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ScienceDirect

Energy Procedia 155 (2018) 403–411

Energy Procedia

www.elsevier.com/locate/procedia

12th International Renewable Energy Storage Conference, IRES 2018

Combining Floating Solar Photovoltaic Power Plants and Hydropower Reservoirs: A Virtual Battery of Great Global Potential

Javier Farfan*, Christian Breyer

Lappeenranta University of Technology, School of Energy Systems, Skinnarilankatu 34, 53850, Lappeenranta, Finland

Abstract

Artificial water reservoirs have been created over history for a variety of purposes such as flood control, seasonal water storage for irrigation, fishing, hydropower generation, energy storage, etc. Globally, hydropower represents still the largest share of renewable electricity generation, with over 1170 GW of capacity installed, thereof 328 GW is hydro Run-of-River capacity, and the rest is hydro reservoir based (141 GW of which is hydro pumped storage), controlled to different degrees. These reservoirs cover a surface of approximately 265.7 thousand km^2 with the potential to host 4400 GW of floating photovoltaic (PV) power plants at 25% reservoir surface coverage and generate approximately 6270 TWh of electricity. This capacity can be extended to 5700 GW and about 8000 TWh of electricity if all reservoirs (hydropower and for other purposes) are covered at 25%, in both cases generating already more electricity than hydropower from reservoirs at about 2510 TWh. The flexibility of operation of hydro reservoir based power plants and their current connection to grids facilitates a "virtual battery" consisting of supplying the electricity demand with solar energy during peak irradiation hours, while balancing grids with hydropower during low/no irradiation times and providing a zero impact area for PV power plant deployment. The characteristics of the "virtual battery" are investigated and presented in this study. The PV power plants also could prevent approximately 74 billion m^3 of water evaporation, further benefiting hydropower production and water conservation, increasing water availability by an estimated 6.3%, adding an estimated 142.5 TWh of production to reservoir-based hydropower plants.

Keywords: Renewable energy; floating photovoltaic; virtual battery; water reservoir; hydropower

* Corresponding author. Tel.: + 358 417 057 569;
E-mail address: javier.farfan.orozco@lut.fi

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Selection and peer-review under responsibility of the scientific committee of the 12th International Renewable Energy Storage Conference.
10.1016/j.egypro.2018.11.038

1. Introduction

Hydropower is a well established technology that has played an important role in the global power system since the beginning of centralized power distribution systems. The oldest (but still operating) hydropower plants have been active since the end of the 19th century [1]. Hydropower plants are operating throughout the planet, with presence in almost every country in the world. There is 701.1 GW of active hydropower plant, reservoir-based capacity installed worldwide (see Figure 1) and 138.7 GW of hydro pumped storage capacity [1].

Shown in Figure 1 is the distribution of reservoir-based hydropower plants globally. It can be noticed that in large, commonly dry areas (Sahara, Northern Mexico, Central USA, Persian Gulf, Australia, etc.) the level of hydropower installations are noticeable lower, nevertheless present. This is due to the fact that hydropower is a major, localized resource.

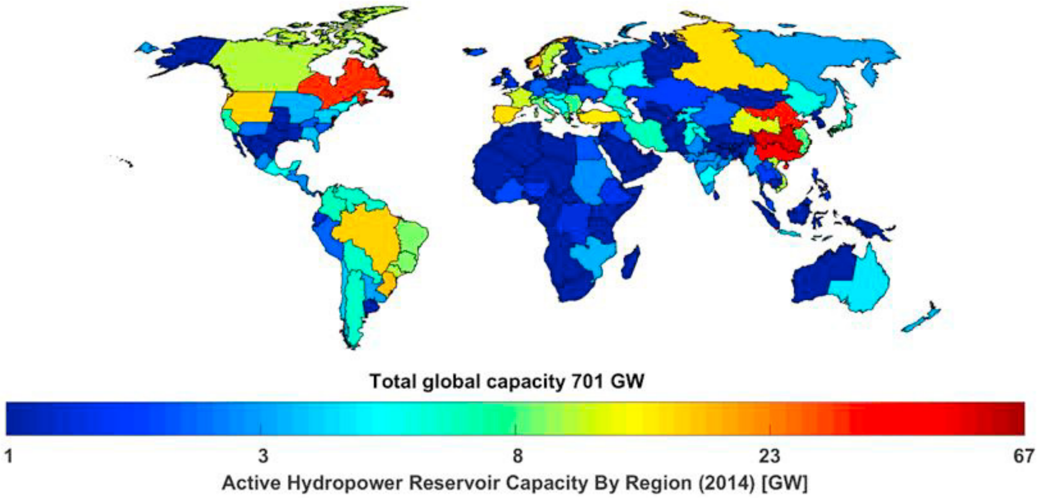

Fig 1. Active global installed capacity of reservoir-based hydropower plants in 2014. Data is taken from [1].

