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Photovoltaic (PV)-Hydro-Battery Case Study on Tarbela Dam

A Desktop Study for Pakistan

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Definitions

PV-Hydro-Battery: In this Study, the combined power generation of hydro reservoirs and solar panels will be called **PV-Hydro-Battery.** The Battery can be charged by storing water and discharged by releasing water in the respective hydro reservoirs.

Conventional Power Generation: The conventional power supply consists of thermal power plants, nuclear power plants, the remaining (e.g. run of river) hydropower and power from wind and bioenergy.

Peak Load Effect: The reduction of the peak of conventional power supply.

1. Introduction

To achieve the condition derived from the Paris Agreement of 32% Renewable Energy (RE) Generation by 2030 in EU-countries[1], renewable energies must become systemically relevant. It is therefore necessary to analyze large renewable energies projects, starting with countries with high RE potential such as wind, solar irradiation and hydro resources.

The problem with renewable energies (RE) is the volatile power generation depending on weather conditions such as wind, sun and water levels. The solar power peak at midday for example leads to a reduction of conventional power generation. This negative midday peak in the conventional load and the following ramp-up in the afternoon hours has negative effects on conventional power plants[2]. The question of good storage facilities is therefore essential. There are a large number of studies dealing with the implementation of new storage options such as large battery systems, power-to-gas or pumped-hydro storage. The development of these technologies usually includes negative impacts such as the use of rare earth metals or interference with natural processes of forests and fish habitats.

But what if we can use existing sources? The ten biggest hydro reservoirs worldwide (rated by storage volume) already have a combined installed capacity of around 37,000 MW and a water storage capacity of around 1,182 billion cubic meters[3]. This storage capacity can be used to smoothen the problems of volatile RE generation.

Due to its climate, Pakistan is a country with large dam hydro power plants and a high solar power potential. The government decided to aim for 30% RE generation by 2030[4]. Therefore, Pakistan is a good example for the simulation of dam hydro power in combination with solar power to evaluate the effects of a more constant energy generation of RE.

2. Objective

Usually, there is a power demand peak at midday and in the evening. If solar power can contribute to the midday peak, hydro power can be retained in the meantime. In the evening, when demand is very high, the water can be released from the reservoir to contribute to the generation peak. With this approach, it is possible to use the stored water volume for power generation to smoothen the volatile generation of RE. This simulation can thus lead to a reduction in the installed capacity of conventional power plants. Therefore, the main objective of the simulation is to reduce fossil peak power.

To identify these potentials, a study was carried out using the Tarbela Dam with a capacity of 6.3 GW as an example. The solar power implementation was analyzed in two analyses of 3 GW AC each: The first analysis describes scattered PV power across Pakistan. The second considers the installation of floating PV panels on the Tarbela Reservoir. The simulation models are based on three typical reference days; one in summer season, one in winter season and one in middle season.

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[1] U. Nations, "Paris Agreement" 2015.

[2] Office of Energy Efficiency & Renewable Energy, "Confronting the Duck Curve: How to Address Over-Generation of Solar Energy | Department of Energy," 2017. [Online]. Available: https://www.energy.gov/eere/articles/confronting-duck-curve-how-address-over-generation-solar-energy. [Accessed: 27-Sep-2019].

[3] Water Technology, "Top 10 biggest dams," 2013. [Online]. Available: http://documents.worldbank.org/curated/en/112881468289211993/pdf/SFG1900-V1-EA-P157372-Box394869B-PUBLIC-Disclosed-3-3-2016.pdf.

[4] GIZ, "Draft ARE Policy," pp. 1–38, 2019

3. Fields of Study

3.1. Load

In the present study, conventional power generation is understood to mean all generation which does not come from PV power or the currently used hydropower reservoir. Usually, the majority of conventional power consists of fossil power, but also nuclear, wind, bagasse and remaining hydro power.

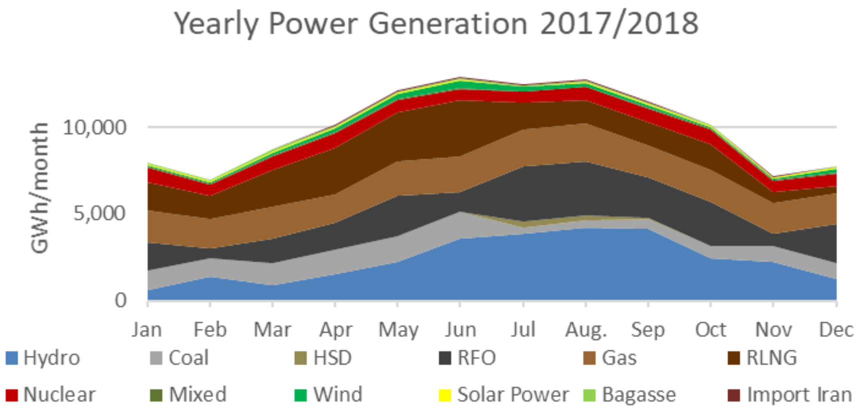

Figure 1: Yearly Power Generation (Source: Industry Report 2018)

This means that the load curve consists of the conventional power generation, PV power and hydropower of the currently used reservoir, taking into account that the demand is always met (load=power generation).

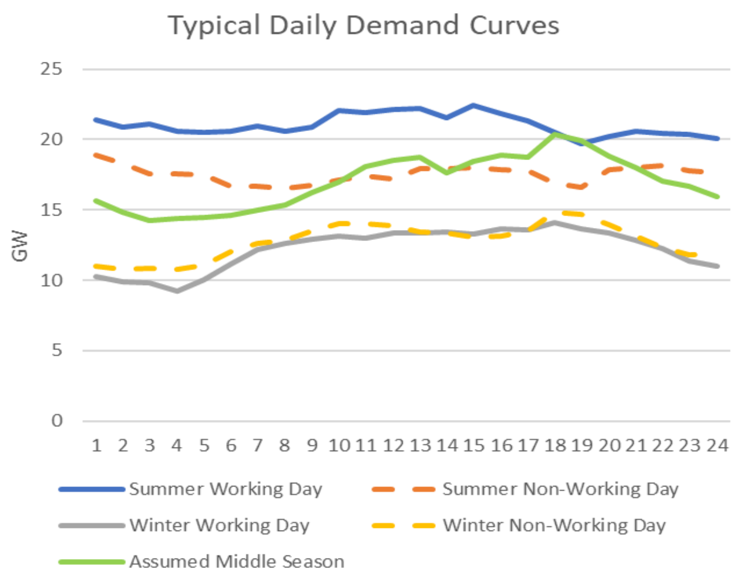

Figure 2: Typical Daily Demand Curves

In Pakistan the yearly demand (load) curve varies within the year. There is a higher energy supply in summertime due to increased usage of air-condition in these months.
The study is based on the data of three reference days, which are shown in figure 2. Since the load curve for the middle season is not available, it was upscaled from a typical day of the winter season. For this study, only working days were considered.

