Hybrid Power Plants systems in Africa
Introduction of Hybrid Configurator PV-Hydro in Zambia

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Introduction

In many African countries, especially in rural areas, diesel generators are the sole source of electricity. Due to the high transport cost of diesel fuel, the electricity cost is ranging between 0.4-0.5 US$/kWh. Apart form that, these countries dispose of a large unexploited renewable energy potential, solar, hydro and wind. Recognizing the undeveloped potential of renewable energies, Fichtner developed the Hybrid Configurator in order to analyze and design hybrid power plants regarding the technical and financial impact.

The Fichtner Hybrid Configurator has been certified according to VDE-PB-014 for bankable hybrid plant simulations. As part of the ongoing development of the configurator, it has now been extended to include hydropower as an additional energy source. Based on a given load profile, the PV-Hydro hybrid system power plant will be optimized by varying dam height, design discharge of the hydro power plant and PV power plant size to find the least levelized cost of electricity (LCOE).

The Mwomboshi HPP site in Zambia has been selected for a case study to present the methodology, principles of the Fichtner Hybrid Configurator.

1. Fichtner Hybrid Configurator

The Fichtner Hybrid Configurator has been developed in Fichtner in order to analysis and design hybrid power plants regarding the technical and financial impact. The software has been programmed in MATLAB with interfaces to other simulation tools.

In order to have the highest possible accuracy of the simulation results the Fichtner Hybrid Configurator can process data from market standard simulation tools such as PVSyst for PV power plants and WindPRO for Wind power plants. SolPRO another in-house development from Fichtner simulates Concentrated Solar Thermal Power Plants. Recently, the technology of hydropower was added to the Hybrid Configurator.

The utilization of these market leading simulation software allows with their various input parameters the most accurate modeling of the energy output of predefined system size. All of these so called bankable simulation tools are used in large-scale projects to decide whether the project is technical and financially feasible.

Besides the input from other software several other technical and financial parameters can be adjusted to model the existing project and therefore adapt the configurator to the individual project needs. These input parameters combine a model to assess which and how much power and energy is available from each technology at each predefined time-step.

The Fichtner Hybrid Configurator includes a dispatcher (or main power plant controller) which performs the energy management. The goals are a safe, reliable and cost-efficient operation depending on the load and other technical input parameters such as required spinning reserves and ramp-rate capabilities. A safe and reliable operation has a higher priority compared to the most cost efficient operation which is not necessarily always the same.

<u>Example:</u> In order to prevent the diesel generators operating below their minimum acceptable partial load the PV power will be reduced and the share of the renewable energies in the power grid will be limited.

The dispatcher automatically detects which types of technology are required and available and changes the operation strategy accordingly to ensure the most reliable and economic operation.

The CAPEX and OPEX (fixed and variable) of each technology is being assessed during the entire project lifetime taken into account also potential reinvestments. With a dynamic cash flow model the key financial results are determined.

The assessment of the hybrid system is however only the first step. The Fichtner Hybrid Configurator can also be used to simulate a vast number of configurations with different technologies and system sizes. The system size of each technology is kept variable in the Hybrid Configurator and allows for an adjustment to optimize the most important financial or technical key parameters for power plant owner and investor.

Currently the Fichtner Hybrid Configurator can simulate and optimize the following generation technologies:

- Diesel generators
- Gas generators
- Photovoltaic
- Hydropower
- Wind power
- Concentrated Solar Thermal Power with Thermal Storage
- Electrical Storage
- Biomass/Biogas
- Geothermal
- Grid connection

The Fichtner Hybrid Configurator simulates each configuration for their entire project lifetime considering e.g. PV module degradation, battery cell aging or operation maintenance cost of a hydro power plant. This way the optimum system configuration can be determined for each key financial or technical parameter.

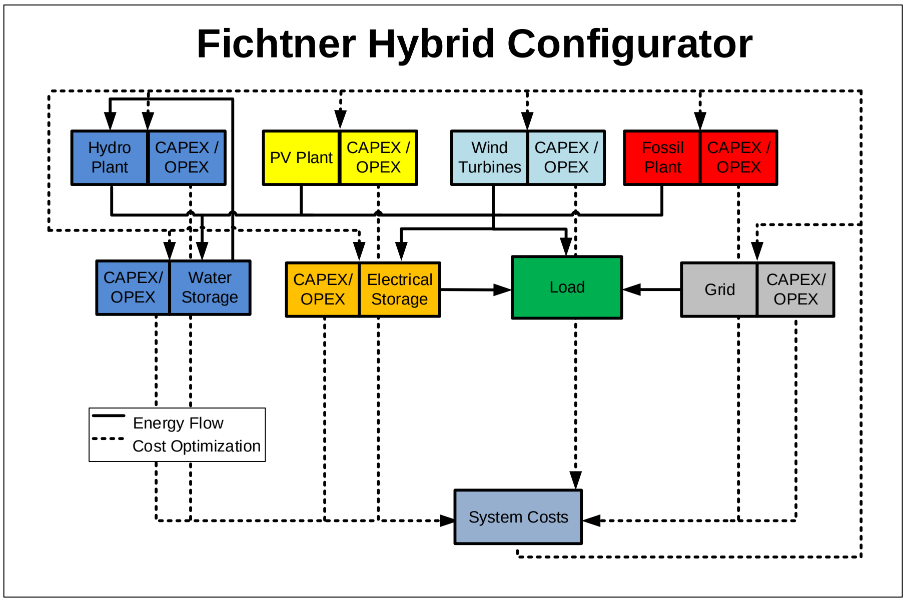

Figure 1: Simplified schematic layout of the Fichtner Hybrid Configurator

2. Selected hydropower site in Zambia

Fichtner did a country wide GIS-based screening for potential hydro power sites in Zambia and thereby identified several attractive greenfield hydropower plant (HPP) sites.
An attractive HPP site could be identified at the Mwomboshi River in the central province of Zambia. The selected section of the Mwombishi River has a natural slope of 190 m over a length of 1 km, which is ideal for the development of a HPP.

