor. These information have been transferred into figures.

The set of data can be distinguished into two generally differing set-up: Wind/PV Hybrid solutions and Wind/PV Hybrid + BESS solutions. Both groups of combinations are displayed separately in the following Chapters 4.2.1 and 4.2.2.

4.2.1 Wind/ Solar PV Hybrid

Figure 8 has been prepared to display the results of the analysis of the Wind/Solar PV Hybrid cases. The labels at certain points of the graph correspondent to the variants introduced in Table 9. No.0 reflects the "wind only" solution, No. 1 to No.7 are displaying the results for the variants analysed in Task A and Task B report. No. 8 shows the installation or PV power far above the external grid limit (102.96 MWac).



Modalities:

Grid connection		**PV**	
Supply limit	50 MW	Degradation	0.607 %/a
CAPEX	7 million USD	CAPEX	811.2 USD/kWac
OPEX	80,650 USD/a	OPEX	13.2 USD/kWac
LCOE		**Wind**	
Discount rate	6%	Degradation	0.000 %/a
Plant-Lifetime	25 years	CAPEX	1,450 USD/kW
Construction phase	1 year	OPEX	24.9 USD/kW

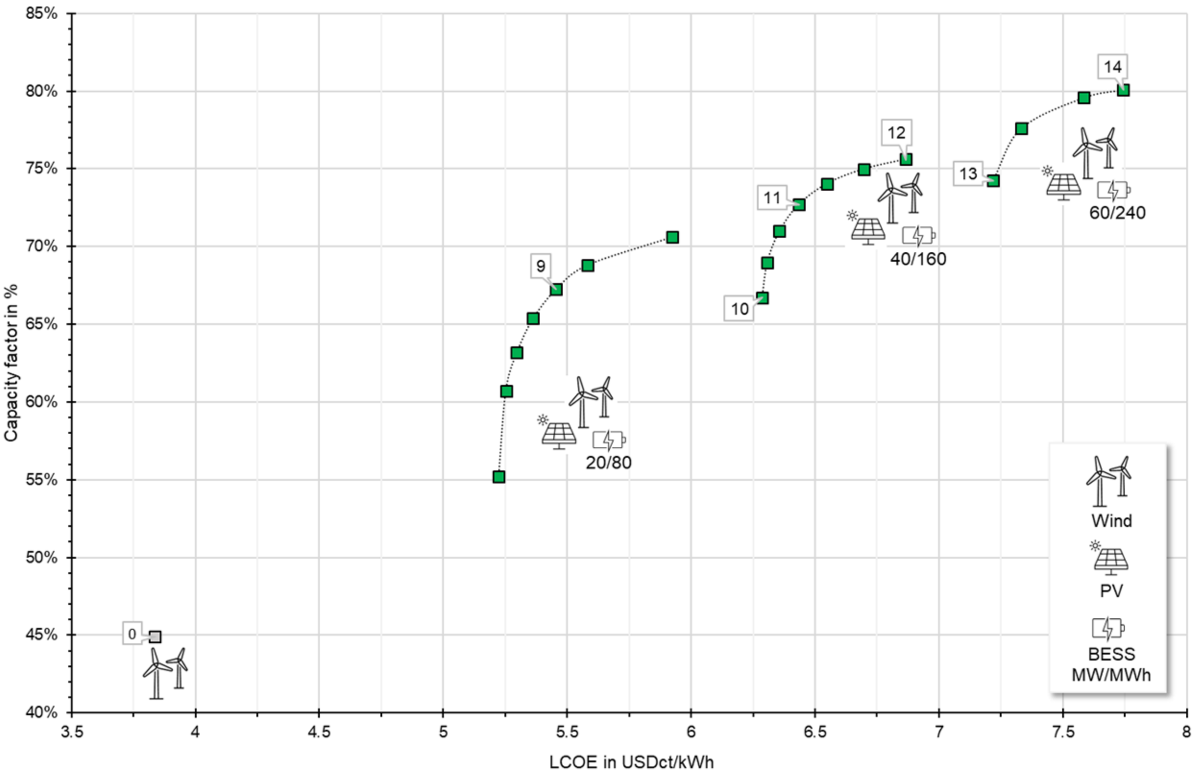
Figure 8: LCoE and Capacity Factor ratio of a Wind/PV Hybrid

It is not surprising that the wind only installation with up-to-date WTGs shows the lowest LCoE. The following variants No.1 to No.4 show a slight increase in the LCoE but a steep increase in the Capacity Factor as well. All variants with higher No.s are more to the right side of the graph and the gradient of the curve turn to lower values, reflecting the need for more increase on the x-axis. This seems to be a point where the economic efficiency of the installations decreases.

4.2.2 Wind/ Solar PV Hybrid + BESS

Figure 9 displays the results for Wind/Solar PV Hybrid +BESS cases. Again, the labels at certain points of the graph correspondent to the variants introduced in Table 9 and No.0 reflects the "wind only" solution.

Also this figure shows the steep increase in LCoE for all BESS variants. The curves seen in the diagram are always connected at the same storage capacity and they show a comparable gradient and trend. All variants with BESS led to LCoEs far higher than the wind only solution, reaching from almost 140% to around 200% of the "wind only" LCoE. On the other hand an additional increase in the Power Factor can be derived from the diagram.



Modalities:

Grid connection		**PV**		**BESS**	
Supply limit	50 MW	Degradation	0.607 %/a	Loss of charge	6 %
CAPEX	7 million USD	CAPEX	811.2 USD/kWac	Loss of discharge	6 %
OPEX	80,650 USD/a	OPEX	13.2 USD/kWac	Degradation	1.84 %/a
				Replacement	50 % after 13 Years
LCOE		**Wind**		CAPEX	190 USD/kW
Discount rate	6%	Degradation	0.000 %/a		290 USD/kWh
Plant-Lifetime	25 years	CAPEX	1,450 USD/kW	OPEX	7 USD/(kWh a)
Construction phase	1 year	OPEX	24.9 USD/kW	Include Salvage value of BESS	

Figure 9: LCoE and Capacity Factor ratio of a Wind/PV Hybrid + BESS

It is important to emphasize that all LCoE calculations for variants including BESS do not consider any other advantages of BESS then time shifting. Opportunities of further services to be delivered by BESS are discussed in Chapter 5.

5. Ancillary Services

The electricity grid must provide its customers with electricity and is supposed to work all day every day. It always must be at the right frequency and voltage, otherwise, it will collapse. To make this possible, compensation possibilities must be present to regulate and support the stability. Control energy and regulation is a very important resource for the grid and one of the many services which a grid connected battery electricity storage system (BESS) can provide. In general, BESS can bring several different benefits to the grid.