3.2. PV Power

The PV generation curve is generated with the program PVSOL software using Meteonorm irradiation data. This program creates hourly data for a synthetical year based on historical data. For a basic plant unit 25 kW AC / 30.5 kWp is assumed. This modelled generation curve is then scaled upwards, depending on the installed capacity of PV power, to generate the actual PV generation. The study is carried out with two different scenarios of solar power.

<u>Scattered PV</u>

The first scenario is implemented with ground mounted/roof solar power plants which are scattered across Pakistan at 12 different locations. As shown on an example day in figure 3, the average of the 12 locations leads to the modelled PV generation curve for each day of an entire year.

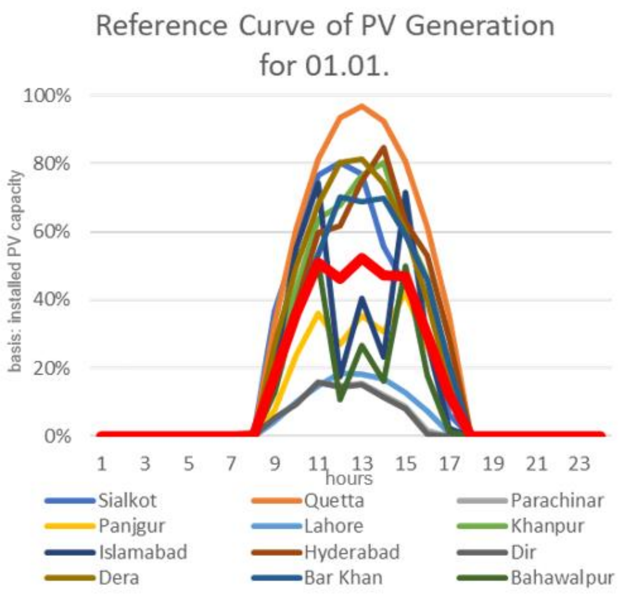

Figure 3: Reference Curve of PV Generation for 01.01

Figure 4: Selection of Reference Locations

As shown in Figure 5, solar power varies over the year. In summertime there is a higher PV power supply than in winter season.

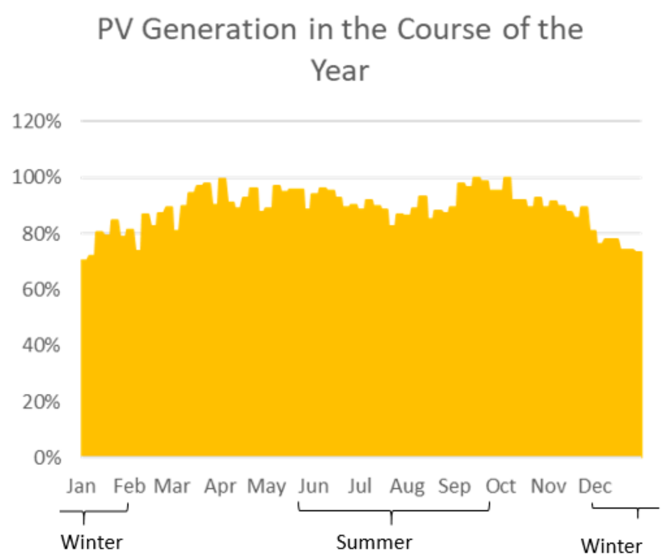

Figure 5: PV Generation in the Course of the Year

Floating PV

In the second scenario, floating solar power is installed on the currently used hydropower reservoir. For that scenario, it is assumed that the water-cooling effect leads to an 7% energy gain. Some floating PV projects report an improved energy yield of more than 10% compared to ground-mounted PV systems[5].
Assuming that approx. 1 hectare per 1 MW AC is required, Tarbela reservoir provides a sufficient surface area for floating PV applications of approx. 3 GW in the main stream and side arms. For a feasibility study the anchoring of the floating devices has to be analysed, especially in the main stream of the Indus river during summer season when the water flow is high. At low water level during winter season, the solar floating devices partially might fall dry, e.g. in side arms.

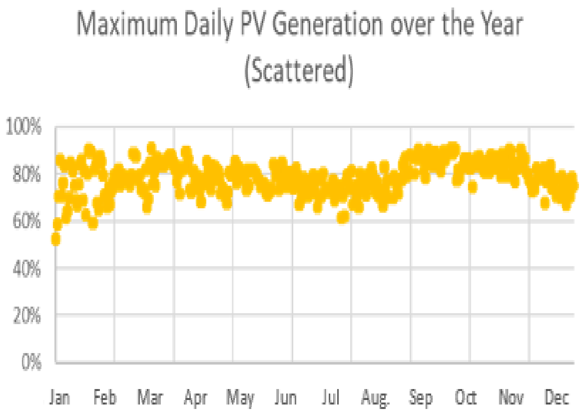

Figure 6: Maximum Daily PV Generation over the Year (Scattered)

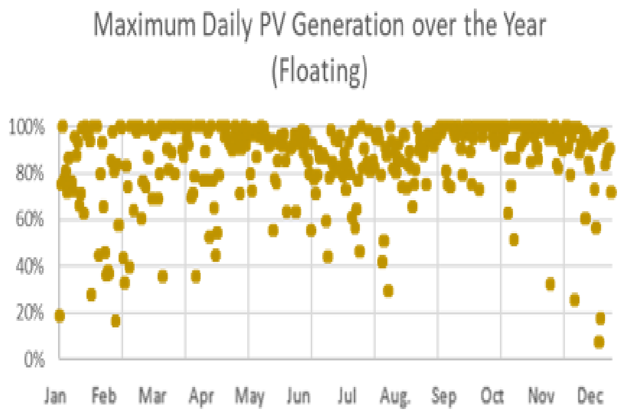

Figure 7: Maximum Daily PV Generation over the Year (Floating)

As shown in Figure 6 and 7 the floating PV power curve shows more variation. This is because there is a lack of risk diversion in floating solar power plants if the panels are only installed on one reservoir. The variation of irradiation can lead to problems of using the PV-Hydro-Battery as there is a high probability for days with low solar power supply. This effect can be reduced by scattering the floating solar power on different hydropower reservoirs across the country. The main differences between Floating Solar and Scattered are shown in the table below.

