APPLICATIONS

Exploiting existing dams for solar PV system installations

Ioannis Kougias*, Katalin Bódis, Arnulf Jäger-Waldau, Fabio Monforti-Ferrario and Sándor Szabó

European Commission Joint Research Centre (DG-JRC), Institute for Energy and Transport, F07: Renewables and Energy Efficiency Unit, Ispra, Italy

ABSTRACT

Recognizing the issues of land shortage and growing concerns for protecting natural lands, installers and project developers, with the help of scientists and engineers, continuously try to locate alternative spots for photovoltaic (PV) system installations. In the present paper a novel approach is suggested and analysed: installing solar PV systems on the downstream face of existing dams. This approach provides advantages that could favour even large-scale systems with a capacity of several MWp. First, produced energy could cover water reservoirs’ needs supporting energy-intensive processes as water pumping and treatment in a sustainable manner. Moreover, energy provision to inhabited areas near the dams and the subsequent creation of independent mini grids could mitigate energy poverty. In the case of hydroelectric dams, the so-created hybrid system (PV-hydro) could become notably efficient, because the intermittent solar energy would be counterbalanced by the flexibility of hydropower. Finally, we found a notable number of existing water reservoirs in Africa that are either under-utilized or non-powered. That unexploited energy potential can also be amplified by PV-system installation. The analysis included data collection from various sources. Datasets have been cross-checked and extended in the newly created GIS-based model, enabling the selection of the most suitable sites in South Africa, taken as case studies. Following their identification, the selected dams have been analysed using the PVGIS tool in order to estimate the annual energy production. The results have been very encouraging, indicating that PV systems on the face of dams are an advantageous option for renewable energy production.

KEYWORDS

PV on dams; hybrid PV-hydro; sustainable development; GIS analysis for renewable energy; energy access in Africa

*Correspondence

Ioannis Kougias, European Commission Joint Research Centre (DG-JRC), Institute for Energy and Transport, Via E. Fermi, 2749, IPR45 01/113A, I-21027 Ispra, Italy.
E-mail: ioannis.kougias@ec.europa.eu

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1. INTRODUCTION: EXPANDING THE FEASIBLE PV APPLICATION SITES ON WATER STORAGE INFRASTRUCTURE

In certain geographical areas the development of Renewable Energy Sources through the installation of solar systems needs to overcome limitations in land space. In smaller countries or in densely populated areas it is not always possible to secure enough spaces for photovoltaic power generation facilities on the ground. In such cases, local land shortage issues can be a barrier for PV installations. Furthermore, growing public opposition to large-scale installations is becoming a significant obstacle to greatly expanding the photovoltaic installed capacity and to fulfilling the promises of independency from fossil fuels [1,2]. In some cases environmentally protected areas, natural and agricultural lands might pose additional limitations to solar PV-system installations.

As it is unquestioned that solar PV systems will play a leading role in the production of clean, sustainable energy in the near future, in the present paper the authors examine the effectiveness of PV solar installation on water reservoirs, on the face of existing dams. The advantages of such a potentially effective practice will be presented in the following paragraphs.
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The present analysis has been inspired by the observation that a large number of existing dams in Africa are not producing energy. These already existing infrastructures offer a competitive potential for the development of the proposed scheme, especially considering that most of these dams are used to collect irrigation water and are located in rural agricultural areas. Indeed, rural Africa has a significantly lower energy access rate when compared to urban areas: it is estimated that in Sub-Saharan Africa (excluding South Africa) only 14% of rural households have access to electricity [3]. Thus, energy poverty mitigation strategies should focus on rural areas and installing PV systems on dams located in such areas will certainly enhance decentralized energy production and have a positive impact on energy access rates. Moreover, inventive solutions that have the potential to decrease the cost of energy provision could be beneficial for both the concession companies and the citizens.

2. SOLAR PV SYSTEMS ON THE FACE OF DAMS

Generally, dams offer a plane surface, on which PV module installation could be applicable (Figure 2). Therefore, the surface of existing dams offers an investment opportunity to the administrative authorities that operate water reservoirs. Accordingly, PV system installation will augment a dam’s role, resulting to advanced utilization of water infrastructure.