The capability and the ability to deliver ancillary services into the grid needs a number of conditions to be fulfilled. One condition is a meaningful amount of money to be paid for these services. And this is where the BESS might bring its "skills" into when paid in an attractive way. For the project in hand this means that a regulation must be opened and implemented to allow IPPs to deliver such services (and to be paid for). With these additional incomes BESS will be more likely to be attractive from as commercial point of view.

In general, three different target groups of stakeholders are identified. The first group are services for system operators or regional transmission organizations. This is at the transmission level of the grid and, therefore, the closest to the generation. The second level is at the distribution level, where services for utilities can be provided. At last is the installation behind the meter at the customer level. This application is the most far away from the electricity production and usually has the lowest capacity of the three.

Additionally, the services can be divided in active and passive services. While active services assist the grid by charging and discharging at specific times to relieve the transmission and distribution lines or to compensate load peaks. Passive services can provide resources, which are just available in case they are needed. For example, black start support or regulation services for voltage and frequency.

The difference between technical and economic benefits is just the point of view. While technical benefits assist the grid in stability and reliability, economic benefits bring a financial aspect and assign a value to their respective technical counterpart.

The above-mentioned technical benefits can also result in economic advantages. These advantages consist of payments for provided grid-services or conserve money due to higher self-consumption or lower electricity prices. Next to the technical benefits, which are connected to an economic value, there are a number of additional services a BESS can generate profit with. As for the technical benefits, the economic can be split in three categories and differentiated between active and passive services.

The main point about BESS and its economic benefits is that a battery is rarely beneficial when only providing one service. None of the active services keep the battery busy for the entire time, which enables the battery to provide secondary active or passive services at otherwise idle times. This concept is commonly known as revenue stacking.

While active services provide value by saving money with cheaper electricity prices, passive services have their asset in providing capacities in case they are needed.

5.1 Transmission Level

This chapter refers to the services which are requested on the transmission level.

Energy Arbitrage
Energy Arbitrage is the purchasing of energy when the local market prices are at a low level and selling the energy back at higher prices. This service is an active service, which only consumes a part of the time of the day. The battery can perform different services in-between.

Frequency Regulation
Frequency Regulation exists to keep the grid stable. The grid frequency has to be at a certain frequency plus or minus a small tolerance at all times. Battery systems can provide immediate response of power to frequency fluctuations to prevent spices or dips in the system.

Spinning reserve
Spinning reserve is immediate electricity capacity available to serve load in case of unexpected generation outages, when the load could otherwise not be covered. Batteries can serve as a bridge until the outage is fixed or other reserves, which cannot react as fast, are able to provide compensation electricity.

Voltage Support
Voltage Support is like frequency regulation. To keep the grid stable, the voltage must be maintained at the right level by keeping the active and reactive power production the same as the demand.

Black Start
Black Start support is needed in case of a grid outage. To help large power stations back in operation and bring the grid back online.

5.2 Distribution Level

This chapter refers to the services which are possible on the distribution level.

Resource Adequacy
Resource Adequacy is a way to reduce the need for new generation capacity to meet the electricity demand in peak consumption hours. Instead of investing in new electricity generation plants, battery storage will provide the necessary capacity at peak times.

Distribution/ Transmission Deferral
Distribution and Transmission Deferral enables the delay or completely avoids the necessity of upgrades in the transmission or distribution system by compensating the load growth with battery systems in specific regions of the grid.

Transmission Congestion Relief
Transmission Congestion Relief is achieved by batteries discharging or charging in times of congested transmission corridors. Utilities get charged by system operators when using congested transmission corridors, which can be avoided by this relief system.

6. Conclusion

The Task B report in hand is a follow-up of the Task A report dated September 2021. Whereas the Task A report was reflecting the technical details of a Wind/PV hybrid system implemented in Sindh, Pakistan, the Task B report in hand displays opportunities for adding an electrical storage system plus analysing the economic impact by presenting the Levelized Cost of Energy for a number of combinations.

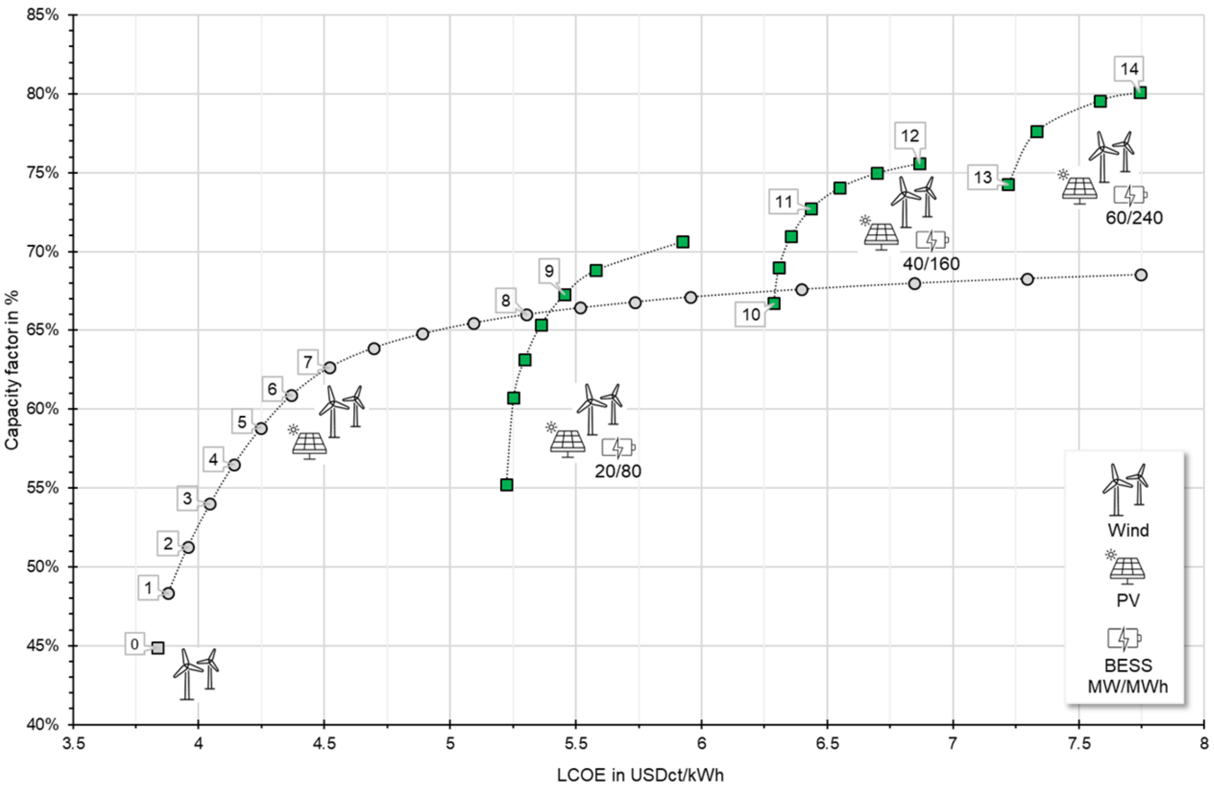
Within an extensive Chapter 2 different ESS technologies have been analysed and the best suited BESS technology for the purpose of extending a Wind/Solar PV Hybrid park has been identified to be the Li-ion battery technology. Within Chapter 3 possible combinations of Wind/Solar PV and BESS technologies have been introduced and the methodology for calculating the yield details are introduced. Specifics regarding the degradation of the BESS and its impact onto the whole system have been discussed and the result showed that, due to the mitigation of the degradation by the curtailment issue, no simplified and linear calculation over the plant lifetime was possible. This is why the assessment focussed on the calculation of an annual result for the lifetime of 25 years.