The following figure shows the selected river stretch and gives an overview of the conceptual design of the power plant. The design has been developed in the framework of a desk study by using free available topographical data. The HPP consists of a concrete gravity dam with an intake structure and subsequent concrete headrace channel which ends at the forebay. The forebay and powerhouse structure are connected with exposed steel penstocks. The powerhouse itself is equipped with two Francis turbines. A short tailrace channel diverts the water from powerhouse to the Mwomboshi River.

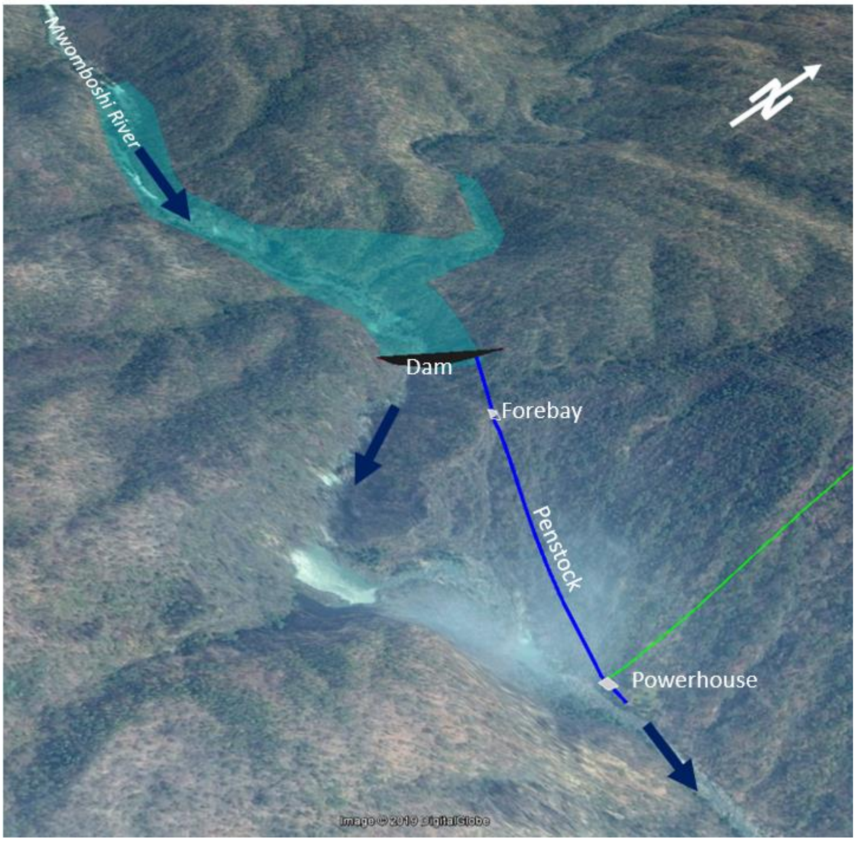

Figure 2: Principal layout of the HPP site, Google Earth

The Mwomboshi River has a mean annual flow of 9 m³/s with mean monthly flow ranging from 21.7 m³/s during the wet season (January - April) in March and 2.8 m³/s during dry season (May - December) in October.

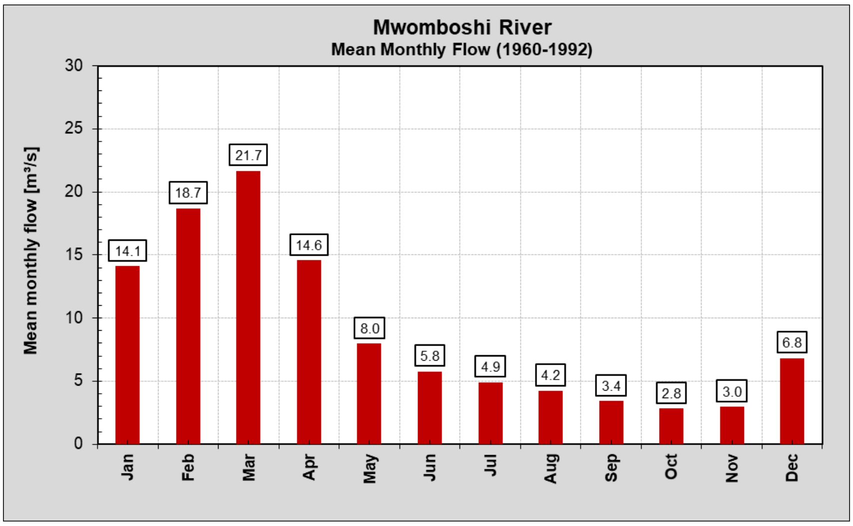

Figure 3: Mean monthly flow at the Mwomboshi River

By means of the in-house developed software called HydroPowerApp (HyPApp) Fichtner considered several design options for the Mwomboshi HPP by varying dam height and design discharge and estimated quantities and costs of civil works as well as hydromechanical and electrical equipment. By means of trend lines, estimated costs have been put into relation to dam height for the dam structure and discharge for water ways hydromechanical and electrical equipment.