Obviously, different types and size of dams need different solutions. Therefore, following a review of recent real-world applications on dams, the authors describe the different characteristics and the particularities of each type of dam. Subsequently, the authors present the assessment methodology, developed in order to evaluate the energy potential of different sites. To achieve this goal, different tools had to be combined in order to identify first-rate sites, where the concept of PV installations on dams’ face will find the most favourable conditions. Different data sources were integrated, through harmonically combining existing datasets, including solar radiation and PV energy output estimations. This result has been achieved by coupling the newly created GIS model (see Section 6) with PVGIS, an open-source tool, developed in the Renewables and Energy Efficiency Unit, JRC, providing a well validated map-based inventory of solar energy resources and assessment of the electricity generation from PV systems for Europe and Africa.

2.1. PV system installations in different types of dams

According to their size, shape, use, construction methods and material, dams are distinguished in four different types. Apparently, the particularities of each type of dam affect both the potential and the required approach for a PV system installation with geometry and features of certain types of dams being more favourable for PV installations, when compared to others.

Selecting the type of dam for a specific site is a complicated, site-specific task, performed during the dam’s planning phase. In the following paragraphs the authors present the main types of dams (Figure 1) along with their technical characteristics that are relevant to PV installations.

2.1.1. Gravity dams.

Gravity dams are usually made from concrete or masonry (Figure 1.1). Their structural stability is achieved by their own weight. The upstream face is vertical or slightly inclined, whereas the slope of the downstream face usually varies between 50° and 60°. The plane, flat surface of their downstream face is appropriate for mounting PV systems. However, the relatively high inclination, although beneficial for the natural removal of snowfall, might impose some technical difficulties during the system’s installation and maintenance. Assuming that PV-modules are mounted almost parallel to the downstream face, gravity dams favour installations in regions having geographical latitude of about 50–60° provided they are South/North facing (depending on the hemisphere). On the contrary, installations closer to the equator will be less efficient.

2.1.2. Embankment dams.

Embarkment dams are created by the emplacement and compaction of a mound of soil, sand, clay and rock (Figure 1.2). The two main types are earth-fill dams and rock-fill dams. Upstream and downstream faces may have different slope, which is in both cases between 20° and 30°. Thus, compared to gravity dams, embankments favour efficient PV installation on dams in regions with relatively lower geographical latitude.

Moreover, embankments’ lower slope facilitates both installation and maintenance of PV systems. This is the reason all the installations in Hyogo, Japan (see 2.2) are on embankments. In case the PV system is selected to be
installed on concrete slabs an additional design and construction cost will apply.

2.1.3. Arch dams.

Arch dams are curved in plan and carry most of the water load horizontally to abutments by arch action (Figure 1.3). The curved shape of arch dams hampers PV installation. In cases of highly curved shape, PV modules will need to be distanced, to avoid shading. On-site, accurate measurements of solar irradiation may also be needed in order to develop ad-hoc solutions that are feasible. However, the additional engineering labour along with the only partial utilization of the dam’s area for PV installation, rarely result to a financially attractive investment.

An additional drawback is associated to the typical location of arch dams. Because they are usually constructed in narrow valleys, they are surrounded by mountains. Therefore, mountains’ shade will decrease the received insolation.

2.1.4. Buttress dams.

Buttress dams (Figure 1.4) are generally concrete dams with a watertight upstream side that is supported by triangular shaped walls or arches (buttresses). There are several designs of buttress dams. However, in all cases the downstream face includes recesses with only limited flat areas suitable for PV installation. Therefore, buttress dams are not suitable for the proposed scheme.

2.2. Real examples

Until recently the installation of PV systems on the face of dams was discussed only on theoretical basis. However, such projects have recently become a reality in Japan and their operation during 2014 proves their technical feasibility. Following the tragic nuclear accident in Fukushima, the Japanese government has strived to find practical, effective and economically viable applications that will promptly increase the domestic renewable energy production. Accordingly, local energy authorities in Hyogo Prefecture announced in mid-2013 the outline of a megawatt-scale solar project.²

Aiming to make the most effective use of existing water infrastructure such as dams, Japanese public enterprise agencies will support energy companies to build solar power facilities that improve energy production in the local scale. Accordingly, they have planned modifications such as the transformation of Kotani dam (Himeji city) to PV-powered dam (Figure 2).

The development plans also include the exploitation of sloping faces and borrow pits at Heiso-1 and Gongen-1 dams near Kakogawa city, apart from Kotani Dam. None of the aforementioned dams requires major adaptation in order to accommodate solar PV installations. These dams collect drinking water for the nearby cities and also cover industrial water demand.