	Floating Solar PV	**Ground Mounted PV**
Land/area lease cost	Assumed none	Lease benchmarked to agricultural use
Performance	Higher specific yield (5-10%) due to - lower module temperature and - lower soiling compared to ground mounted, but inclination limited and tracking-systems not possible	Optimal inclination state of the art; additional yield improvement possible through tracking-systems and bifacial modules
Installation	Costly floating devices and transportation; mooring and anchoring are challenging	High standardization of mounting structures at low cost is market standard
Grid access	Synergy of grid access of floating PV and hydropower; avoidance of costly separate PV access	Costly grid access of large plants to medium or high voltage systems

[5] Floating Solar Market Report, World Bank Group 2019

	Floating Solar PV	Ground Mounted PV
Environment	Positive: water cooling effect, reduced evaporation, less algae, higher O_2 content of water	Large plants compete with agriculture or forestry
Investment	Higher CAPEX due to mooring and anchoring; currently, high floats' costs tend to decrease	Even technology is mature, cost still decrease on components; civil costs do not decrease any further
O&M	Accessibility of plant and replacement of parts is more complicated; bird droppings; higher maintenance cost	Matured technology, easy to access, very low maintenance cost

Table 1: General Difference between Ground Mounted and Floating Solar

3.3. Hydropower

The historic data of outflow include irrigation, outflow through turbines and non-usable outflow summarized as the components of outflow. figure 8 shows the outflow and head data for Tarbela Dam in 2016. Currently, the Tarbela Dam only contains a capacity of 4,888 MW, but the development of the future extension is in progress. Therefore, the study is carried out with a maximum capacity of 6,298 MW.

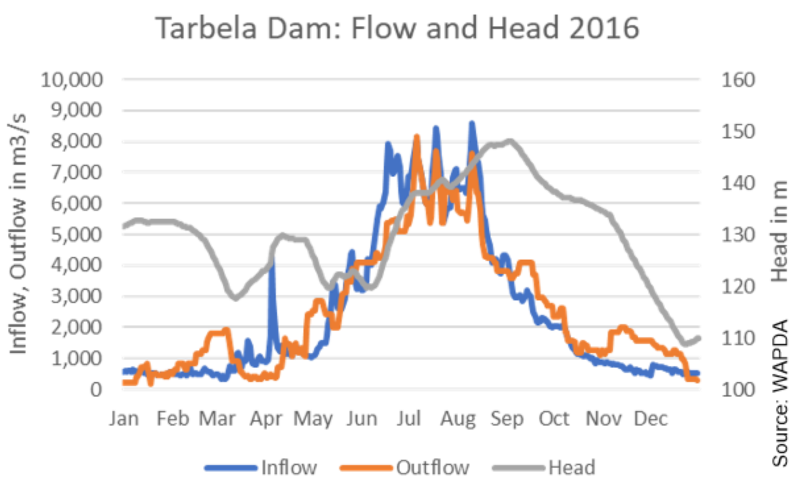

Figure 8: Tarbela Dam: Flow and Head 2016 (Source: WAPDA)

Facts about Tarbela Dam
Water level reservoir between 95 to 148 m
Max water capacity 2659 m^3/s
Max power generation 3478 MW (2017)

Table 2: Facts about Tarbela Dam

The facts and researched data of Tarbela dam is used to generate a model of the hydropower dam. Since the model does not take into account downtime for e.g. O&M works, the variation of the modelled power generation (17,000 GWh) in 2016 is approx. 2,000 GWh compared to the researched data (15,000 GWh).

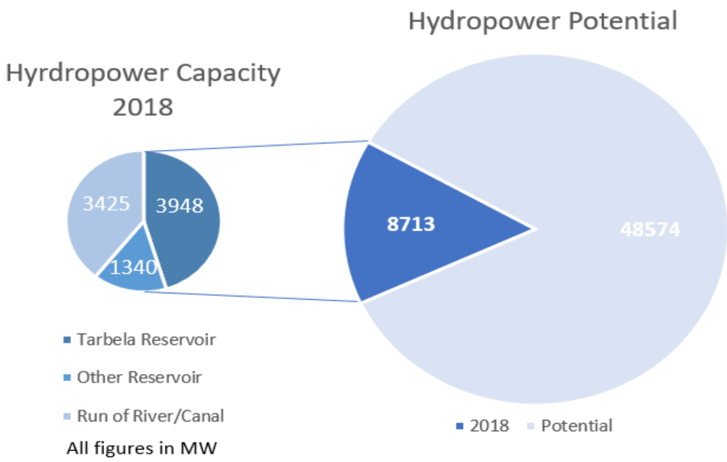

Figure 9: Hydropower Potential of Pakistan:

The study was carried out using Tarbela Dam as an example, as the effect of the PV-Hydro-Battery can be shown clearly here. Pakistan also has more hydropower capacities and hydropower potential. Run-of-river plants cannot be used for PV-Hydro-Battery due to lack of reservoirs. Therefore, only 60.7% of installed capacities account eligible for PV-Hydro-Battery. The Tarbela dam amounts to 45.3% out of those 60.7%. Approximately 66% (up to 37,000 MW) of the total hydro-power potential (~57,000 MW) can be considered suitable for PV-Hydro-Battery applications, as these plants are large dam reservoir systems.

4. Results of the Reference Days

This chapter first explains how the reference days were selected. After that, the results for each reference day for scattered PV power across Pakistan are shown. Since the selection of reference days is identical for floating solar, the results for it are presented in form of an over-view.

4.1. Selection of Reference Days

For the study, three reference days are analyzed. The decision on the reference days to be selected is mainly based on the amount of water supply. figure 10 shows the amount of water supply in each season and the resulting selection of the reference days.

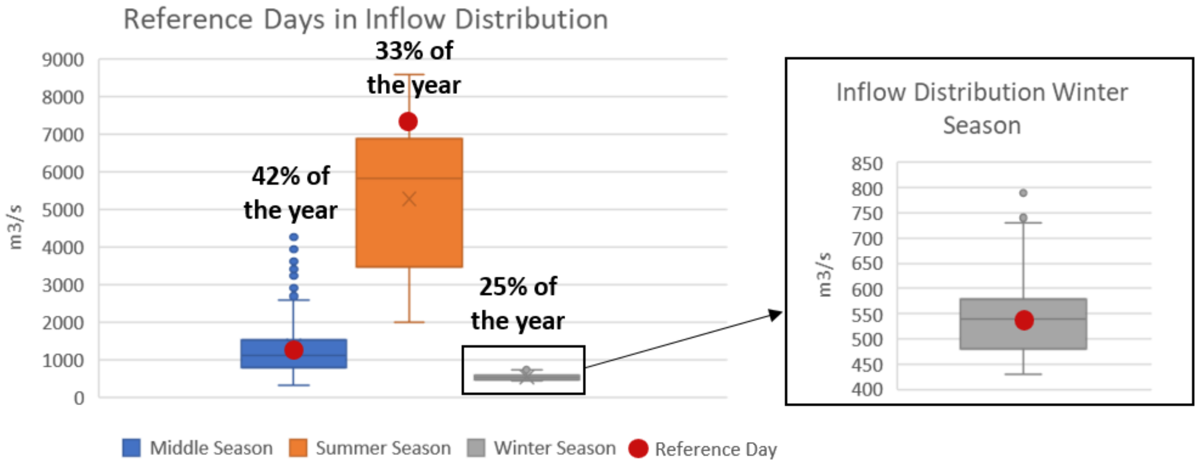

Figure 10: Reference Days in Inflow Distribution

Figure 11 shows the reference days in the course of the year. In the summer season, when hydro generation is high, the demand is also high. In winter season the demand is lower. When demand is higher, the daily demand curve shows a different shape due to the increased use of air-condition at midday.

