LARGE SCALE HYBRID PV HYDRO ELECTRICITY PRODUCTION IN FLOATING DEVICES ON WATER

Innovative Approach to Accelerate the Impact of PV in worldwide Power Production

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ABSTRACT: The combination of PV and hydro power opens up new potential in photovoltaic power generation. The hydro electric reservoir can be the platform and the storage for a grid-connected PV plant. In this paper, a scenario and a case study for such a PV system in Switzerland is discussed. In co-operation with a Norwegian specialist team on arctic research, a floating PV platform will be designed and constructed. Several new aspects of PV power generation have to be analysed. The goal of this project is to establish a pilot plant in Switzerland and in Norway, to gain further knowledge and experience in the field of "PV on the Water".

Keywords: Large Grid-connected PV systems, Hybrid, Storage, Cost reduction, Environmental Effect.

1 BACKGROUND

The dissemination of terrestrial PV applications for grid-connected energy production around the world is focusing on roofs and facades of buildings or on larger, ground-based installations. Both sorts of applications suffer, besides the still high up front capital costs, from the large time-consumption for project development. In the building sector, each project needs an individual approach, approval and financing. For ground-based PV arrays it seems to be simpler, but there are a lot of justified concerns about extra land-use etc. The goal of this additional effort is to create a new dimension of terrestrial PV applications with a very high cost reduction and multiplication potential. The worldwide demand for new sustainable and environmentally friendly forms of electricity production is serious and needs an appropriate response from the PV community.

2 SCENARIO

Norway and Switzerland are frontrunners for hydro power production in Europe. In Norway hydro power has a market share of 98.5%, in Switzerland of 52.5%, compared to Germany with 4.5%. Switzerland has 116.4km^2 of artificial lakes to feed its hydro power stations. This represents 0.3% of the total land available, or a tenth of the surface of the natural lakes of 1'300km^2. The project approach applied makes use of these capacities, as the country needs only 6.3m^2 of PV per inhabitant to produce 10% of the electrical energy demand. A TNC case study 2006/07 shows, that for the "Sihlsee"-reservoir, with a surface area of 11km^2, only about 18% of the surface is needed for PV to double the present annual electric energy production of the hydro power plant of 270Mio. kWh. This corresponds to an installed PV capacity of around 280 MW$_p$ (approximately one third of the demand of the German market in 2006) and a gross area of around 4km^2, which is one third of the artificial lake surface. The comparison of power demand and power production by hydro power and solar PV shows a perfect supplementation.

2.1 Why combine PV and Hydro power?

Building integrated or building based PV installations are desirable considering the double use of infrastructure used for civilization, but suffer from high individuality factors, resulting in a low multiplication potential and high individual project costs. On the other hand, ground-based large PV plants have a high potential for multiplication, but often are in conflict with the desire to protect landscapes, raise the living quality, especially in densely populated areas, and the aim of integrating PV power production into the existing power grid without the necessity of extra power lines. In Switzerland, 4'712m^2 of land are available per inhabitant. Out of this area, 397m^2 (including hydro-electric reservoirs) are already used for civilization and are therefore perfectly suited for a double use with PV applications (Figure 1). The challenge is finding a uniform area for easy multiplication of PV power plants while not having to use additional land resources.

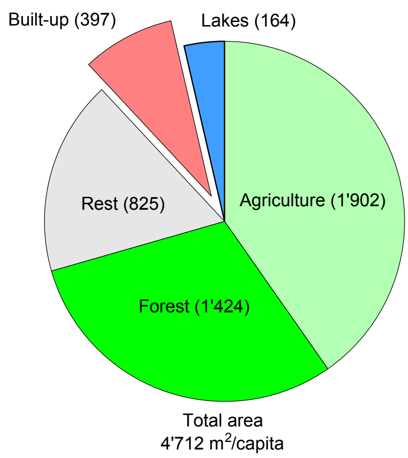

Figure 1, Land use per capita in Switzerland [m^2/capita].