They all have south orientation and gentle slopes. Their near-optimal orientation and tilt result in excellent energy production of PV systems. Indicatively, the Kotani dam has a south orientation and a tilt of 26° which is very close to the optimal PV-system installation that suggests a 31° tilt facing south.

The design capacity of the PV installation in Kotani dam is 4.99 MWp also expanding to the surrounding 3.2-hectare area (Figure 2b). The installation cost is estimated at ¥1.3 billion (about €9.5 million) and along with the management and maintenance costs the total investment throughout a 20-year operation is estimated at ¥2.1 billion (about €15.5 million). In that period the produced electricity is estimated to worth ¥2.8 billion (about €20.5 million), resulting to revenues of ¥700 million (about €5 million).

3. PV on dams: Main advantages

Installing PV systems on the face of existing dams has several advantages compared to ground-mount or rooftop systems. These advantages are distinguished in those related to the practicality of the proposed scheme and those related to the advantageous energy production of the created system.

3.1. Practicality

An important aspect supporting the practicality of this approach is the easy access to the installation area as well as dam’s proximity to the energy grid. Easy access through the existing road network facilitates both the construction and maintenance of PV systems. Besides, dams generally have access to the grid to operate their own machinery. Therefore, the installation of PV systems on dam’s faces does not impose the additional—often substantial—cost of grid extension. Obviously, grid’s capacity needs to correspond to PV installations in order to accommodate the additional generated electricity. In the case of hydroelectric dams the equipment (transformers, circuit breakers etc.) usually is able to adjust in small increases in capacity (about 15%) by design. Still, the proposed scheme needs to take into account grid’s technical characteristics during the planning phase.

An additional advantage of the proposed scheme is that in the case of earth dams PV modules’ installation protects the surface from direct solar radiation that might negatively affect the stability of low-head earth dams, especially during summer [4]. These incidents may occur in areas with large temperature fluctuations (summer following cold winter), and it is expected that the proposed scheme will increase dams’ durability.

3.2. Land-use and environmental impact

The proposed approach exploits available areas without affecting land uses. As available land for renewable energy source exploitation is sparse, the issue of land use has already raised some concerns among analysts [5,6]
especially in the context of the water–energy–food nexus [7]. The systems described here do not affect land uses and local activities; on the contrary, they harmonically cooperate with water reservoirs, supporting renewable energy production. They mitigate the demand for continuous energy production from stored water, better securing urban and irrigation water provision.

This scheme poses no additional environmental impact neither to land or water. It is appropriate for areas where environmental or economic reasons hamper the deployment of typical large-scale free field installations. Thus, it is applicable, among others, to touristic areas, agricultural regions with a high land value (e.g. vineyards) and also in land scarce countries with high density of water bodies (e.g. Singapore).

3.3. Advantageous energy production

Installing PV modules on the face of dams can be advantageous in both energy producing and non-electrified reservoirs. In the first case, the PV installation will result to an efficient hybrid system. In the case of non-powered dams, the produced solar energy will partly operate water pumping [8], reducing dam’s energy dependence. Storing PV-produced energy in battery systems is also an option for autonomous operation of pumping systems in small ponds.

Considering that irrigation dams are important infrastructure for rural, agricultural areas, this new approach can support rural electrification schemes and mini-grids, and in Section 5 the authors will examine the potential of PV installation on the face of irrigation dams in South Africa, in regions where the energy access rates are still low.

Generally, exploiting existing infrastructure to increase the energy production is an effective policy in the current international economic environment. The synergetic integration of PV technology to existing infrastructure networks can generate multiple efficiencies and cost saving opportunities [1]. Water storage dams are high-cost civil works that in many cases serve multiple purposes. Thus, their exploitation towards increased share of renewable energy production will have a significant economic impact.

3.4. Installation on pumped-storage dams

PV-system installations on the face of pumped-storage dams can further expand the scope of the PV-dam synergy. Pumped-storage hydroelectric power plants are the most mature energy-storage technology [9]. This characteristic justifies their key role in stabilizing the energy grid and securing energy availability. The increase of the intermittency in energy production following the dissemination of renewable energy sources production is expected to increase the need for pumped-storage facilities [10]. PV installation on pumped-storage dams will increase the aggregated power capacity and the energy production. Accordingly, the additional capacity will support energy storage and hybrid operations will assist pumped-storage stations on their crucial role.