A detailed review of possible C-rates of the BESS showed that the given condition allow for reducing the power of the BESS to a fourth of its capacity (C-rate = 0.25) without suffering from considerable yield losses. This low value of the C-rate is important as the installed power of a Li-ion BESS mirrors a considerable share of CAPEX for the system. Simply said: It is technically possible to increase a C-rate for Li-ion systems to 1 or above but this needs (far) more investment. Further reduction beneath 0.25 will not lead to considerable CAPEX reduction, but in the analysed case such approach would also lead to reduced results. This is why the final decision was taken for a C-rate of 0.25 for all analysed systems.

From the huge number of calculation run along this analyses most important 15 variants have been displayed in detail. Partly, other variants can be seen within the related graphs. They do not include a labelling (as they are not described in the related tables) but are shown in form of dots in the said diagrams.

The Chapter 4 includes information regarding the commercial results. The final target is to evaluate the LCoE for all labelled variants. After introducing basics of the CAPEX and OPEX conditions for the assets (wind/PV/BESS/on-site substation) the general approach for the LCoE calculation are outlined. The whole calculation is done for a 25 years operation time plus a one year construction time. A discount rate of 6 %/a has been considered. The results have been shown in two steps: First step considered the variants addressed technically in the Task A report and results are displayed in Figure 8 and the combinations with BESS are included in Figure 9. These figures are the comprehensive results of the study.

For this "Conclusion" chapter the mentioned two diagrams have been displayed in one figure, Figure 10. The numbering of the important dots ("labelling) are following Table 9 of this report. The figure generally shows three different styles of dots: Square Grey representing the "wind only" case, Circle Grey for wind/PV hybrids and Square Green for combination with BESS. Generally, Figure 10 displays the LCoE on the x-axis whereas the y-axis displays the Capacity Factor of the grid connection.



Modalities:

Grid connection

Supply limit	50 MW
CAPEX	7 million USD
OPEX	80,650 USD/a

LCOE

Discount rate	6%
Plant-Lifetime	25 years
Construction phase	1 year

PV

Degradation	0.607 %/a
CAPEX	811.2 USD/kWac
OPEX	13.2 USD/kWac

Wind

Degradation	0.000 %/a
CAPEX	1,450 USD/kW
OPEX	24.9 USD/kW

BESS

Loss of charge	6 %
Loss of discharge	6 %
Degradation	1.84 %/a
Replacement	50 % after 13 Years
CAPEX	190 USD/kW
	290 USD/kWh
OPEX	7 USD/(kWh a)

Include Salvage value of BESS

Figure 10: LCoE and Capacity Factor for Wind/PV Hybrid and Hybrid + BESS

It is quite clear that under current conditions (means based on calculation with an up-to-date WTG) still the "wind only" plant is the configuration with the lowest LCoE. This result shows that the region in Sindh is not only labelled to be a "wind corridor" but also delivers such results. Going along on the a-axis the next point is quite close, but represents a bit higher LCoE. This grey and circular dot (labelled "1") represents a hybrid system including 50 MW wind power part plus a 9.36 MWac PV power part. As said, slightly higher LCoE is calculated but at the same time a considerable higher Capacity Factor. Following this curve to somewhere between label no. 3 (Wind 50MW, PV 28.08 MWac) and no. 4 (Wind 50MW, PV 37.44 MWac) the gradient of the curve seems to turn to lower values. This is from whereon increase in Capacity Factor will cause higher increase in LCoE. All BESS solutions (shown in lines with green squares) are located far more to the right within the diagram. They represent higher LCoEs due to reasons explained above in the second bullet.

One can clearly understand that all green square dots being located beneath the line with the grey circles represent installation / combinations which are less effective with regard to the increase of the Capacity Factor while increasing the LCoE as well. These cases are not worth to consider because there are pure wind/ PV combinations being equal or more efficient but with lower LCoE. The lines with the green squares are crossing the line with the grey circles only at relatively high LCoEs.

From a technical point of view a lot of combination bring additional value into the system, but commercially assessed the selection of a preferred combination shows a different picture.

Figure 10 summarizes the main conclusion of the analyses: When optimizing purely focussed on the lowest LCoE, a "wind only" plant with up-to-date WTGs will be the first choice. Combinations with PV plants give little higher LCoEs but much better Capacity Factors. Currently, there is no change for this ranking to be seen in the future. BESS adaptions are widely out of economic range and this is bound to the fact that the only "earnings" for these systems come from sales of energy at the same price as if produced and delivered directly. Using BESS technologies for more than the currently defined options, e.g. with regard to grid services delivery, will add an additional opportunity to count on income from BESS installations. This will help to reduce the applicable costs for the time shift purpose.

Finally, the result of the study goes back to the discussion on the value of additional Capacity Factor. With no doubt, the installation of the grid access from the site to the grid substation has been paid for as well (but is not considered in this study). Increasing the Capacity Factor will lead to an increased efficiency of this investment. But, increasing Capacity Factors need to be "bought" and the correct point for such additional LCoE values is subject to a decision of the responsible entities.