The relation between dam height and potential storage volume at the Mwomboshi HPP site is expressed in the following reservoir capacity curve.

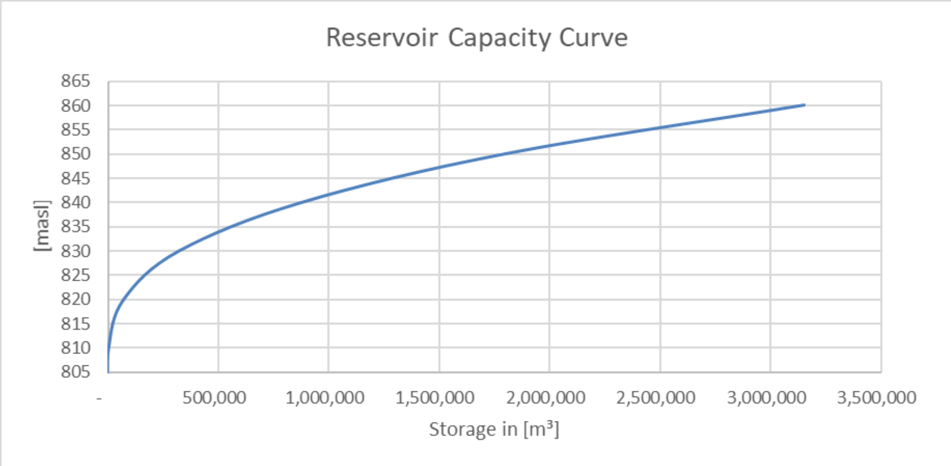

Figure 4: Reservoir Capacity Curve at the Mwomboshi HPP site

The design discharge has been varied within a range of 6 to 12 m³/s while a dam height from 10 to 30 m has been considered. Therefore, the rated power of the HPP is in range of 10 to 20 MW depending on discharge and dam height. The best HPP size in terms of least levelized cost of electricity (LCOE) and load coverage of the load profile in the grid was determined by applying the hybrid configurator.

3. Application of the Fichtner Hybrid Configurator

The Fichtner Hybrid Configurator was applied for a case study of the Mwomboshi HPP in Zambia. The two renewable energy sources hydro and photovoltaic were considered to supply into a typical Zambian grid. In the framework of this desk study the following load profile was considered.

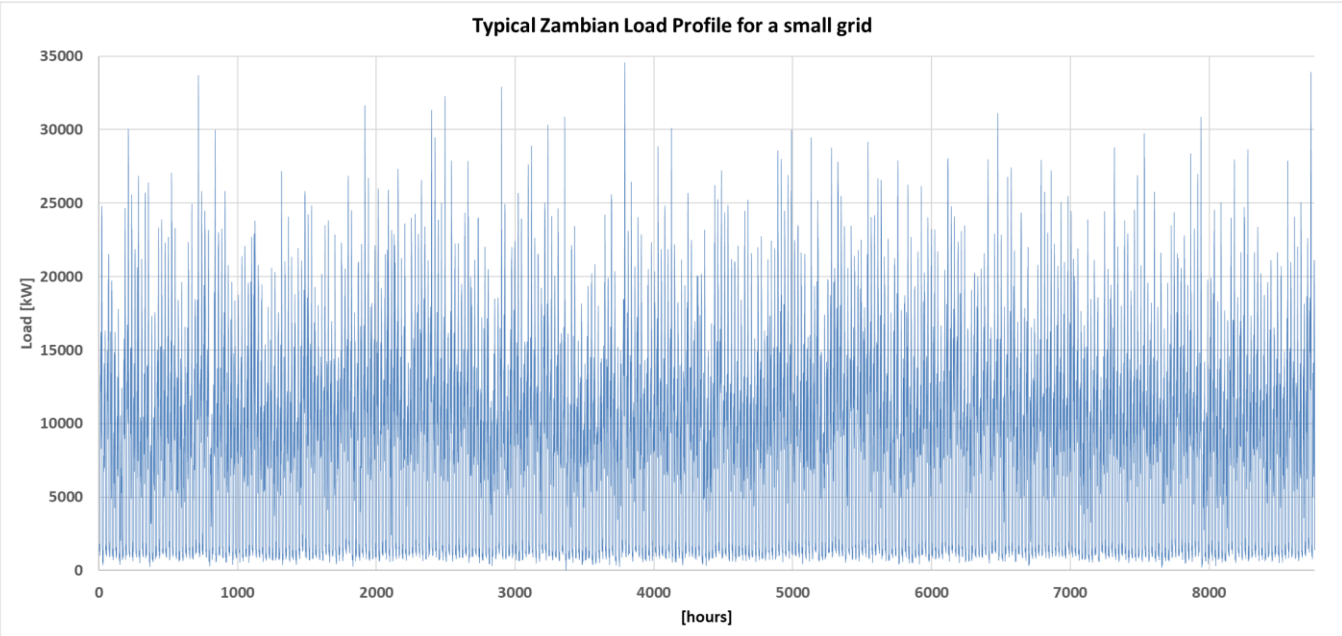

Figure 5: Typical Zambian load curve for a smaller grid over the period of one year

The above shown load profile represents a typical Zambian load curve for a smaller grid over the period of one year with a maximum load of approximately 34 MW and mean annual load of 8.3 MW.