With a closer look at the land distribution, we can see that out of the 397m^2 per capita used for civilization, 107m^2 are used for roads and their infrastructure, 52m^2 are used for buildings, 11m² for railways, 10m² for industry and another 17m² are used for hydro power generation. Of course, most of the area used for hydro power generation is in form of artificial lakes holding back the necessary water for on-demand power production. On the other hand, with only 6.3m² of PV, 10% of the annual electricity demand in Switzerland could be produced with PV. Taking into account the high uniformity of the surface of a lake used for hydro power, the combination of PV on water with hydro power storage lakes is a win-win-situation for a new field of PV applications. The case of Switzerland shows that the storage lakes for hydro power account for about 9.5% of the total lake area in Switzerland, or 0.3% of the total land available. Opposing natural lakes, the area of storage lakes for hydro power has to be taken into account for the area used for civilization.

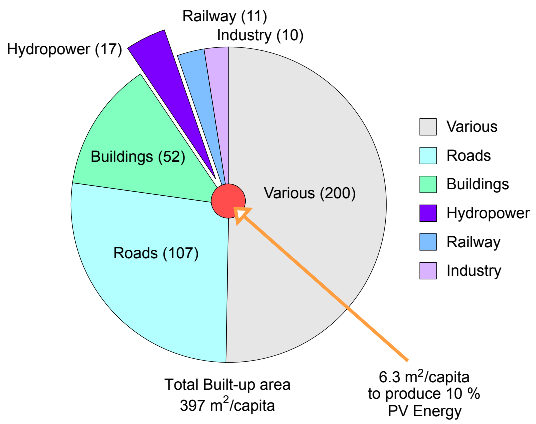

Figure 2, Distribution of built up area in Switzerland [m2/capita].

Switzerland has a rather high percentage of hydro power in the power generation mix with a share of about 52.5%. Other countries, such as Norway, have an even higher share of hydro power generation with 98.5%. In Germany, only about 4.5% of the power is produced using hydro power plants. To better understand the benefits of the combination PV on water and hydro power storage lakes, the case study of the "Sihlsee" in Switzerland shall be explained in more detail. One of the challenges is the design and construction of a floating structure for PV, which is able to resist all the influences of warm and cold weather over the expected lifetime.

3 CASE STUDY

The Sihlsee lies close to the city of Zurich. The hydro power plant is owned and operated by the Federal Railway Company of Switzerland, the SBB. The hydro power produced is mainly used for operating the public transport system in the area of Zurich. The SBB distributes electricity over their own power grid with an operating frequency of 16 2/3Hz. The public transportation system has a demand curve similar to the production curve of PV during daytime. The Sihlsee reaches a maximum altitude of 889m above sea level, which makes ice an important issue during wintertime.

3.1 Situation

It has a surface of around 11km², with a usable water volume of 91.6 Mio m³ for hydro power generation. This corresponds to an allowed change of sea level of around 9m, which has to be taken into account when system layout of PV is done. Over the period of one year, the water inflow is about 236 Mio m³, allowing the lake to be refilled about 2.5 times per year. With a peak overflow given by the hydrological properties of a year of around 3.5 Mio m³ per year and a required environmental drain of around 29 Mio m³ (more than 12% of the annual inflow), 270 GWh of electrical energy is produced with the existing hydro power plant.

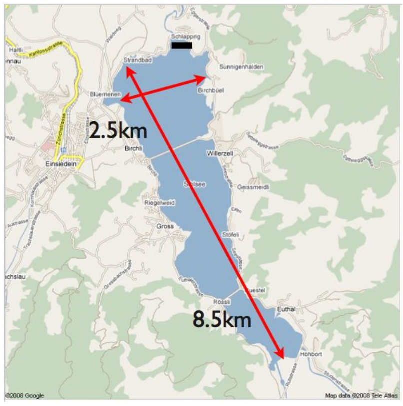

Figure 3 Area of Silsee, Switzerland.

The catchment area of the Sihlsee covers about 157km². In other words, the surface of the lake accounts for only about 7% of the total catchment area, which makes overall power density [kWh/m²] rather poor for this hydro power plant. In order to double the electrical power output of the hydro power plant of 270 GWh with PV, about 280 MW_p of PV have to be installed in addition to the already installed 158 MW_p of the hydro power plant. This corresponds to a net area of around 2km² for the modules, or a gross area of 4km² for the PV plant with spacing between the structures to avoid shading and will produce around 266 Mio kWh of PV energy per year. In figure 5, the areas within each other; power production, nominal power and water flows are displayed in corresponding sizes and colours within their categories.