7. References

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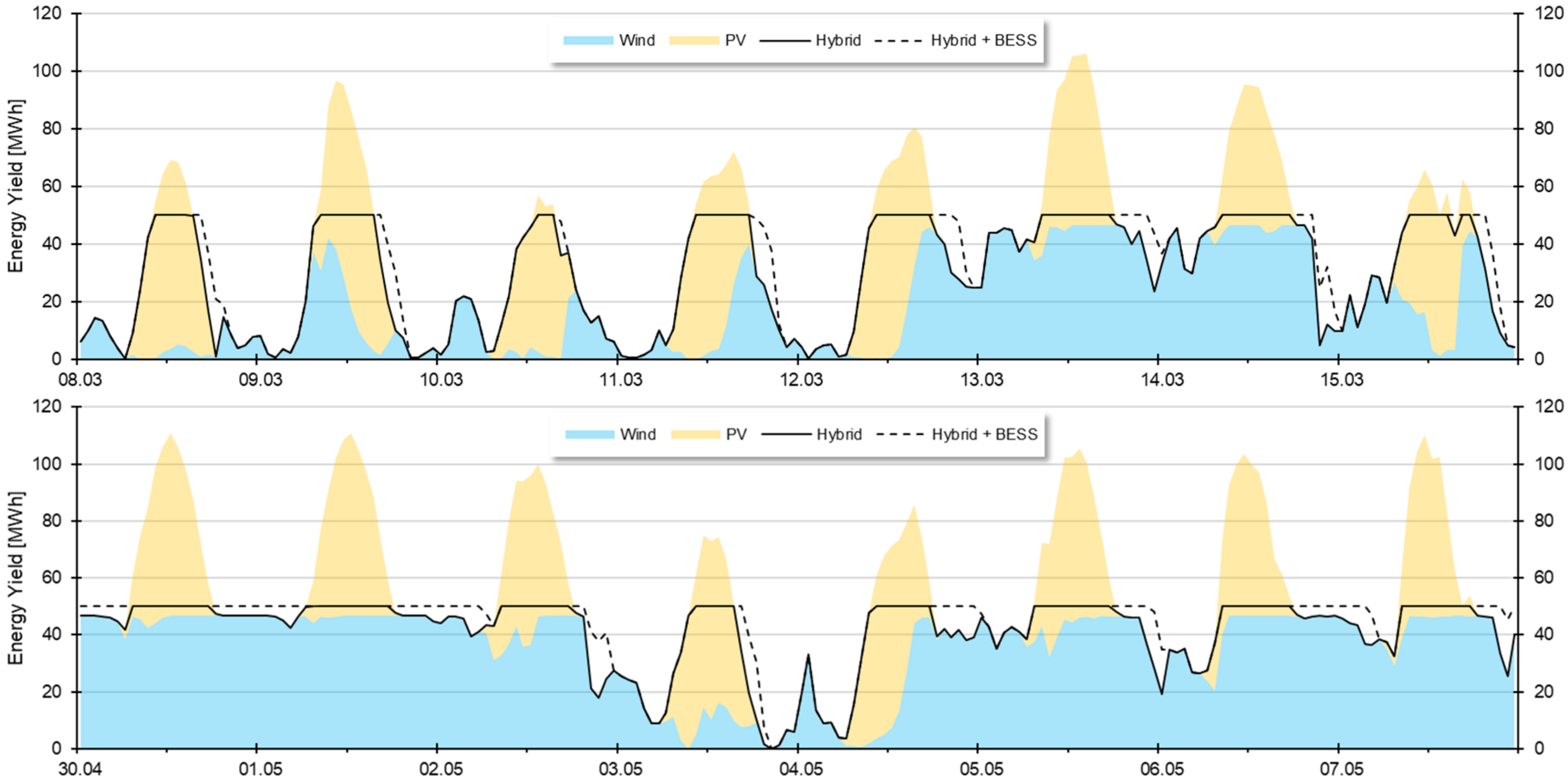
[2] X. Luo, J. Wang, M. Dooner and J. Clarke, “Overview of current development in electrical energy storage technologies and the application potential in power system operation”, Applied Energy, vol. 37, p. 511–536, 2015.
[3] H. Lopes Ferreira, R. Garde, G. Fulli, W. Kling and J. Pecas Lopes, “Characterisation of electrical energy storage technologies”, Energy, vol. 53, pp. 288-298, 2013.
[4] U. D. o. Energy, “Grid Energy Storage”, December 2013.