For a better readability of the above shown load profile, an extract of a daily load curve is indicated in the figure below. It can be noted that there are two peaks, one at noon and bigger one in the evening.

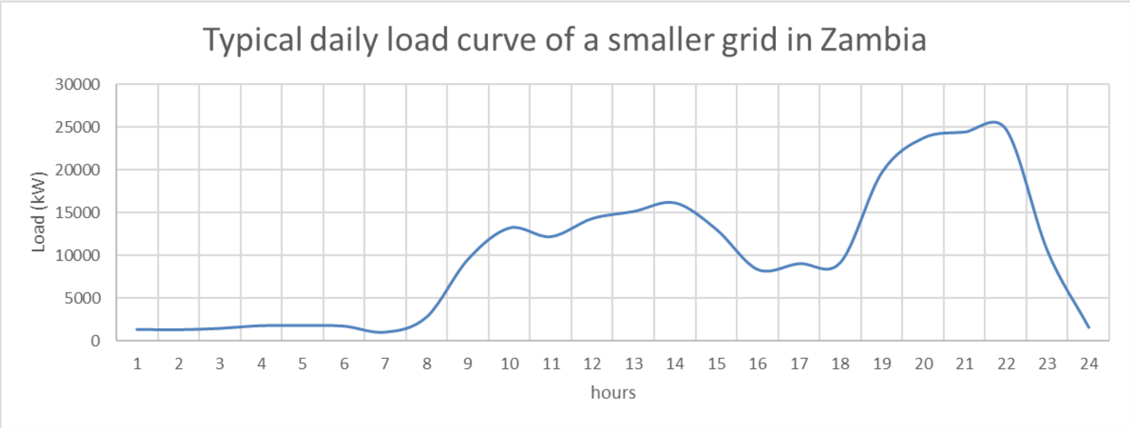

Figure 6: Typical daily load curve of a smaller grid in Zambia

3.1 Input for the Configurator

The following principal input data are needed for the application of the Fichtner Hybrid Configurator.

For the hydropower plant:

- hydrology (mean monthly flows or daily flows)
- reservoir capacity curve
- operation limits (minimum admissible turbine flow, dead storage)
- CAPEX and OPEX of the HPP in relation to dam height and discharge.

For the PV plant:

- site specific satellite irradiation (kWh/m²) and temperature data of a typical meteorological year in hourly resolution
- degradation of PV panels over the life time
- PVSyst simulation results including all losses
- CAPEX and OPEX of the PV plant in relation to the PV plant size.

Financial parameters:

- operation time
- discount rate
- loan period
- Interest rate of debt.

As already mentioned in Chapter 2, depending on the availability, further parameters/input data can be added from other software or other technical and financial parameters can be adjusted in the configurator to suit the individual project needs.

3.2 Methodology

The different design options of Mwomboshi HPP (dam height, design discharge) are combined with different photovoltaic (PV) power plant sizes and evaluated against the calculated levelized cost of electricity (LCOE).

The Fichtner Hybrid Configurator calculates the LCOE for every possible combination between the three variables (design discharge, dam height, PV plant size) within the given ranges. In the beginning larger step widths are chosen for the variables to keep the computing effort lower. As soon as the optimal setup for the hybrid power plant can be estimated, the step width will be refined.

Based on the following figure the methodology and procedure of the Fichtner Hybrid Configurator will be explained more comprehensively. The figure shows a three-day period in June with a mean monthly flow of around 5.8 m³/s. The left y-axis indicates the power in kW and right y-axis presents the storage volume. The Fichtner Hybrid Configurator follows a merit order in a way that the PV power plant shall first feed into the grid and if the PV power is enough to cover the load in the grid, then the HPP will be switched off. Otherwise the HPP will cover the gap between load and available PV power. Each time the HPP is switch off or the HPP is operated in partial load the storage will be filled as can be seen by the green graph. The violet graph represents the total generated power of the hybrid plant. The code of the configurator is written in such a way that the total generated power will not exceed the load demanded in the grid.