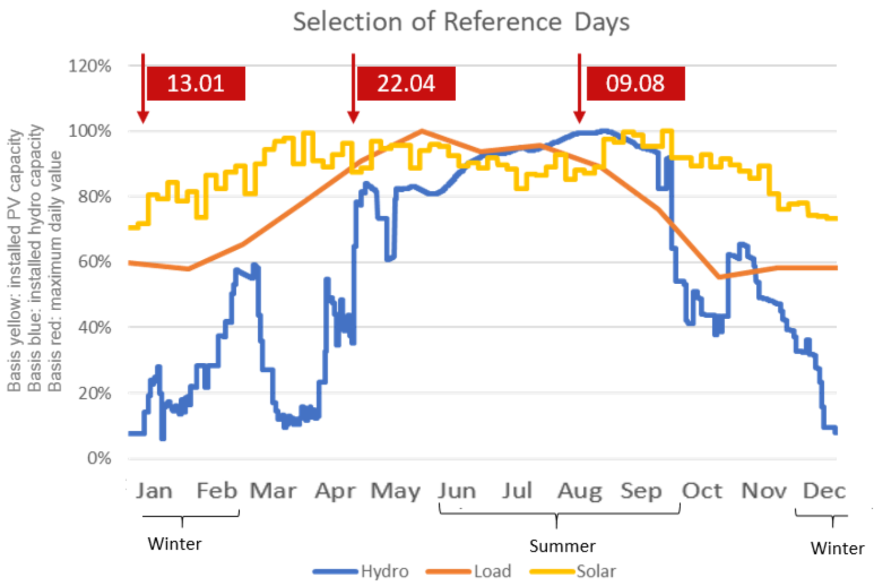

Figure 11: Selection of Reference Days

Table 3 shows an overview of the data used for each reference day.

Data Source	Photovoltaic	Hydro	Load
Middle season	22.04. as of reference year	22.04.2016; WAPDA	assumed profile
Summer season	09.08. as of reference year	09.08.2016; WAPDA	typical working day 2017; industrial report 2018
Winter season	13.01. as of reference year	13.01.2016; WAPDA	typical working day 2017; industrial report 2018

Table 3: Data Sources of Reference Days

4.2. Middle Season

With an installed PV capacity of 3 GW AC it is possible to obtain the following data:

Storage Volume	27.45 mio. m^3
PV Generation	17.1 GWh/day
Storage Energy	8.69 GWh/day
Reservoir Level Fluctuation	13 cm
Outflow Fluctuation	Min 181 to max 3279 m^3/s

Table 4: Findings on Middle Season

As shown in figure 12 and 13, PV power at midday is used to store water. In the evening peak, when demand is high, the stored water can be used to overcome the evening peak.

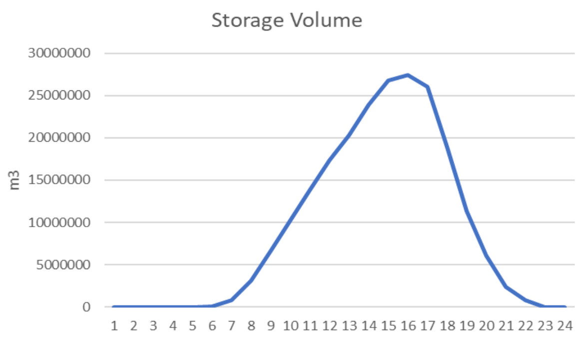

Figure 12: Storage Volume of Reference Day in Middle Season

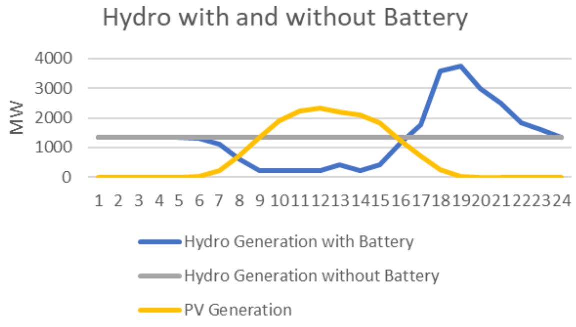

Figure 13: Hydropower Curve of Reference Day in Middle Season

The peak load effect is generated by reducing peak demand. Compared to the as-of-today scenario (evenly distributed hydropower generation over the whole day) the evening peak hour can be reduced by 2,460 MW.

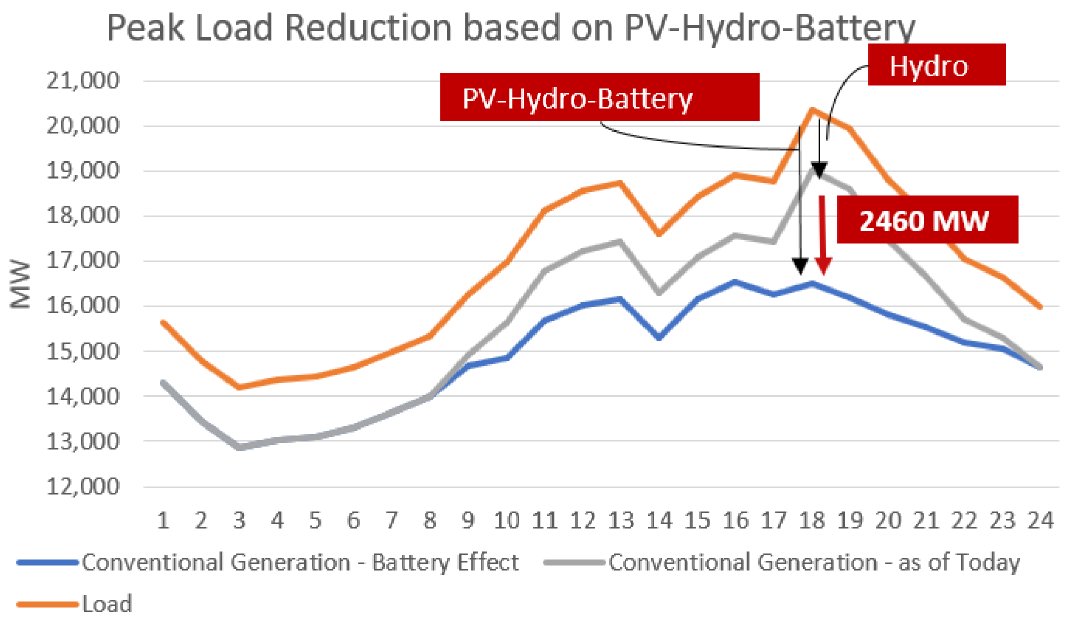

Figure 14: Peak Load Reduction of Reference Day in Middle Season

On the selected day approx. 250 MW of the peak load reduction are contributed by PV directly. The rest of the peak load effect occurs because of the stored water which is also generated by the PV power indirectly.