8. Appendix

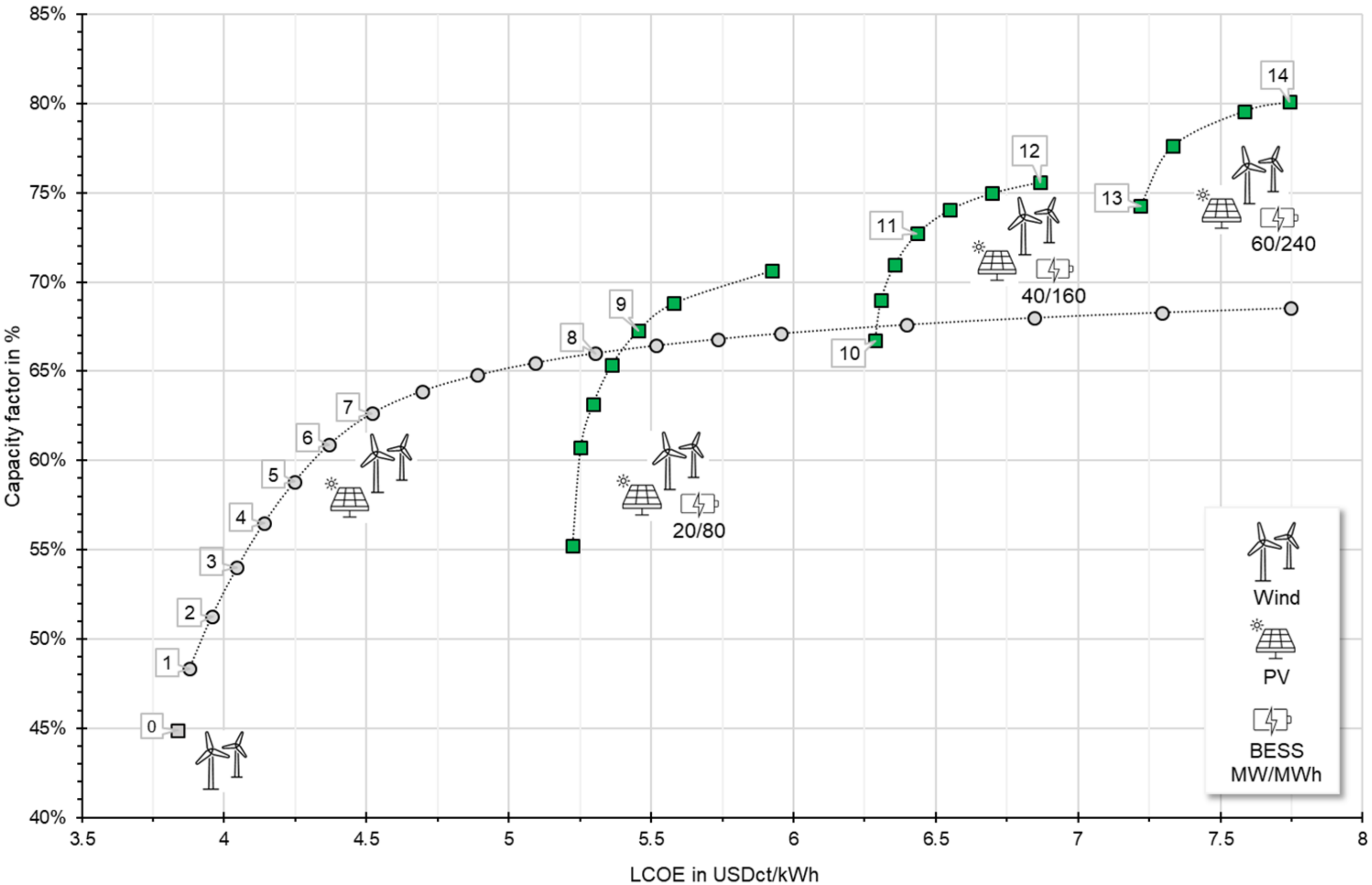


Examplary non-representative Time Series (10 year)

Modalities:

Grid connection			**PV**			**Wind**			**BESS (20 MW / 80 MWh)**	
Supply limit	50 MW		Rated Power	74.88 MWac		Nominal Power	50 MW		Loss of charge	6 %
			Degradation	0.607 %/a		Degradation	0.000 %/a		Loss of discharge	6 %
									Degradation	1.84 %/a

Figure 11: Exemplary non-representative Time Series for a Hybrid + BESS (enlarged)



Modalities:

Grid connection	
Supply limit	50 MW
CAPEX	7 million USD
OPEX	80,650 USD/a

LCOE	
Discount rate	6%
Plant-Lifetime	25 years
Construction phase	1 year

PV	
Degradation	0.607 %/a
CAPEX	811.2 USD/kWac
OPEX	13.2 USD/kWac

Wind	
Degradation	0.000 %/a
CAPEX	1,450 USD/kW
OPEX	24.9 USD/kW

BESS	
Loss of charge	6 %
Loss of discharge	6 %
Degradation	1.84 %/a
Replacement	50 % after 13 Years
CAPEX	190 USD/kW 290 USD/kWh
OPEX	7 USD/(kWh a)
Include Salvage value of BESS	

Figure 12: LCoE and Capacity Factor ratio of a Wind/PV Hybrid and Hybrid + BESS (enlarged)

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für Internationale
Zusammenarbeit (GIZ) GmbH

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Feasibility Study to determine optimal capacity of hybrid wind/solar PV projects in Pakistan
Amendment on Task B

Amendment Study Report
December 2021

Study Report

Feasibility Study to determine optimal capacity of hybrid wind/solar PV projects in Pakistan

Renewable Energy and Energy Efficiency II - Pakistan
Amendment Task B

For:	Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH
Assignment:	REEE II
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Table of Contents

1. Reasons for Amending the Task B Report

This Amendment has been prepared to extend the initial Task B report, dated October 2021 and named "BESS and LCoE Calculations". The Task B report addressed BESS solutions for large scale PV part additions to the 50 MW wind power plant.

This Amendment analyses the technical and economical results of BESS with Solar / wind hybrid combinations addressed in the Task A report, dated September 2021 and displays PV parts added to the wind power part of less than 70 MWac.

Additionally, the focus of this Amendment shall be additionally on the avoidance of curtailments, not ignoring the LCoE results of the proposed solution. Going in parallel with the importance of LCoE results, the Amendment is requested to reflect adapted CAPEX and OPEX parameters. These parameters shall be based on the recent results gained in project tenders and contracted for the installation of wind as well as PV projects.

From the technical point of view considered BESS solutions shall focus on smaller scales than done within the Task B report. This is due to the smaller scale of the PV part within the hybrid solution. As within the Task B report the C-factor of the BESS was considered to be 0.25 as the most economical solution, this Amendment shall consider a C-factor of 0.5, additionally.

2. Description of Conditions for the Calculations

2.1 CAPEX and OPEX

The Amendment is prepared on the bases of two sets on CAPEX and OPEX conditions:

- All CAPEX and OPEX conditions described within the Task B report remain valid for the calculation of the "Study LCoE". The Consultant still considers these estimations reasonable based on their latest international market knowledge. As some small scale BESS solutions have been considered, the limits for the CAPEX estimations for these BESS solutions are exceeded. This is why solutions with a power of 10 MW consider an increase of 5% for their CAPEX, whereas 5 MW solutions face 10% increase and for 1 MW solutions a 20% increase regarding the Task B report values are considered.
- A second LCoE value has been determined based on figures recently reached and contracted by NEPRA for wind power and PV power projects in Pakistan. Related CAPEX and OPEX conditions has been provided and within this Amendment the related LCoE results are called "NEPRA LCoE". It needs to be emphasised that the Consultant considers these figures quite optimistic for the PV installations as they are calculated from bigger projects (100 MWdc). Additionally, the last months showed a considerable increase of costs for PV products, among other reasons, due to the ongoing pandemic. The influence of these two factors was not considered and the figures were not adopted by the Consultant.
  As the NEPRA based figures included a grid connection per technology, the costs for the grid connection as displayed within the Task B report have been deducted one time. The figures used for the calculation of the "NEPRA LCoE" are displayed in the following table.

	Wind (incl Gid Connection)	PV (excl Gid Connection)
	[USD /MW]	[USD /MWdc]
CAPEX	1,259,000	485,900
OPEX	23,000	9,500

2.2 C-Rates

Furthermore, this Amendment considers the variants 1 to 7 from the Task A and Task B report. All variants have been calculated with two different C-rates for the BESS: C= 0.5 and C= 0.25. The C-rate definition from Task B report remains unchanged.