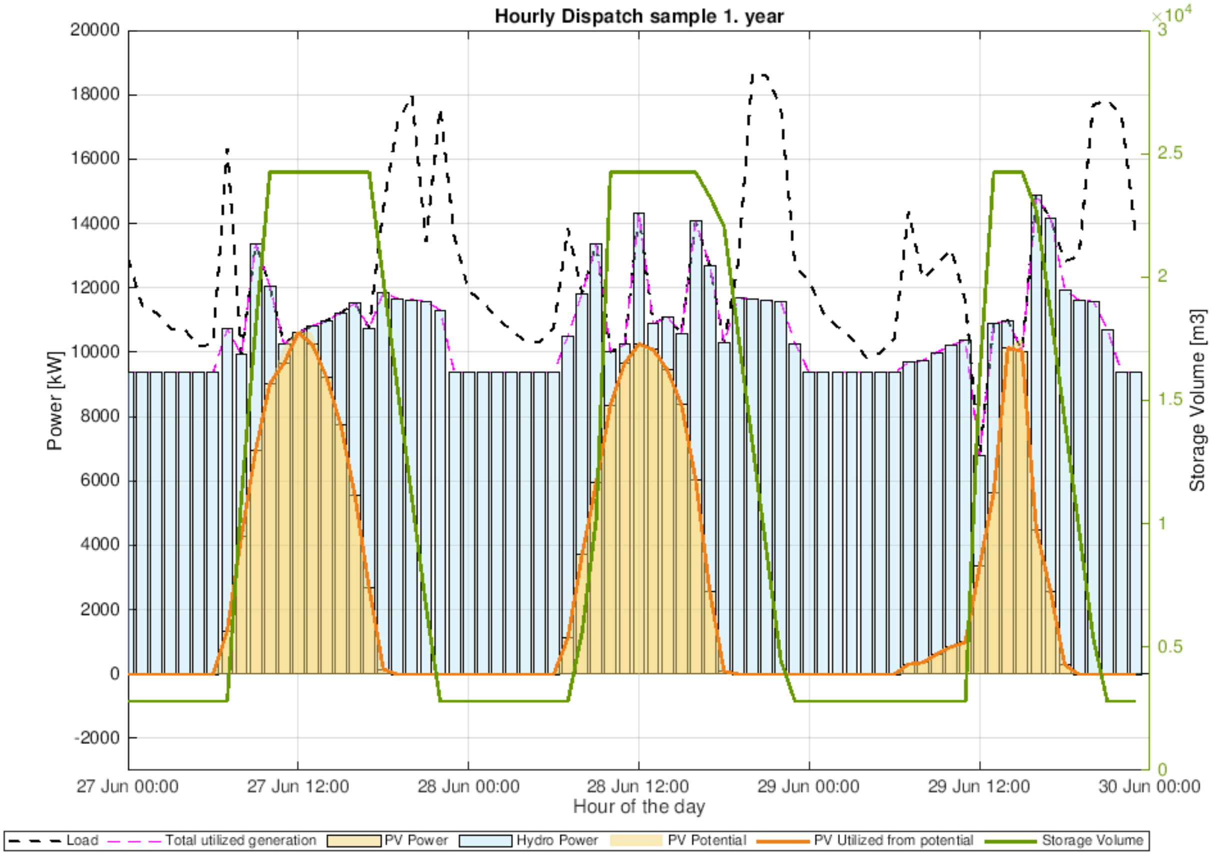

Figure 7: Visualization of the methodology of Fichtner Hybrid Configurator

The light blue bars in the figure indicate the produced hydro power in kW. It can be noted that during the night the storage is completely empty and the HPP is operated as a run-of-river plant with the available inflow of 5.8 m³/s and a power output of around 9.6 MW. Only during the daytime where the PV plant is operating the storage will be filled, which then after the PV is switch off at around 6pm, enables the HPP to operate 4 hours almost at full load (11.7 MW).

3.3 Results

The Fichtner Hybrid Configurator has been applied for the Mwomboshi HPP site. Therefore, for the HPP, the design discharge has been varied from 6 to 12 m³/s and the dam height has been varied from 10 to 30 m. The upper limit for the PV plant size has been set to 35 MW.

The following figure shows that the least LCOE is at 7 m³/s design discharge and 10 m dam height. The HPP has a rated power of 11.7 MW and a total rated head of 198 m. This HPP layout achieves a load coverage of 69% having LCOE of 7.23 USDct/kWh. The storage volume of the reservoir is around 24 250 m³. Considering a design discharge of 7 m³/s, the reservoir will be emptied within less than an hour. Higher dam heights with bigger storages have been calculated but are not economic at the Mwomboshi HPP site since the civil cost will increase tremendously with increasing dam height without having special financial incentives, such as a peaking tariff.

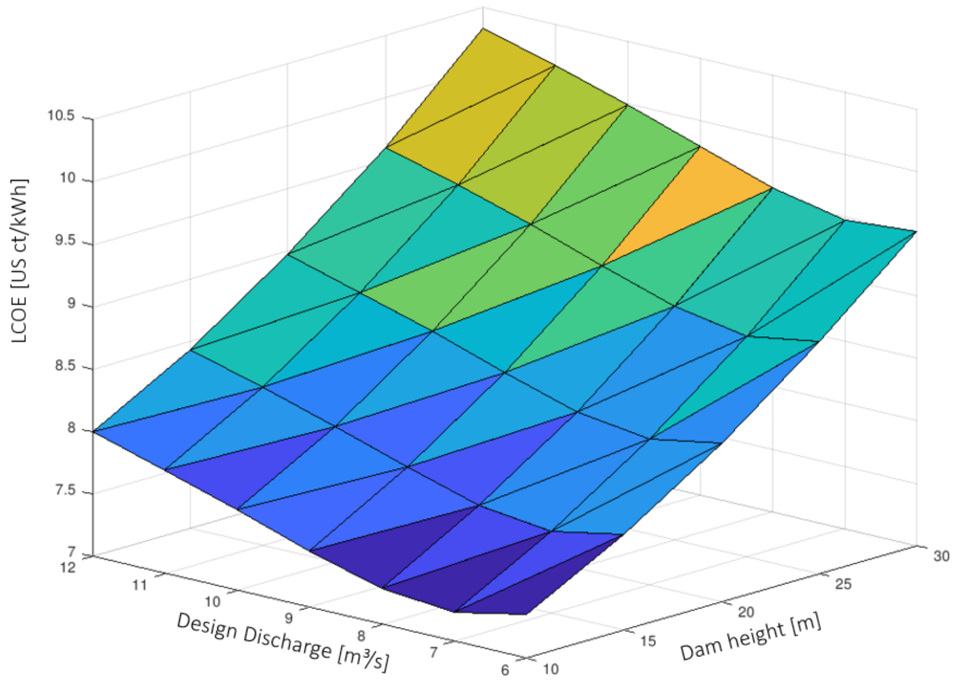

Figure 8: LCOE in conjunction with different design discharge and dam heights

The figure below shows the correlation between the load coverage (left y-axis) and the LCOE (right y-axis) while varying the PV plant size (x-axis) from 0 to 35 MW.