In contrast, solar photovoltaic (PV) generation started having a limited presence in the 1980s, but since then installations have increased in an exponential manner, matching the exponential fall of the price of solar PV panels, occupying a significant share of the new power installations since the year 2010 [1,2]. By end of 2016 the global cumulative installed PV capacity was 306 GW [2], and in 2017 new PV capacity of about 100 GW was added [3]. A very strong growth of PV capacity in the multi TW scale is expected till the mid of the 21st century [1, 2, 4]. However, despite both technologies having shares of the global electricity system for a few decades already, PV and hydropower have only recently started to meet [5-10]. A wide array of designs is currently being either designed, tested or deployed [11], including concepts such as floating platforms, floating thin films, submerged PV panels, etc. Though the characteristics differ from one design to another, the advantages of floating PV (FPV) systems are very clear:

- Using water surfaces for FPV deployment provides areas of potential zero impact and hardly any alternative use
- The cooling provided by the water increases the PV panels' efficiency
- The shading provided by the FPV panels prevents a significant amount of water evaporation
- The shading provided by the PV panels significantly reduces algae growth, thus improving water quality
- Water surfaces provide areas free of shading objects (trees, buildings, etc.) and a higher sunlight reflection coefficient, optimal for PV deployment

Due to the aforementioned reasons, FPV plants hold a huge potential globally. Moreover, further advantages occur when both FPV and hydropower reservoirs meet, such as grid connectivity (with transmission lines, transformers, etc.) already present, every litre of water prevented from evaporation will produce additional hydropower energy, etc. An additional feature that has not yet been analysed is the ability of the hydropower plant to act as a virtual battery of the FPV plant.

One of the disadvantages of solar energy is that it depends on weather conditions and patterns, location-specific radiation levels, and daily natural cycles. Because of this, solar energy production is not controllable. On the other hand, reservoir-based hydropower (when sufficient water is present) is highly controllable, though due to its historic low cost is normally used as baseline capacity production. However, the current and projected fall in cost of PV systems [12, 13] can shift this tendency. The now potentially cheaper solar energy can be used directly while using the water reservoir and hydropower plant as virtual batteries to balance intermittent electricity generation.

Under a "virtual battery" configuration, during high irradiation time, the power generated by the FPV panels would be transmitted to the grid and used directly, while either the reservoir accumulates (when there is an inflow stream) or just holds water that can be then later used during times of low or absent solar irradiation. In this manner, the reservoir itself becomes a battery, where the "charge" is the water spared from being used or accumulated while the direct solar energy is being used. This is of course feasible due to the high flexibility of hydropower plant operation.

2. Methodology

The base data used to perform this research is the global reservoir and dam (GRanD) database [14]. The database compiles all known water reservoirs for which the water level can be purposely controlled. A total of 6863 reservoirs are listed, of which 2134 are listed with hydropower capabilities, either as main or secondary use. Among the data fields, specified information includes location coordinates, name of the reservoir/dam, province, country, closest population centre, average water discharge, reported reservoir surface area, volume capacity, maximum and minimum reported surface areas, main and secondary use of the reservoir, head of the dam, etc. In total, the water reservoirs that fuel hydropower plants provide a reported surface area [14] of approximately 263 thousand km2 of water, which represents an area of potential zero impact. The 263 thousand km^2 of total surface is obtained by adding up the minimum reported surface area of each reservoir, when indicated, or the reported surface area (when minimum area is not indicated).

For the 2134 reservoirs marked with hydropower function, reservoir capacity (in million cubic meters) and annual average discharge (in litres per second) information is always listed, but only 1768 list a number for reported area (square kilometres). The rest of the unspecified area was estimated according to a global average volume-to-surface ratio, as area is a vital factor for FPV potential calculation.