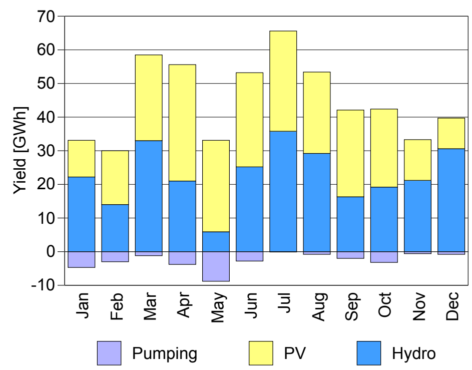

Figure 4 Hybrid energy production, Silsee (Hydro-electric data for 2007).

The Sihlsee can also be used as pump storage plant, meaning that water can be pumped into the lake with the same infrastructure available for power generation, allowing storage of energy over time. The Sihlsee becomes a very large battery, which can be used for storing PV power. In the year 2007, about 20 Mio m³ of water have been pumped into the lake with an electrical energy consumption of around 32 Mio kWh. One of the main advantages of combining PV on water with hydro power is the already available grid for power distribution. This makes PV on water a retrofit solution applicable on almost all hydro power storage lakes.

	surface area km²	nominal power MW	cost Mio €	energy cost 3) € cent / kWh		annual yield kWh/kW	annual yield GWh	yield hybrid GWh	
hydro	–	158				1,708	270		100%
PV 1)	2.0	280	**840**	**28**	4)	950	266	536	199%
			1,120	37	5)				
PV 2)	2.7	440	**1,320**	**23**	4)	1,125	495	765	283%
			1,760	31	5)				

1) 14% module efficiency
2) 16% module efficiency
3) capital cost 5% • annuity 8.02% for 20 years
annual cost for maintenance, 0.75% of investment
4) at 3 €/W
5) at 4 €/W

Table 1 Scenario, hybrid PV-hydro electric system, Silsee.

3.2 Potential

For the Sihlsee case study, different scenarios have been calculated, assuming a module efficiency of 14% for the medium case and a module efficiency of 16% for the best case. For solar irradiation, simulations have been made and compared to measured data in close-by PV plants.

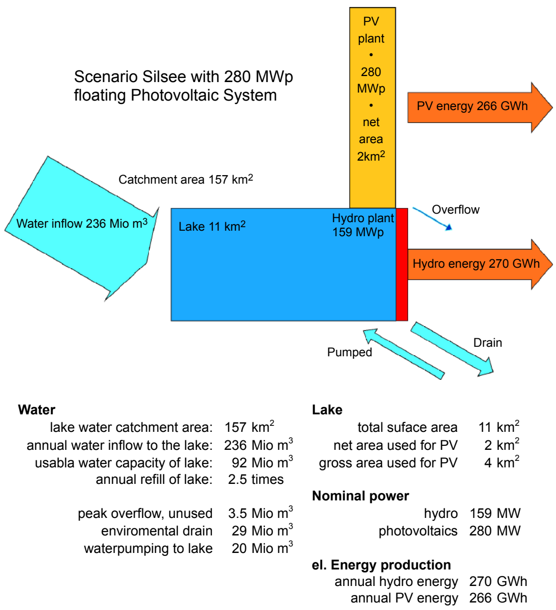

Figure 5 Scenario Silsee, waterflow and energy produced, from PV and hydro.

The yield of 950 kWh/kW_p is rather low for Switzerland, but takes into account the not ideal inclination of the modules, while 1'125 kWh/kW_p for the best case calculation is obtained with optimal orientation and inclination. With the aim of doubling the electrical power output of the existing hydro power plant, these two assumptions lead for the medium case to a net PV area needed of $2km^2$, corresponding astonishingly only to 18% of the surface of the lake. In the medium case calculations, the hydro power plant produces 270 Mio kWh/a while the PV plant produces another 266 Mio kWh/a. The best case calculations for a net area of the surface of still only 25% show that 440MW_p of PV power can be installed, producing 495 Mio kWh/a in electrical power and almost tripling the annual electrical output of the hydro power plant. One single PV plant on a medium size storage lake with only 25% of the surface covered can take up more than 1/3 of the annual installed PV in Germany, still the worlds largest PV market! This opens a new dimension for fast PV growth without using areas not already used for civilization.