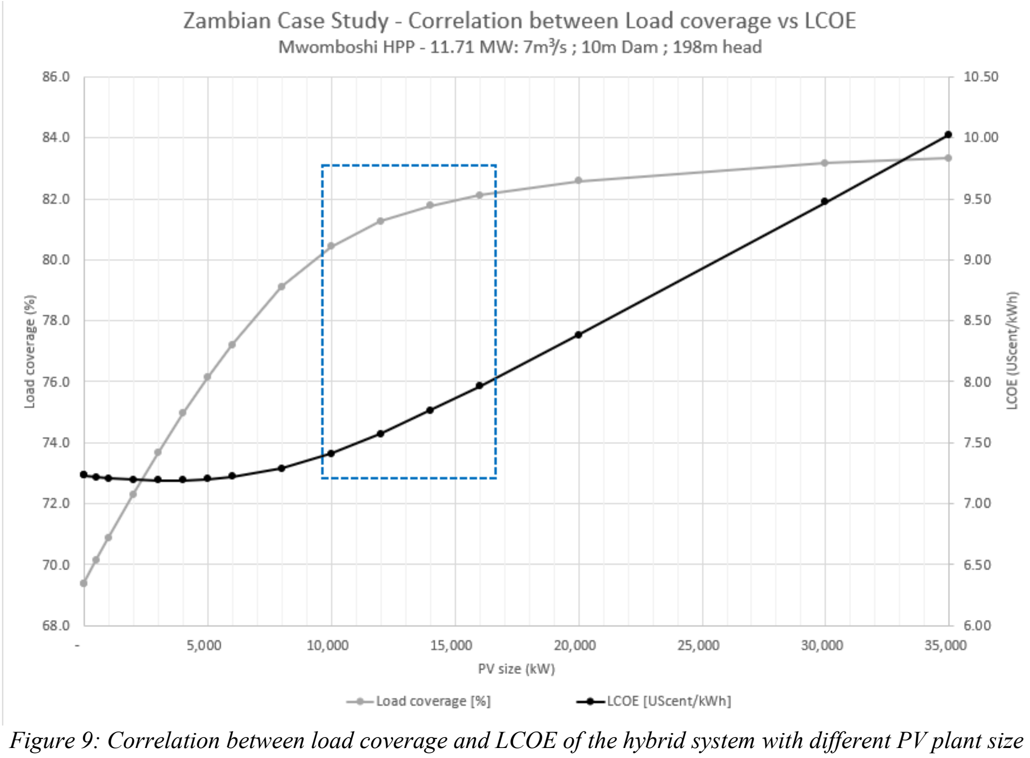

Figure 9: Correlation between load coverage and LCOE of the hybrid system with different PV plant size

If the focus is only on the least LCOE then a PV plant with 4 MW LCOE of 7.19 USct/kWh and a load coverage of almost 75 % could be achieved by the hybrid power plant. Compared to the HPP without PV the LCOE have been slightly decreased but the load coverage could be improved by 6% from 69 to 75 %. By looking at the load coverage graph, it is noted that graph has a logarithmic function with a saturation at around 83.5 %. The blue rectangular in the figure above indicates an economical range with a PV plant size from 10 to 16 MW where the LCOE (7.4 - 8.0 USct/kWh) vary only slightly but there is still considerable gain in load coverage (80.4 - 82.1 %). The final set up for the hybrid power plant ultimately needs to be determined in conjunction with the power utility in order to best respond to their needs.

For the hybrid power plant with HPP of 11.7 MW and a PV plant of 12 MW, the following two plots have been created to show the operation of the hybrid power plant at the driest and wettest month in terms of mean monthly flow.

Having a look at the driest month in terms of mean monthly flow (2.8 m³/s), it can be seen in the following figure that the HPP power output drops to 4.7 MW. In conjunction with the PV plants still good coverage of the daily peaks at noon can be achieved. Even though due to the little inflow into the reservoir the storage will be emptied promptly when hydro is needed to cover the gap between PV and load or the night period. Nevertheless, the peak in the evening can't be covered and the HPP operates only with the mean monthly flow.
As a next step the Fichtner Hybrid Configurator could be further developed by defining hours of operation of the HPP to be able to cover more load in the evening.