4.3. Summer Season

With an installed PV capacity of 3 GW AC it is possible to gain PV power of 16.6 GWh. However, it is not possible to store water in summer time because the hydropower turbines operate at full capacity. Therefore, storing water would not lead to increased hydropower generation when releasing the water.

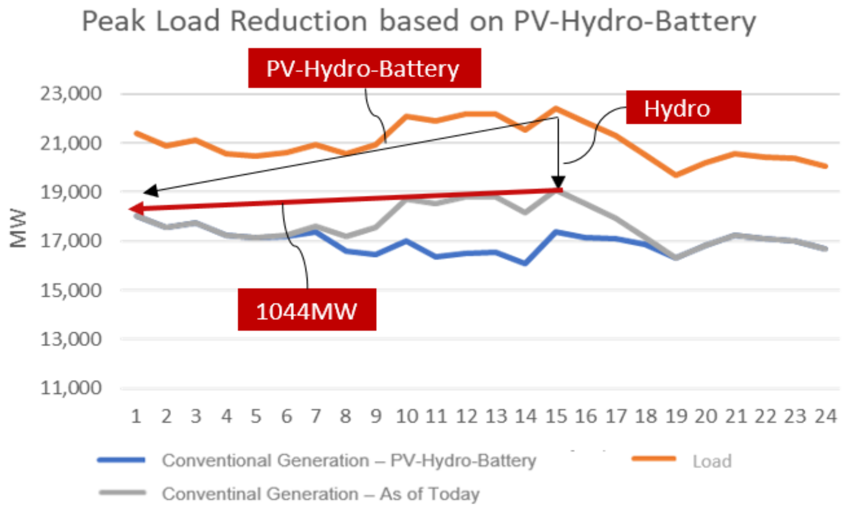

Figure 15: Peak Load Reduction of Reference Day in Summer Season

But even without storage possibility the PV-Hydro-Battery leads to a peak load effect. The increased use of the air-condition in summer leads to a load curve which has its peak at mid-day. At midday, PV power can reduce the peak load by 1 GW. Therefore, the peak load effect in the summer season is completely covered directly by PV power.

4.4. Winter Season

With an installed PV capacity of 3 GW AC it is possible to obtain the following data:

Storage Volume	12.8 mio m^3
PV Generation	15.9 GWh/day
Storage Energy	4.2 GWh/day
Reservoir Level Fluctuation	6 cm
Outflow Fluctuation	Min 181 to max 1726 m^3/s

Table 5: Findings on Winter Season

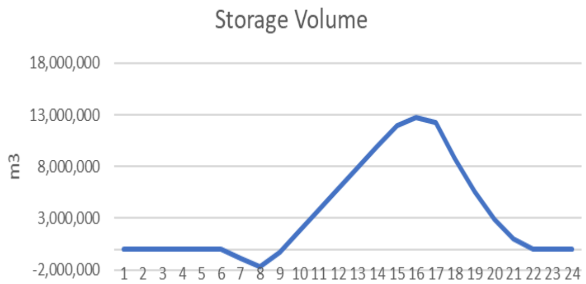

Figure 16: Storage Volume of Reference Day in Winter Season

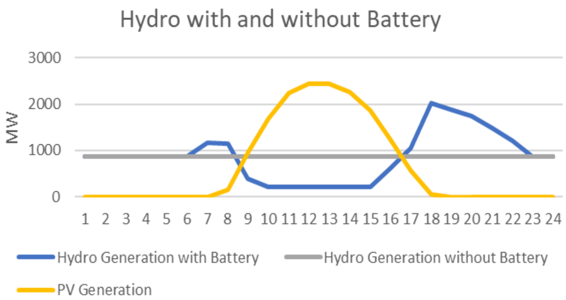

Figure 17: Hydropower Curve of Reference Day in Winter Season

As shown in figure 16 and 17, PV power at midday is used to store water. In the evening, when demand is high, the stored water can be used to overcome the evening peak. On the reference day, a high demand in the morning hours leads to an increased use of the hydropower storage at this time.

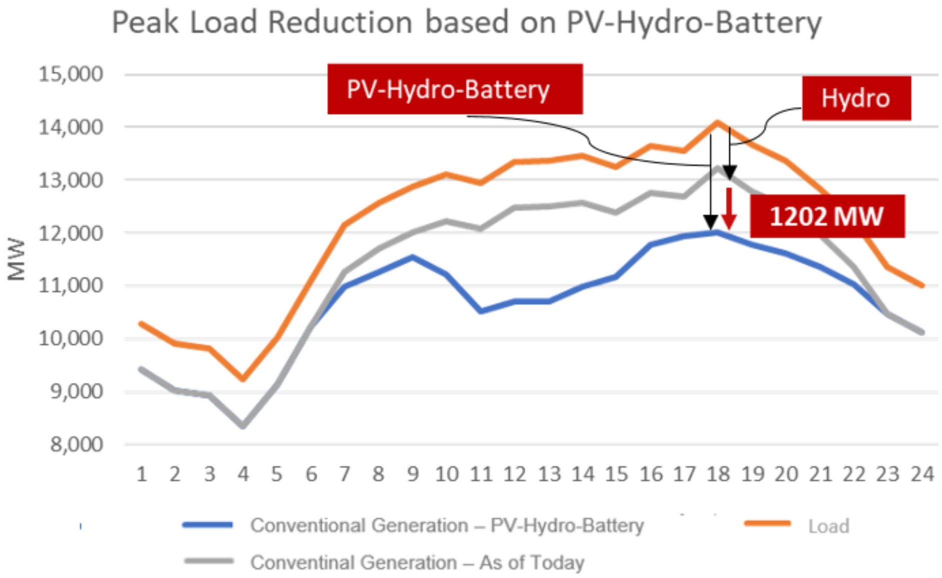

Figure 18: Peak Load Reduction of Reference Day in Winter Season

Compared to the as-of-today scenario (evenly distributed hydropower generation over the whole day) the peak hour of the evening can be reduced by 1,202 MW.
On the reference day, 56 MW of the peak load reduction will be covered by PV directly. The rest of the peak load effect is caused by the stored water, which is indirectly generated by PV power.