The electricity storage capacity of the dam is calculated according to Equations 1 and 2;

$$E = \eta * \rho * g * h * \dot{O} * T \quad (1)$$

$$\mathrm{T} = \phi / \theta \quad (2)$$

Table 1: Definition of terms for Equations 1 and 2

Symbols	Description
E	Maximum electricity storage capacity of the reservoir (Wh)
η	Efficiency of turbine + generator (assumed 90% for hydropower)
ρ	Density of water (kg/m3)
Ȯ	Water flow (m3/s)
g	Gravity constant (rounded to 9.81 m/s2)
h	Head of the dam (m)
T	Time (hours)
φ	Volume capacity of the reservoir (m3)
θ	Yearly average discharge ratio of the reservoir (m3/s)

For the FPV plant assumptions, the power density and water evaporation prevention ratios are obtained from [5], at 66.82 Wp/m^2 and 1.1 m^3_{H2O}/m^2_{FPV}, respectively. As for FPV energy production, a simulation of the irradiation maps for optimally fixed-tilted PV systems was calculated per location according to the global annual irradiation profiles used by [15]. Influencing effects of the surrounding waters are neglected, such as cooling or albedo effects. Every reservoir surface area was assumed to be covered by only 25%, to protect the FPV from being affected by fluctuating water levels, (though as tested by [5] it seems not to be a constraint). The results are simulated according to the 145 geographic regions defined by [15].

3. Results and Discussion

Under the assumptions and methods previously presented, the following findings have been obtained. Figure 2 presents the potential installation capacity (bottom) and the potential electricity generation (top) by FPV for the reservoirs with hydropower capabilities (regardless of whether it is the main or secondary purpose of the reservoir). The focus on hydropower capable reservoirs is due to the fact that they have lower potential cost integration, as grid connectivity is already available. A total of 4400 GWp of FPV capacity could be installed and 6270 TWh could be generated globally by covering only 25% of the estimated surface area of the reservoirs, which can then be used virtually as a battery. The regions of the world with the highest potential for virtual battery operation are mostly in Siberia, Eastern Europe, the Nordic countries, some parts of North and South America, and Central Africa. As expected, areas predominantly dry, such as the Persian Gulf and North Africa, have significantly less potential (as they have less available water). The largest controllable water reservoir is located in Africa, within the borders of the integrated region of the territories of Kenya and Uganda, which, combined with pristine solar irradiation conditions, creates the spot with the most potential of hydropower combined with FPV.