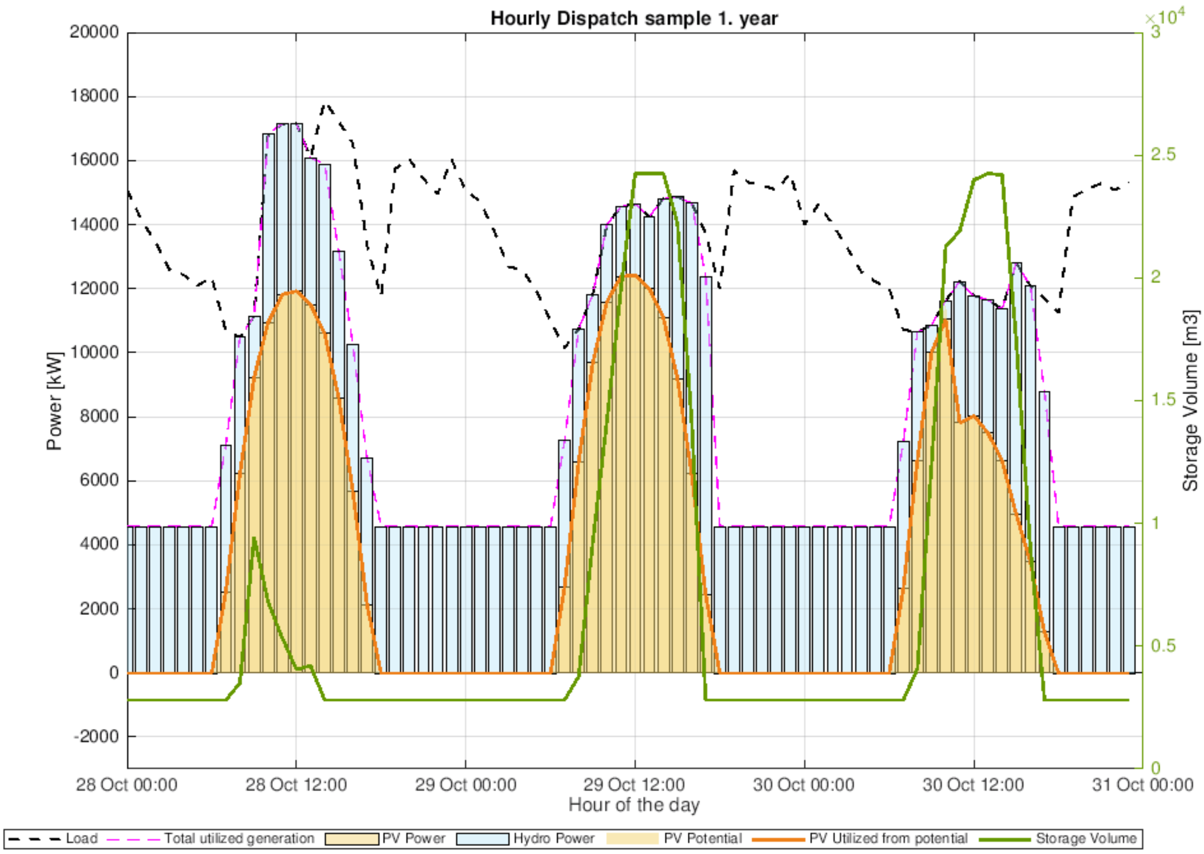

Figure 10: Visualization of the methodology of Fichtner Hybrid Configurator in a very dry month

During the wet season, in March with a mean monthly flow of 21.7 m³/s, it can be noted in the following figure that the reservoir is always full since the inflow is higher than the design discharge of the turbines (7 m³/s). The lower power generation of the PV plant due to the rainy season can be compensated by the HPP which can be constantly operated with a power output of 11.7 MW if the load profile so requires.