4.5. Limitations of Floating PV

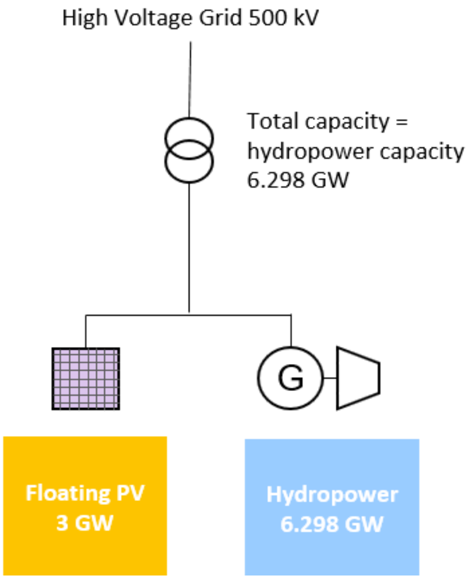

Figure 19: Grid Access Point of Floating Solar

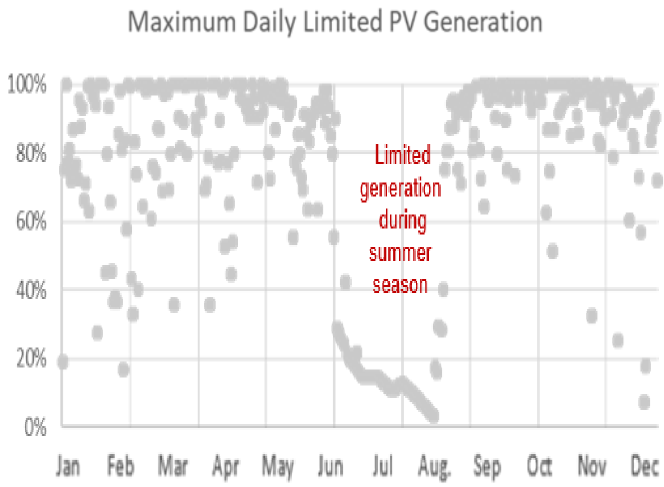

Figure 20: Maximum Daily Limited PV Generation of Floating Solar

It is assumed that all power to be generated by floating PV will have to be evacuated via the existing grid access of the hydropower plant at Tarbela dam. Hydropower has priority in summer, which is the high flow season, which is why PV evacuation cannot take place simultaneously. In summer, the hydropower plant runs at full capacity and the grid access is used 100% by hydropower. The grid access becomes a bottleneck and no PV power can be exported as shown in figure 20. This principle scheme of floating PV applies as long as the existing grid access is used by the given hydropower plant.

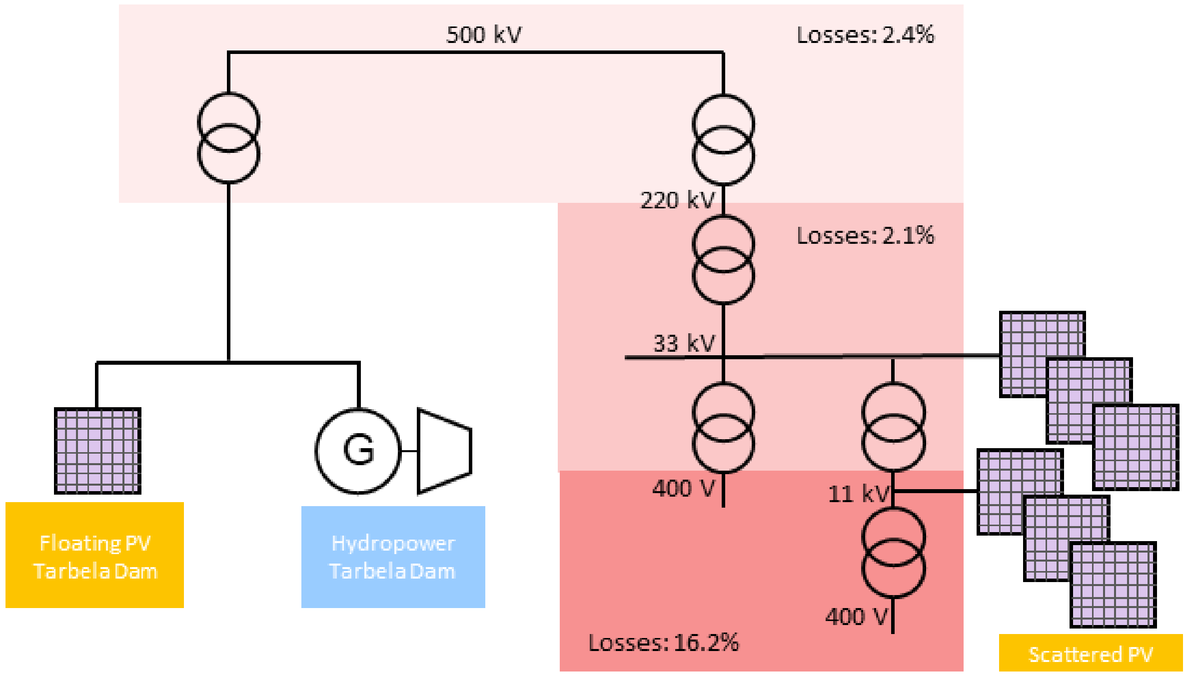

Figure 21: Grid Losses of PV Generation (Scattered and Floating)

There are also high losses with floating solar because it is using the high voltage grid system. As scattered PV is connected closer to the customer, grid losses of floating solar systems are higher in comparison.

The limited grid access point and the higher transmission losses result in higher total grid losses for floating solar compared to scattered solar. These totallosses exceed the higher PV power generation which arise from cooling effects.