3. FLOATING DEVICES

Challenges with floating structures for PV and infrastructure

Technology related to cold climate is one of the priority research and development areas at Norut Narvik and Narvik University College (NUC). The cold climate phenomena can be defined as the mutual effects from low temperatures, snow, ice and wind. It is not directly related to latitudes. The absence of daylight in periods when the sun is under the horizon can also be included to this definition. Cold Climate technology is technology developed particularly to reduce disadvantages, or to utilize advantages, with cold climate. The concept covers a broad, multidisciplinary research area that spans over many subjects.

Figure 6 The challenge of atmospheric icing in Norway.

Structures placed in an environment where the presence of ice and snow can be a threat to their safety and operational functionality need to be designed and built strong enough to resist any ice and snow influence. The force required to fail an ice feature against a structure like a floating PV plant generally limits the interaction force resulting from a relative motion between them. An ice layer may lead to failure of the structure in bending, buckling, crushing or any combination of these failure modes.

The main challenges that have to be taken care of here are severe icing and atmospheric icing during the winter. Cold water and low temperature means a dramatic impact of ice in wintertime, and ice forces can be a threat to the safety of the floating structures. Nonlinear finite element analysis is a tool to efficiently investigate and predict ice forces on structures. Structures in cold climate will also suffer from additional freezing stresses, thermal stresses and strains. A floating PV plant will consist of different types of materials, which have different coefficients of expansion. Testing of materials, structures and equipment can be done in a low-temperature laboratory at Norut Narvik, where temperatures down to -40 deg C can be controlled. Solar cells and modules are sensitive to phase transitions. Simulation of phase transitions (freezing/thawing) in materials can be done using finite element analyses.

Atmospheric icing of structures occurs regularly in varying latitudes and altitudes around the world. Occurring frequency depends on the local climate, terrain and height of the structure. Atmospheric icing occurs when water droplets in the air freeze on objects they come in contact with. This may be very dangerous for some types of structures, because it can build up an ice layer, imposing extra forces on the structure. Eventually, this could lead to a total collapse of the structure. Moreover, research at Norut Narvik has shown, that the solar cell module will not work when covered with a thick enough ice layer.

Another challenge for floating PV systems lies in the adjustment of the floating level to the filling degree of the reservoir. Conventional systems to adjust floating levels are often based on poles, casting shadows on the surrounding PV modules. Anchors with non-flexible lengths of anchor chains on the other hand allow the floating PV structures to move within a large radius during low water levels. Risk of collisions with land or within several floating structures leading to damages to the structures rises.

4. IMPLEMENTATION

To add this new dimension to the PV market, we are confronted with a number of challenges.

4.1 Floating devices carrying PV modules, which can be mass produced in factories and launched on a central launch point to be anchored in the artificial lake.

4.2 The need to control the impact of warm and cold water. Warm water means deposition of barnacles as seen on surfaces of boats, influencing maintenance and lifetime expectancy. Cold water and low temperature means a dramatic impact of ice in wintertime. Ice forces can be a threat to the integral safety of the structure. Nonlinear finite element analysis is an efficient tool to investigate and predict the strength of ice forces on structures.

4.3 To study the ecological influence of a floating PV plant to the immediate environment.

4.4 The combination of hydro power and floating PV devices means taking advantage of the already existing electrical infrastructure of the hydro power plant for feeding PV power into the grid and using the artificial reservoir as storage capacity.

4.5 Economics This deployment would make use of and support the ongoing economical and technical development of the PV technology worldwide by providing a new dimension to the PV market. Since hydro power plants using artificial lakes produce peak energy, PV can also be used to supply peak energy, resulting in higher benchmark costs.

5 PROGRESS

In the progress of this project prototypes of these devices will be constructed and tested on the aquatic side mainly by Norut and on the PV plant design side mainly by TNC. A prototype multi-kW plant is planned to be exposed to the winter environment in Norway and in Switzerland. A patent for the project (Photovoltaic and Hydro power) has been applied for.

6 CONCLUSIONS

If the challenges of this specific application area can be kept largely under control, a new dimension to the PV market will be added. An almost identical layout and design would then be applicable almost worldwide. Using mass production, economy of volume and economy of scale can be successfully applied. We can foresee, that in future years one project could absorb the annual production capacity of several PV companies.

There are some critical hurdles to be studied and overcome.

- What are the costs and a reliable way of mass-producing floating devices?
- How con we control the impact of the environment to the PV plant?
- How can we control the impact of the plant to the lake environment?
- What is the maintenance cost for such a plant?

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