2.3 Total number of calculations

All in all a number of 37 different plant set-ups have been identified. One additional plant set-up has been added as this set-up represents the only overlap of the Task B report and this Amendment including a BESS. All plant set-ups have been calculated with the two different CAPEX and OPEX conditions.

3. Definition of the Adapted Calculations

As described Chapter 2 of this Amendment a total number of 38 (37 + 1) plant set-ups have been calculated. All set-ups are sub-variants of the variant 1 to variant 7 of the Task A and Task B report, adding varying BESS solutions to the respective variant. The lines within the following table marked

- "light yellow" are the variants without BESS which are included in both, Task A and Task B report; and marked
- "yellow" is the variant which has been calculated in the Task B report as well. This set-up was named No. 10 within the Task B report.

The column "Solar [MWac]" reflects the throughout the reports used AC power after the inverters. The often used "Name Plate Capacity" of these systems is included in the column "Solar [MWdc]". The quotient of these two values gives the calculated DC / AC ratio for the inverter, described within the Task A report.

No.	Variant	Wind [MW]	Solar [MWdc]	Solar [MWac]	C-Rate	BESS Power [MW]	BESS Capacity [MWh]
1	1	50	11,23	9,36	-	-	-
2	1	50	11,23	9,36	0,50	1	2
3	1	50	11,23	9,36	0,25	1	4
4	1	50	11,23	9,36	0,50	5	10

No.	Variant	Wind [MW]	Solar [MWdc]	Solar [MWac]	C-Rate	BESS Power [MW]	BESS Capacity [MWh]
5	1	50	11,23	9,36	0,25	5	20
6	1	50	11,23	9,36	0,50	10	20
7	1	50	11,23	9,36	0,25	10	40
8	2	50	22,46	18,72	-	-	-
9	2	50	22,46	18,72	0,50	10	20
10	2	50	22,46	18,72	0,25	10	40
11	2	50	22,46	18,72	0,50	20	40
12	2	50	22,46	18,72	0,25	20	80
13	3	50	33,70	28,08	-	-	-
14	3	50	33,70	28,08	0,50	20	40
15	3	50	33,70	28,08	0,50	30	60
16	3	50	33,70	28,08	0,25	20	80
17	3	50	33,70	28,08	0,25	30	120
18	4	50	44,93	37,44	-	-	-
19	4	50	44,93	37,44	0,50	30	60
20	4	50	44,93	37,44	0,50	40	80
21	4	50	44,93	37,44	0,25	30	120
22	4	50	44,93	37,44	0,25	40	160
23	5	50	56,16	46,80	-	-	-
24	5	50	56,16	46,80	0,50	30	60
25	5	50	56,16	46,80	0,50	50	100
26	5	50	56,16	46,80	0,25	30	120
27	5	50	56,16	46,80	0,25	50	200
28	6	50	67,39	56,16	-	-	-
29	6	50	67,39	56,16	0,50	40	80
30	6	50	67,39	56,16	0,50	60	120
31	6	50	67,39	56,16	0,25	40	160
32	6	50	67,39	56,16	0,25	60	240
33	7	50	78,62	65,52	-	-	-
34	7	50	78,62	65,52	0,50	50	100
35	7	50	78,62	65,52	0,50	70	140
36	7	50	78,62	65,52	0,25	40	160

No.	Variant	Wind [MW]	Solar [MWdc]	Solar [MWac]	C-Rate	BESS Power [MW]	BESS Capacity [MWh]
37	7	50	78,62	65,52	0,25	50	200
38	7	50	78,62	65,52	0,25	70	280

4. Results of the Calculations

For all 38 plant set-ups a number of parameters have been calculated. These parameters have been defined in a way allowing the technical as well as the commercial evaluation of the plant set-ups.

The calculated parameters are:

- "Capacity Factor": This factor is calculated fully in line with the definition given in the Task B report. As the Capacity Factor might vary slightly over the years (depending on degradation and replacement activities) and is estimated to be lowest after 25 years of operation, the Capacity Factor is displayed for the 25^{th} year of operation.
- "Generated Annual Yield": The generated annual yield reflects the yield presuming all produced energy can be fed in the grid without any curtailments.
- "Delivered Annual Yield": This value demonstrates the yield which is delivered into the public grid. All curtailments and all losses due to charging and discharging have been considered.
- "Reduced Curtailment": This figure compares the curtailment needed in case of plant set-up without BESS and with BESS. Round-trip losses have been considered as they are unavoidable. Consequently, this value displays the percentage of reduction of the curtailments by including BESS into the plant set-up.
- "Study LCoE ": The Study LCoE mirrors the LCoE value calculated based on the conditions and figures introduced in the Task B report. For the small scale BESS a surcharge onto the CAPEX have been calculated. Conditions for this surcharge are described in Chapter 2.1 of this Amendment.
- "NEPRA LCoE ": The NEPRA LCoE has been calculated based on the CAPEX and OPEX for wind and PV taken from NEPRA contract recently closed in Pakistan. Figures used for this Amendment and details regarding their calculation are given in in Chapter 2.1 of this Amendment. All CAPEX and OPEX figures related to BESS have been calculated in the same manner as for the Study LCoE.

The following table displays the results.