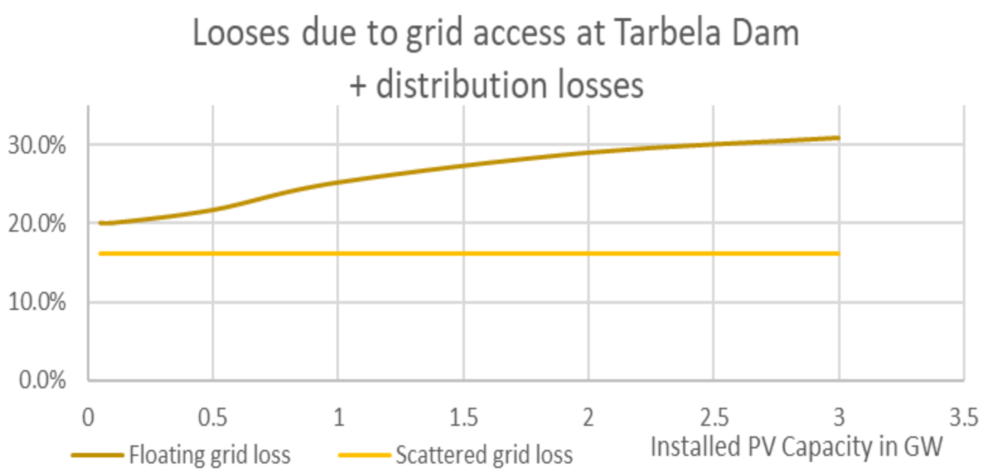

Figure 22: Losses due to Grid Access at Tarbela Dam + Distribution Losses

4.6. Results of Floating PV

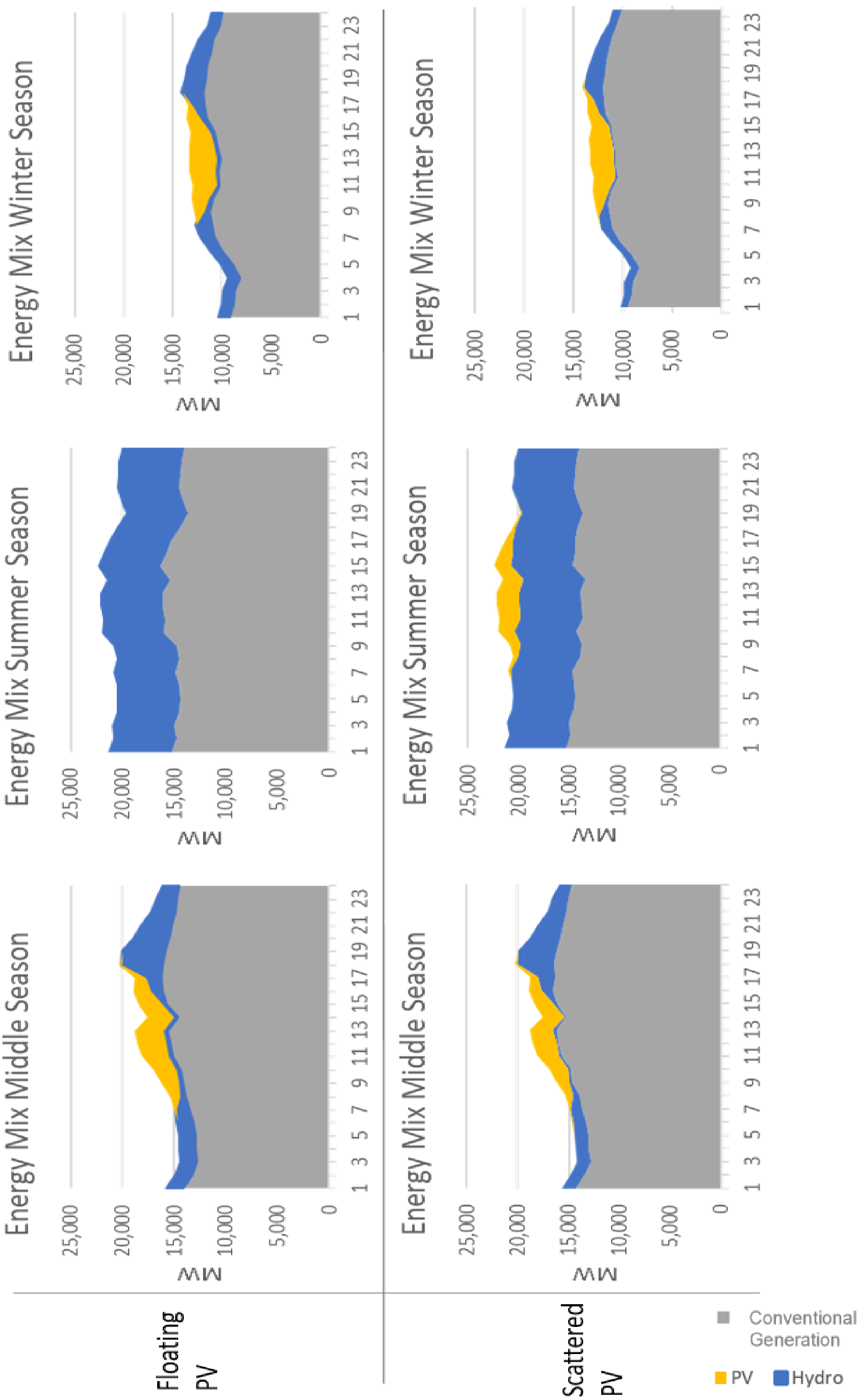

Figure 23: Overview Energy Mix of Reference Days of Floating and Scattered PV

In comparison to scattered solar power, the use of the PV-Hydro-Battery with floating solar does not show any peak load effect in the sumer season. This also means that no PV power can be contributed to the grid during this time.

5. Conclusion

Scattered PV

With an installed PV capacity of 3 GW in combination with the hydro reservoir of Tarbela Dam it is possible to contribute to the peak load of conventional power plants of at least 1 GW in each of the three seasons considered. The reduced peak load in summer season, i.e. the season with the highest demand, is crucial to reduce the actual development of conventional power plants . The reduced peak load for the rest of the year is supportive to take out conventional peak power.

The reduction of the conventional peak load leads to a reduction of of the daily min/max peak demand ratio by 25% to 40%. In addition, grid losses can be reduced by at least 4.5% compared to floating PV or other power plants using the high voltage transmission grid. These grid losses can be reduced because the scattered PV installations are close to the demand areas and therefore are avoiding the high voltage transmission system and its losses. Furthermore, fossil-fuelled power plants can be operated with better efficiency, since the load profile is more straightened during the day.

Besides the positive capacity and efficiency effects, the 3 GW AC of PV leads to a CO_2 reduction of approx. 3.6 mio. ton per year.

Peak Load Effect on Reference Days	Scattered Solar (3 GW AC)	Floating Solar (3 GW AC)
Winter Season	1,202 MW	1,164 MW
Middle Season	2,460 MW	2,682 MW
Summer Season	1,044 MW	none

Table 6: Findings on Winter Season

Floating Solar

Usually floating solar plants are connected to the same grid access point as large hydropower plants as the extension or new construction of a grid access point is rather costly. Looking at the details, a bottleneck was identified: In summer season, the hydropower generation blocks all grid capacity, as the turbines run at full capacity and have to evacuate power. Therefore, power generated by floating PV cannot be evacuated. Furthermore, the water cannot be stored, so that there is no peak load effect in summer season. The peak load effect occurs in winter and middle season only. Hence, it is not possible to reduce the actual development of conventional peak power plants with floating PV.