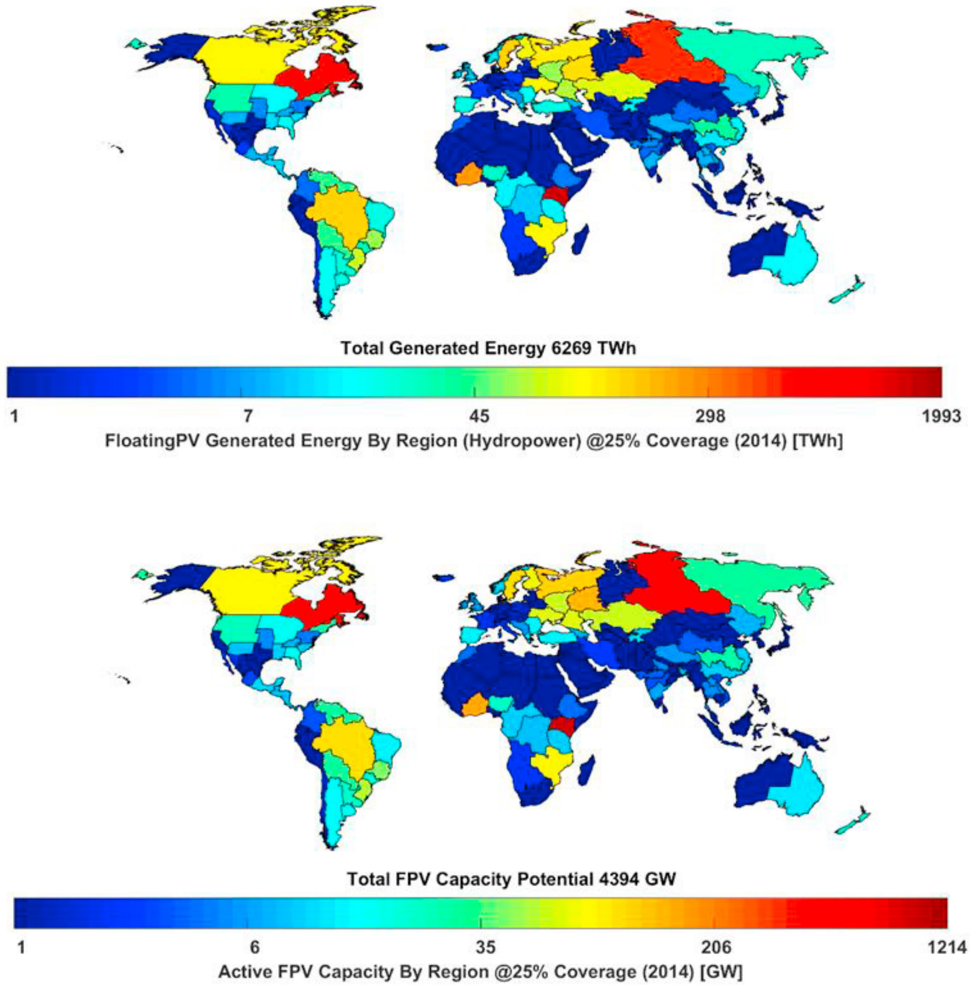

Fig. 2. Potential electricity generated per year from (top) and potential capacity of (bottom) FPV covering 25% of the water surface of hydropower reservoirs.

To put things into perspective, Bloomberg's New Energy Finance [16] estimates that the global demand for electricity storage by 2030 is going to be around 300 GWh, that is, doubling six times from 2016 levels. Whereas, other research [4] indicates a total global storage demand (throughput) of about 15,100 TWh_{el} by 2050 for a global 100% renewable electricity system, and thereof 10,100 TWh_{el} of utility-scale batteries. For reference, it is estimated that hydropower from reservoirs contributes 2510 TWh_{el} to global electricity generation [17], and further growth may be rather limited. This is already less than what can be potentially produced by covering only 25% of the surface of reservoirs by FPV. Extending further the coverage ratio of the reservoir to 50% would then double the potential energy generated by FPV to 12,540 TWh. However, environmental and social constraints should be further investigated.

Furthermore, if the FPV installations were to be extended to reservoirs of all purposes, the installed capacity and generation would extend to 5700 GW (bottom) of FPV capacity and 8039 TWh (top), respectively, as shown in Figure 3. An approximated 74 billion m^3_{H2O} would be prevented from evaporation, thus increasing roughly 6.3% the available water of the reservoirs per year for further energy production (approximately 142.5 TWh assuming 90% hydropower efficiency) or any alternative intended purpose of the reservoir. As reported by [18], just the water conservation advantage is already enough reason for PV systems to be installed over water bodies in high water stress areas, for which, depending on the coverage ratio, evaporation can be reduced by 50% to 80%. Also, up to an additional 7% of efficiency was reported on the solar panels compared to ground mounted systems [18].