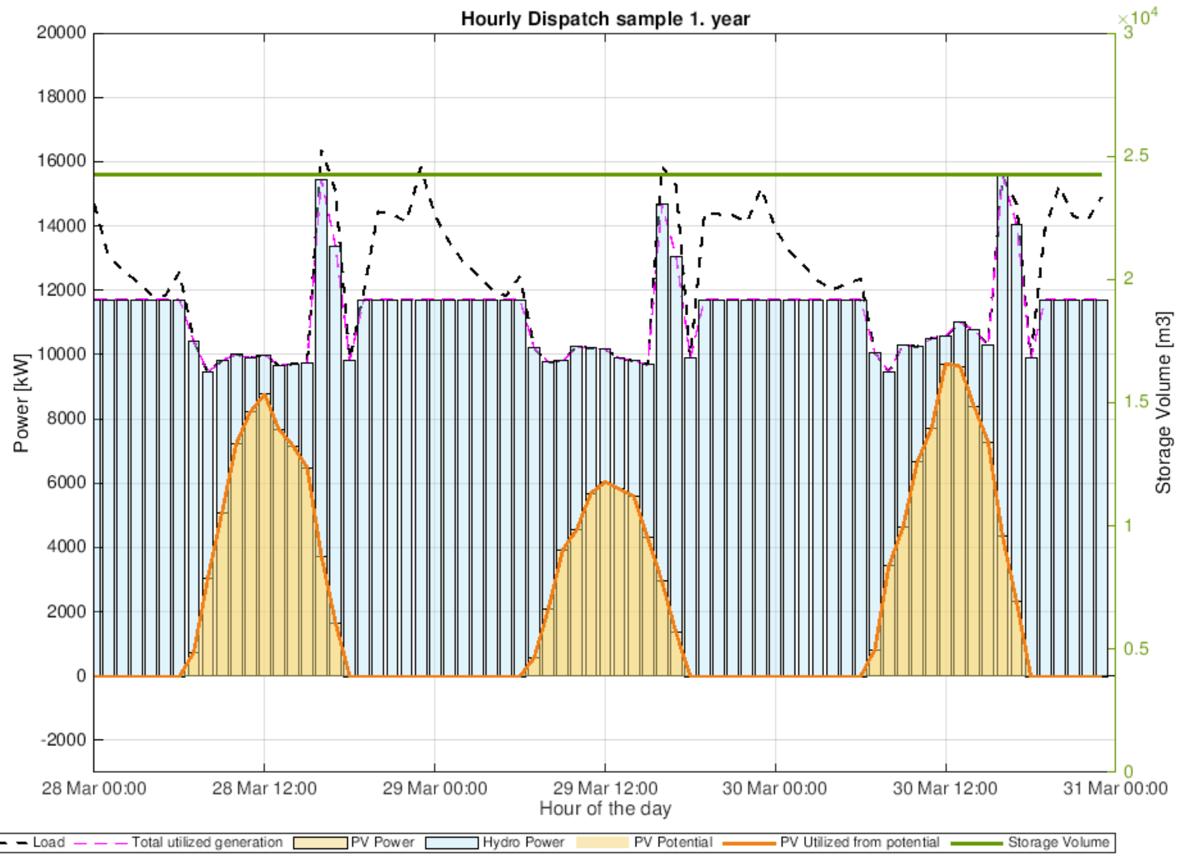

Figure 11: Visualization of the methodology of Fichtner Hybrid Configurator in a wet month

4. Conclusion and outlook

As part of the development of the Fichtner Hybrid Configurator, it has now been expanded to include hydropower as an additional technology. This expansion allows now the combination of the two renewable energies PV and Hydro which have a large unexploited potential in Africa.

The application of the certified Fichtner Hybrid Configurator for the Mwomboshi HPP site resulted in an optimized hybrid power plant which combined PV and Hydro power to supply renewable energy to a typical small Zambian grid. Through the combination of a 11.7 MW HPP with a 12 MW PV plant the coverage of the load profile in the grid could be increased from 69.4 % to 81.4 % by having only a slightly increase of LCOE from 7.19 to 7.57 USct/kWh.

In the meantime, the Fichtner Hybrid Configurator has been applied in projects where the benefits of a PV-Hydro hybrid power plant were also a higher load coverage and even less LCOE.

With the application of the Fichtner Hybrid Configurator for the Mwomboshi HPP site in Zambia an important step has been taken to further develop the Hybrid Configurator. Nevertheless, the configurator is continuously being further developed and extended by further areas of application. As a next step the Fichtner Hybrid Configurator shall be further developed by defining finer operation rules for the PV and Hydro power plant to be able to distribute the generated power in more uniform pattern. This means that the peak at noon shall not be covered 100 % with PV and Hydro power but only 75 % with PV power. Thereby the HPP can cover more load of the evening peak.

The Fichtner Hybrid Configurator provides the possibility to simulate storage HPP with daily, weekly, monthly, seasonal and annual storage as well as peaking power plants for countries where peaking tariffs will be paid.

The Fichtner Hybrid Configurator is also well suited for modelling and optimization of capacities of hybrid systems by finding the best hybrid configuration with the least LCOE out of many different energy sources (Conventional Plants, Photovoltaic, Hydro power, Wind power, Biomass/Biogas, Geothermal). Thereby the Configurator provides a comprehensive overall approach for the electrification of a rural area.

The Authors

Andreas Wetzel graduated in Civil engineering at the University of Karlsruhe in 2012. In the same year he joined Fichtner as project engineer and worked for various small and large hydropower projects in Europe and Africa during feasibility level and tender design. Within the scope of the feasibility studies in the DR Congo, Mr. Wetzel gathered valuable experience in the field of small hydropower plants operating in an isolated grid taking demand side management into account. He was responsible for the hydro power part of the Fichtner Hybrid Configurator.

Sebastian Palt graduated in Civil engineering at the University of Karlsruhe in 1996. From 1996 to 2001 he completed his PhD thesis addressing sediment transport and its impact on hydropower development in mountainous regions at the University of Karlsruhe and was awarded with the Senator Huber award in 2002. In the same year he joined Fichtner as project manager and worked for various projects in Europe, Asia, Africa and Latin America. Between 2007 and 2010 he worked for project development in the International Development Department of E.ON Wasserkraft, where he was active mainly in the Balkan area, Turkey, Romania and France. Since 2013 he is the Executive Director of the Hydropower Department of Fichtner, Germany.

Christian Scholz is holding a master’s Degree in Energy Conversion & Management since 2012. In the same year he joined Fichtner. During his studies outside Germany, he gained experience as an engineer in planning PV plants. For his master's studies, Mr. Scholz developed and programmed a simulation environment for storage systems and energy system optimization. He was able to gather experience in constructing hybrid micro power plants. Christian Scholz was responsible for the development of the Fichtner Hybrid Configurator and his VDE certification.

Martin Stickel graduated in Mechanical engineering at the University of Kaiserslauter in 1997. From 1998-2002 he completed his PhD thesis addressing the transfer of environmental technologies to developing countries. By performing Lender’s as well as Owner’s Engineering and Transaction Advisory services he has accompanied lenders, investors, project developers as well as utilities and government organization in the implementation of PV projects in Europe, Asia, North and South America and Middle East and Africa. Since 2008, he is heading the Fichtner activities in the Photovoltaic Sector.