Moreover, floating solar systems have higher grid losses than scattered solar systems because the floating PV power has to use the transmission grid, whereas scattered solar systems are only fed into medium or lower voltage grids.

Since PV generation is limited in summer season, CO_2 reduction of floating solar is lower compared to scattered solar. Nevertheless, depending on the ratio of installed turbine capacity to water volume, CO_2 reduction amounts to approx. 3.2 mio. ton/year.

PV Results	Scattered Solar (3 GW AC)	Floating Solar (3 GW AC)
Energy generation (after Access Losses; before Grid Losses)	6.1 TWh	5.4 TWh
Losses on Customer Level	~16%	~30%
CO_2 Reduction	3.6 mio. ton/year	3.2 mio. ton/year

Table 7: Findings on Winter Season

6. Recommendations and Follow Up

6.1. Recommendations

This study gives a first overview over the potential of the PV-Hydro-Battery concept and the resulting potential to reduce conventional peak power capacity. In order to get a more comprehensive picture of positive and, where appropriate, negative impacts, an extension of the study is recommended.

For further analysis, it is recommended to evaluate the technical feasibility on the basis of a study lasting at least one year or rather two or three years. An annual analysis would show the peak load effect as well as other effect for each day of the year. On the one hand, a wider data spectrum can be used to create a general understanding of PV-Hydro-Battery interdependencies. On the other hand, days with previously undiscovered occurrences can be identified.

The results of this study refer to Tarbela Dam and represent only a theoretical approach. For actual use, a deployment scenario should include additional hydropower dams to increase potential of the PV-Battery to create redundancy and smooth out potential negative impacts e.g. on surge and wave effects.

For a more detailed understanding of the **hydro dam characteristics**, the following points should be examined using Tarbela Dam as a reference. If necessary, the study could be extended to other hydro dams in a next step.

- Dynamics of hydropower turbines, ramp up and ramp down
- Water level of reservoir and its dynamics following outflow and inflow
- Lower dam reservoir and its smoothening behaviour of water flow downstream in case of variable turbine outflow
- 2-3 years detailed analysis on hourly values of flow data and extrapolation to full capacity of 4815m^3/s for a more detailed analysis of potential daily peak contribution

Furthermore, the PV-Hydro-Battery operation will cause surge or wave effects downstream of Tarbela Dam. The following points should therefore be analysed in more detail:

- Downstream river social and economic effects for settlements
- Downstream river social and economic effects for fishery

- Downstream river social and economic effects for irrigation
- Downstream run-of river hydropower plants, surge or wave effects
- Time delay of such surge and wave effects
- Maximum and minimum allowable peaks of water flow

The **PV power** installations need more consideration in terms of size, distribution and grid access. The following categories need to be analysed:

- Large PV system (≥50 MWp) – impact of scattered installations connected to high and medium voltage level; there are international developers who are interested in installing PV plants of hundreds of MW.
- Large floating PV system (≥50 MWp) – in particular with regard to the limitations and bottlenecks of grid capacity, if they were to be installed on the surface of water reservoirs in combination with hydro power.
- PV systems (<50MWp) scattered to energy demanding areas near cities and villages to minimize distribution grid losses at medium and low voltage.

For the current study, neither nationwide **load or demand** curves with hourly resolution nor detailed profiles of the contribution of fossil power plants could be obtained. In order to increase accuracy and analyze the feasibility of the PV-Hydro-Battery and its peak load impact, the following points are requested in detail:

- Hourly demand or load curves for Pakistan of the past three years.
- Hourly share of different types of power plants, mainly fossil peak power plants and their contribution to peak hours throughout the year.
- Future development plan for new peak power plants to develop a ranking of potential plant avoidance.
- Analysis of load shedding which has not yet been taken into account in the study; load shedding can be seen as an additional (peak) load. Therefore a model of load shedding should be added to simulate to which extend load shedding could be reduced or avoided.

For the application of the PV-Hydro-Battery, an analysis of the **IT/SCADA**[6] implication and grid access must be taken into accout:

- Feasibility of remote IT/SCADA access or link to the national energy management facility in order to combine conventional power plants, hydropower and PV power to an integrated system.
- Discussion of the introduction of artificial intelligence into the optimization of the national energy system in order to exploit the inherent synergies.

[6] German companies being able to provide applicable IT technology: Siemens AG / Energy Automation and Smart Grid; PSI Software AG / Power Grids and Sector Coupling; Kisters AG / Virtual Power Plants.

- Assessment of the grid capacity for the transmission of energy from hydropower from the north to southern demand areas.

An **economic analysis** of the PV-Hydro-Battery will give a better understanding of how the Battery can improve the attractiveness of PV and hydropower. The analysis should take into account:

- Identification of conventional peak power cost (CAPEX and OPEX including CO_2 emission burden) for existing plants as well as for future plants
- Comparing these avoided conventional costs with costs of installing and implementing the concept of the PV-Hydro-Battery, including CO_2 benefits; assuming that the main costs are concentrated on the PV end.
- In consideration of the avoided peak power costs and costs of installing the PV-Hydro-Battery, discussion of business models which could be developed to create a market for peak power: conventional versus renewable PV-Hydro-Battery (using avoided cost and CO_2 benefits/burden).
- Identification of German investment interests and opportunities to participate in new markets.

Finally, the combination of PV-Hydro-Battery with **wind power** may be of interest:

- Analysis of the combination of wind power and PV as well as the hydro-battery effect to further maximize the potential of peak power reduction
- Simulation of the reference days and then of an entire year of PV together with wind power based on the approach chosen in this study.

6.2. Follow up and Workshop

The results of this study were discussed in a webinar on December 13th, 2019 with participants from AEDB, GIZ and E.Quadrat. AEDB expressed its strong interest in continuing and deepening the discussion in a personal workshop in Islamabad.

As discussed in the webinar, the workshop should involve more stakeholders in Pakistan. In addition to GIZ and AEDB, WAPDA, the energy ministry and grid operators should also be invited. Topics could be the following

- Presentation of the results of the PV-Hydro-Battery study and discussion
- Points from stakeholders which should be analysed in more detail or in addition
- Follow up and considering next steps

Additional stakeholders like social and environmental, PV developers, wind power developers etc. should be involved.

The expected results of the workshop should define the scope of the next steps like a comprehensive pre-feasibility study and a corresponding time schedule. The aim should be for all stakeholders involved to be able to participate in a discursive process.