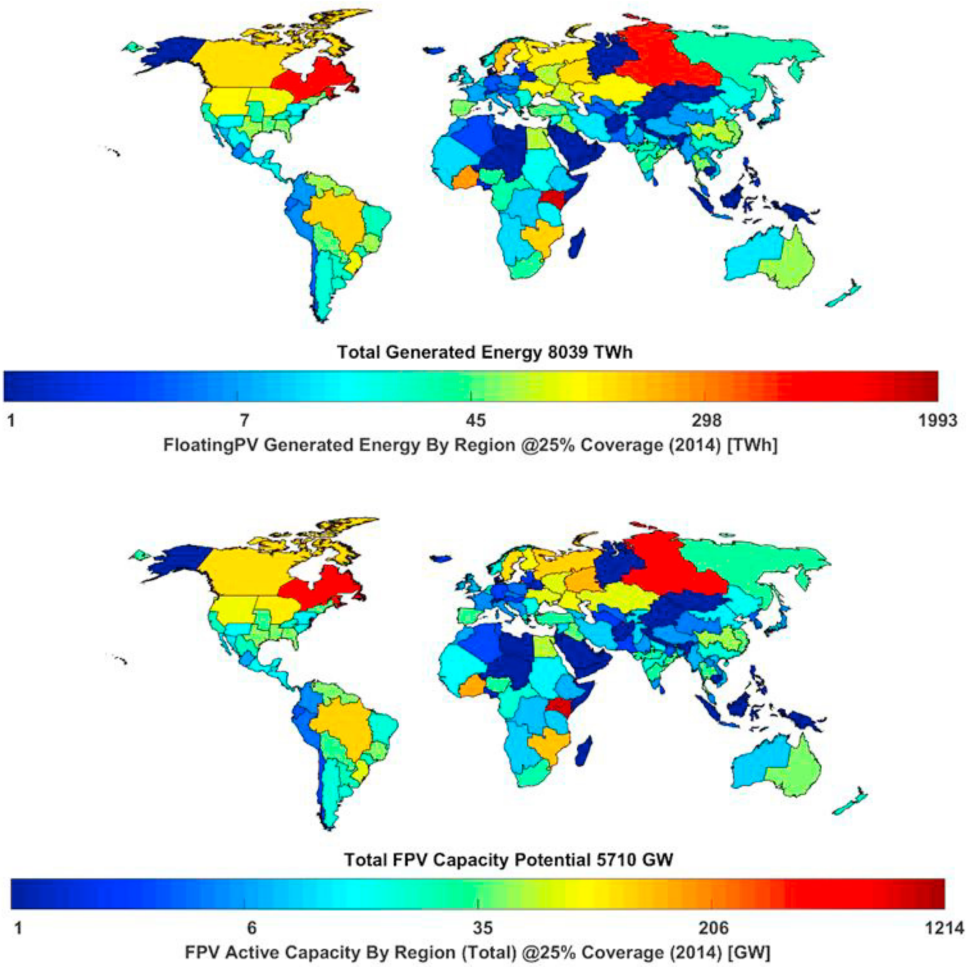

Fig 3. Potential electricity generated per year from (top) and potential capacity of (bottom) FPV plants over water reservoirs of all purposes at a reservoir coverage ratio of 25%.

Figure 3 shows a significantly "brighter" picture than what can be seen in Figure 2, which is caused by an additional 28% of electricity which can be generated when reservoirs of all purposes (hydropower, agriculture, recreation, etc.) have their surface covered at a 25% ratio. This scenario presents some additional advantages. Visible in Figure 3, it can be noticed that water reservoirs for any purpose are more widely distributed globally, and thus are more likely to be able to provide electricity to grids closer to population centers. Despite missing the hydropower virtual battery functionality, such locations would still benefit from decreased water evaporation and increased PV panel efficiency. Furthermore, the technology of FPV's increasing popularity has led to worldwide installations reported by [7, 19] as presented in Table 2.

Table 2. Reported FPV installations worldwide as reported by [7, 19].

Country	Total added capacity
China	376.50 MW
Japan	22.66 MW
United Kingdom	9.33 MW
South Korea	6.00 MW
Australia	4.00 MW
Italy	0.77 MW
United States	0.67 MW
Spain	0.32 MW
France	0.12 MW
India	0.06 MW
Singapore	0.005 MW
Canada	0.0005 MW

Several further FPV projects have been announced, as for Indonesia [20] (200 MW) and China (additional 1.1 GW) [19]. A first combined FPV hydropower project was realized recently in Portugal [21].

An equivalent behavior (balancing hydropower and PV instead of hydropower with FPV) has already been found by various research [22-28]. In areas of the globe where both hydropower (dark blue in Figure 4) and a good solar resource (light yellow and dark yellow from Figure 4) are available, hydropower is expected to shift from the traditional "base generation" operation towards intermittent operation, covering the demand during the low solar irradiation periods, as can be seen in Figure 4 [22]. The depicted example is for Mexico South, and further examples can be found for Turkey [23], Argentina [24], Central America [24], US Mid Atlantics [22], Malaysia West [26], Indonesia Sumatra [26] and Pakistan North [25]. Research results clearly indicate a substantial demand for short and long-term storage and renewable energy easy to dispatch, such as bioenergy and hydro reservoirs, for an electricity system based on variable renewable electricity, mainly solar PV and wind energy. Hydropower from reservoirs can function as short-term and long-term balancing components due to their dispatchability and thus support an energy system integration of high shares of solar PV, which is found as a major source of electricity all around the world [4, 17]. The "virtual battery" dispatch of hydro reservoirs can be studied in detail for all 145 regions for all hours of a year for the simulated case of a 100% renewable electricity system in [23] and respective data can be downloaded.

Alternative hybrid systems of FPV plus energy storage options have been proposed, such as [29, 30]. However, FPV combined with hydro reservoirs present the additional advantage of having the storage part of the system already built, which, with in-depth techno-economic analysis, should prove to be the least cost option.