No.	Var-iant	Wind [MW]	Solar [MWdc]	Solar [MWac]	C-Rate	BESS Power [MW]	BESS Capac-ity [MWh]	Capacity Factor [%]	Generated Annual Yield [GWh]	Delivered Annual Yield [GWh]	Reduced Curtailment [%]	Study LCoE [USD Ct / kWh]	NEPRA LCoE [USD Ct / kWh]
1	1	50	11,23	9,36	-	-	-	48,3%	213,6	212,8	0,00%	3,88	3,10
2	1	50	11,23	9,36	0,50	1	2	48,4%	213,6	212,9	19,82%	3,92	3,15
3	1	50	11,23	9,36	0,25	1	4	48,4%	213,6	213,0	33,47%	3,96	3,18
4	1	50	11,23	9,36	0,50	5	10	48,4%	213,6	213,3	72,96%	4,09	3,32
5	1	50	11,23	9,36	0,25	5	20	48,5%	213,6	213,5	98,60%	4,26	3,49
6	1	50	11,23	9,36	0,50	10	20	48,5%	213,6	213,5	98,60%	4,29	3,52
7	1	50	11,23	9,36	0,25	10	40	48,5%	213,6	213,5	100,00%	4,63	3,86
8	2	50	22,46	18,72	-	-	-	51,3%	230,6	226,4	0,00%	3,96	3,15
9	2	50	22,46	18,72	0,50	10	20	51,6%	230,6	228,2	48,69%	4,33	3,52
10	2	50	22,46	18,72	0,25	10	40	51,9%	230,6	229,4	79,00%	4,62	3,82
11	2	50	22,46	18,72	0,50	20	40	51,9%	230,6	229,4	79,04%	4,67	3,87
12	2	50	22,46	18,72	0,25	20	80	52,0%	230,6	230,1	97,85%	5,26	4,46
13	3	50	33,70	28,08	-	-	-	54,0%	247,6	239,1	0,00%	4,04	3,20
14	3	50	33,70	28,08	0,50	20	40	54,8%	247,6	243,1	53,34%	4,70	3,87
15	3	50	33,70	28,08	0,50	30	60	55,1%	247,6	244,3	69,77%	5,03	4,21
16	3	50	33,70	28,08	0,25	20	80	55,2%	247,6	245,1	79,92%	5,22	4,40
17	3	50	33,70	28,08	0,25	30	120	55,4%	247,6	245,8	89,64%	5,85	5,03
18	4	50	44,93	37,44	-	-	-	56,5%	264,6	250,7	0,00%	4,14	3,26
19	4	50	44,93	37,44	0,50	30	60	57,9%	264,6	257,3	53,84%	5,05	4,20
20	4	50	44,93	37,44	0,50	40	80	58,1%	264,6	258,6	64,02%	5,37	4,52
21	4	50	44,93	37,44	0,25	30	120	58,4%	264,6	260,1	76,34%	5,80	4,95

No.	Var-iant	Wind [MW]	Solar [MWdc]	Solar [MWac]	C-Rate	BESS Power [MW]	BESS Capac-ity [MWh]	Capacity Factor [%]	Generated Annual Yield [GWh]	Delivered Annual Yield [GWh]	Reduced Curtailment [%]	Study LCoE [USD Ct / kWh]	NEPRA LCoE [USD Ct / kWh]
22	4	50	44,93	37,44	0,25	40	160	58,6%	264,6	261,0	83,60%	6,38	5,54
23	5	50	56,16	46,80	-	-	-	58,8%	281,6	261,2	0,00%	4,25	3,34
24	5	50	56,16	46,80	0,50	30	60	60,4%	281,6	269,1	44,02%	5,09	4,21
25	5	50	56,16	46,80	0,50	50	100	61,0%	281,6	272,0	60,25%	5,68	4,81
26	5	50	56,16	46,80	0,25	30	120	61,2%	281,6	273,1	65,89%	5,78	4,91
27	5	50	56,16	46,80	0,25	50	200	61,7%	281,6	275,4	78,97%	6,87	6,00
28	6	50	67,39	56,16	-	-	-	60,9%	298,6	270,3	0,00%	4,37	3,42
29	6	50	67,39	56,16	0,50	40	80	63,2%	298,6	281,9	46,50%	5,42	4,52
30	6	50	67,39	56,16	0,50	60	120	63,8%	298,6	285,0	58,62%	5,98	5,08
31	6	50	67,39	56,16	0,25	40	160	64,2%	298,6	287,0	66,88%	6,29	5,40
32	6	50	67,39	56,16	0,25	60	240	64,7%	298,6	289,2	75,49%	7,33	6,44
33	7	50	78,62	65,52	-	-	-	62,6%	315,6	277,4	0,00%	4,52	3,53
34	7	50	78,62	65,52	0,50	50	100	65,8%	315,6	294,0	49,05%	5,74	4,81
35	7	50	78,62	65,52	0,50	70	140	66,5%	315,6	297,3	58,81%	6,26	5,34
36	7	50	78,62	65,52	0,25	40	160	66,7%	315,6	298,5	62,56%	6,29	5,37
37	7	50	78,62	65,52	0,25	50	200	67,1%	315,6	300,4	68,06%	6,77	5,86
38	7	50	78,62	65,52	0,25	70	280	67,5%	315,6	302,3	73,65%	7,76	6,85

5. Conclusions

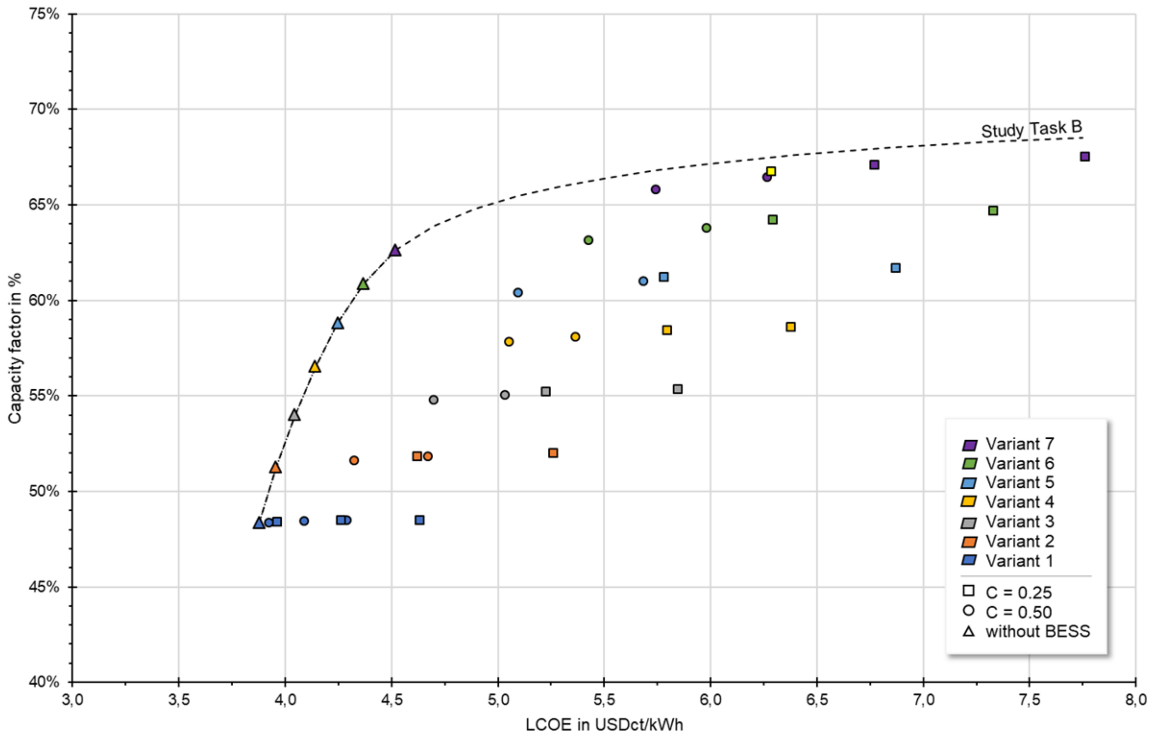
The whole set of data displayed in the table in Chapter 4 of this Amendment has been analysed within diagrams. The diagrams generally follow the formatting that has been applied in the "Conclusion" chapter of the Task B report as well.