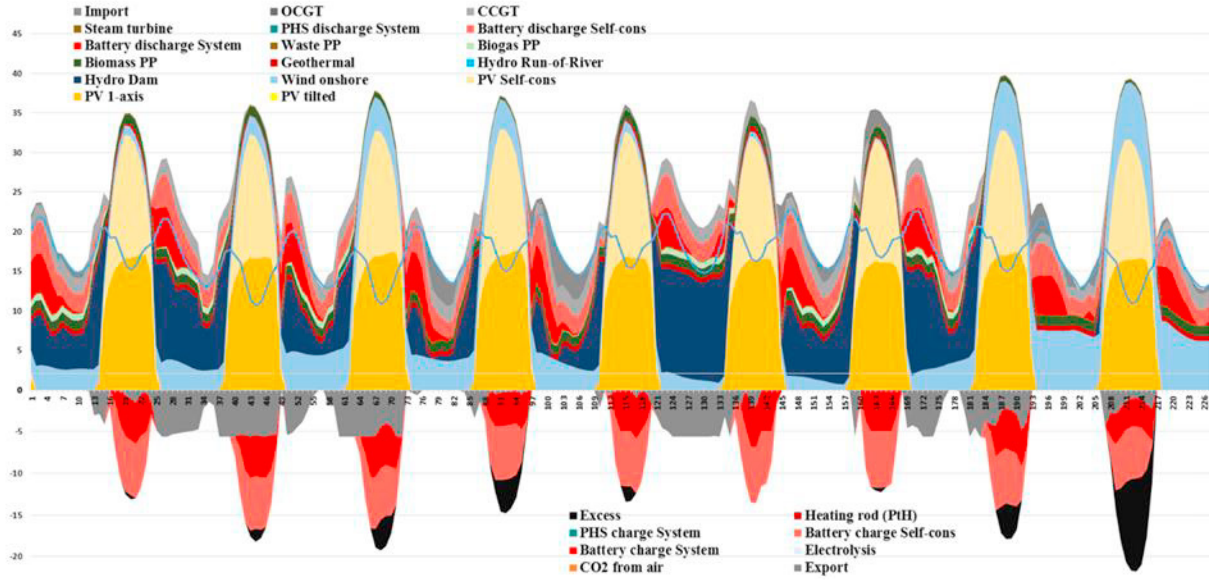

Fig 4. Hourly generation profile for Southern Mexico, an example of a balancing region, obtained from the supplementary material from [22].

4. Conclusions

The benefits of a FPV and hydropower system are significant. FPV, beyond being able to cover manifold the global demand for energy storage, has advantages that extend further. The profiles of operation of hydropower plants and PV plans have also previously been found to work in a good degree of complementarity. FPV is capable of providing significantly more electricity (6270 TWh in total) than hydropower from reservoirs (2510 TWh in total) at a coverage rate of 25%, while providing balance to the FPV intermittent operation. The estimated 6.3% additional water available through prevention of water evaporation can potentially increase hydropower electricity generation by the same ratio under the presented conditions (about 142.5 TWh assuming 90% hydropower efficiency). Depending on the location and additional purposes of the reservoir, higher coverage ratios could be considered, thus providing even more capacity (and electricity), and increasing the rate of water conservation. A surface coverage of 50% (of hydropower-based reservoirs) could increase the contribution of FPV to electricity supply to about 12,540 TWh, which would outstrip that of hydro reservoirs by factors. However, social and environmental constraints may escalate in parallel with increasing reservoir coverage rates.

At the same time, batteries and other alternative energy storage technologies have still a strong role to be played. The main disadvantage of hybrid FPV-hydropower configurations is that they are geographically restricted to specific areas and strongly affected by seasons and weather patterns, and the “virtual battery” functionality is limited to the reservoir’s capacity. Furthermore, the availability does not necessarily match population centre (demand) locations. However, even more renewable electricity could be provided by such regions if hybrid FPV-hydropower plants were applied. Figures 1 and 2 show, for example, high capacities in Siberia and the Amazon jungle, two mostly unpopulated places. On the other hand, due to the immobile nature of the concept, alternative electricity storage technologies would still cover the demand of sectors such as mobility, portable devices, transportation, etc., playing a vital role in global energy systems.

Acknowledgements

The authors would like to thank the Lappeenranta University of Technology for providing the means and the resources to carry on the research and Michael Child for the English proofreading.

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