Two diagrams have been prepared:

- The first one is showing the results of the Capacity Factor over the Study LCoE. This diagram includes a curve mirroring the curve that was displayed in the Task B report as well. This curve connects all points which were calculated without BESS.
- The second diagram displays results of the Capacity Factor over the NEPRA LCoE. As the related CAPEX and OPEX values have not been used within the Task B report, no extension of the plant set-ups without BESS can be shown. Nevertheless, it is possible to imagine how such line would be developing when applying further PV capacities.

The dots marked with triangles represent plant set-ups without BESS of each variant. For both diagrams the colour of the dots representing the same plant set-ups with BESS have been maintained. This allows for simple reference to same PV size within a hybrid project. The dots are represented in either square or circular shape. Square shape dots indicate BESS with C = 0.25, whereas circular dots demonstrate solution with C= 0.5.

The diagram is showing the results for the "Study LCoE" case. The yellow square marks one point which has been considered in the Task B report as well (No. 10):



Modalities:

Grid connection
Supply limit 50 MW
CAPEX 7 million USD
OPEX 80,650 USD/a

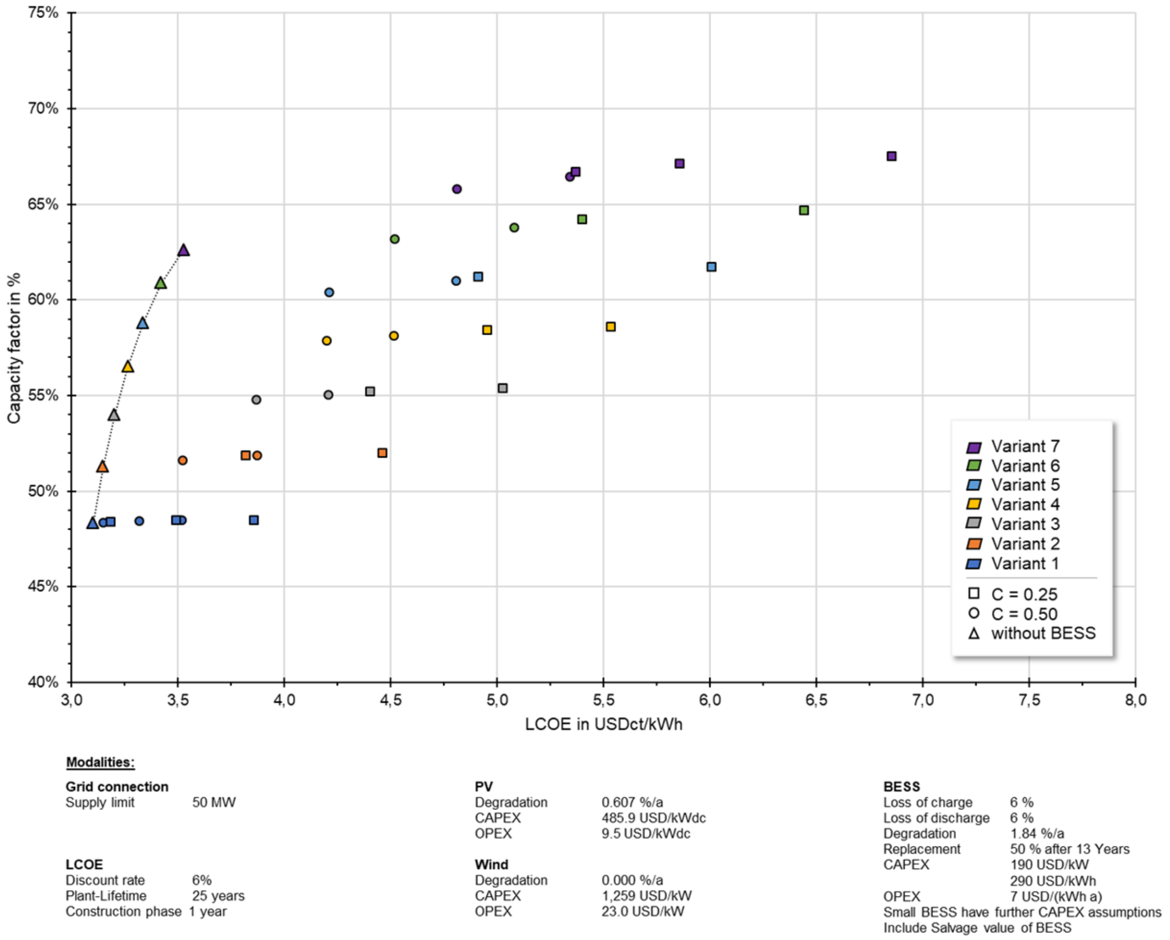
LCOE
Discount rate 6%
Plant-Lifetime 25 years
Construction phase 1 year

PV
Degradation 0.607 %/a
CAPEX 676 USD/kWdc
OPEX 11 USD/kWdc

Wind
Degradation 0.000 %/a
CAPEX 1,450 USD/kW
OPEX 24.9 USD/kW

BESS
Loss of charge 6 %
Loss of discharge 6 %
Degradation 1.84 %/a
Replacement 50 % after 13 Years
CAPEX 190 USD/kW
290 USD/kWh
OPEX 7 USD/(kWh a)
Small BESS have further CAPEX assumptions
Include Salvage value of BESS

Results of the "NEPRA LCoE" analyses are displayed in the following diagram:



Both pictures clearly show the same result and this result has been discussed in the Task B report as well: All dots representing project set-ups with BESS are located beneath the curve without BESS. This conditions are shown in calculation independent from the input CAPEX and OPEX data. From the commercial point of view this means that always a plant set-up without BESS is possible to implement, organising the same Capacity Factor with lesser LCoE (but more curtailments). Having understood this effect, it is still correct to generally name BESS solutions commercially only possible in case further incomes (e.g. for grid services) can be gained.