Pumped-storage stations usually produce energy during the day, when energy demand is high and operate in exactly the opposite way during the night, when energy consumption is significantly lower. During the night-hours, the turbines rotate in the opposite direction, pumping water upstream and storing energy that will be transformed to electricity in peak hours. In the presented scheme PV production will mainly cover the off-peak period (10 am–6 pm in S. Africa). Thus, the flexible pumped-storage stations will cover morning and evening peak-demand periods, resulting in a more efficient exploitation of the available water resource and obvious economic benefits.

4. TECHNICAL ASPECTS AND CHALLENGES

The additional structural weight of the PV installation is not expected to affect the stability of dams. Besides, its weight is negligible compared to the massive structure that constitutes the body of the dam.

Although PV systems’ installation will be in humid areas near artificial lakes it is not expected that additional waterproof protection measures will be needed for the PV panels. Stored water outflows from the sides of the dams, through spillways that have the capacity to discharge even major floods without damage to the dam or any appurtenant structures. Therefore, the proposed PV system will
not be exposed to much more unfavourable conditions than any typical outdoor installation.

A PV array’s output is proportional to the sunlight it receives and PV modules perform best when their surface is perpendicular to the sun rays. PV system installations in direction and tilt that maximize modules’ direct exposure to sunlight increase the produced energy and improve the economic terms of the investment. The angle of the sun varies throughout the year and the optimum tilt for winter is different from the optimum tilt for summer. More important, the optimal angle of the PV arrays varies by latitude.

Designing systems with optimal orientation and tilt angle in the proposed scheme faces certain limitations. Because the area of the installation (dams’ face) is fixed, there is only limited flexibility on the installation of the PV modules.

4.1. Surrounding area of the dam

Examining the appropriateness of this scheme involves examination of the installation area. Trees, mountains and structures might cast shading, and this effect will be changing throughout the year and will most likely be more intense during the winter period and at day-hours when sun is at a low angle.

4.2. Orientation of the PV system

Consequently, the orientation of the dam must be carefully examined as modules will be generally mounted on the dam, at a small distance from its surface and almost parallel to it. Therefore, the orientation of the modules will be usually identical to the orientation of the face of the dam.

Unfortunately, not all existing dams have an ideal orientation. Even so, the installation can be beneficial by adjusting the PV rack but in most cases, the reduction in the produced energy does not prohibit the installation. An array oriented 30° off the optimum will typically suffer less than a 5% reduction in production [11].

4.3. Tilt of the PV system

Generally, non-adjustable solar PV installations perform better when tilted towards the typical sun elevation which is equal to the latitude of the arrays’ location. In that way the system captures most of the annual solar energy. In the proposed scheme PV system’s inclination is almost equal to the slope of the downstream face of the dam, because modules are mounted parallel to dam’s surface and in a small distance from it. Although the tilt is an important parameter for the optimum operation of the installation, deviations from the ideal tilt are not necessarily prohibitive. An array tilted 15° off from the geographical latitude still is expected to produce almost 95%, compared to an array tilted to the ideal latitude.

4.4. Minimizing the distance between PV modules

Although the proposed scheme provides only limited flexibility for inclination, it has a feature that counterbalances this drawback. In typical installations on flat areas, modules need to be distanced to avoid overshadowing each other (Figure 3a). In the proposed scheme PV modules are mounted on an inclined area. This formation, as illustrated in Figure 3b, minimizes the required distance between modules, resulting to a better exploitation of the available area.

5. SOUTH AFRICAN CASE STUDY — INPUT DATA

In order to explore the potential of solar-system installations on dams’ face, the authors have developed a GIS-based methodology, where geographical information are analysed and processed. Recently the authors have developed an integrated dataset of European and African river basins [12]. This work offered an insight into topography, channel geometry, land cover and soil characteristics, exploited in the present research. Realizing that South Africa (SA) has a significant number of non-electrified dams, the authors have chosen to apply the GIS-based methodology on this country, as a case study.

Additional water storage data have also been included in the analysis. According to the FAO and GRanD databases [13], there are about 1200 dams of different sizes in Africa, covering various purposes (irrigation, water supply, hydroelectricity, livestock rearing, flood control, navigation, recreation etc.). Almost half of these (517) are located in SA, offering a substantial potential for the proposed scheme.

**Figure 3.** PV system installation on flat and inclined surface.
5.1. PV solar energy status in South Africa

Every two years, the Department of Energy in SA updates its Integrated Resource Plan (IRP) for energy production. Already in 2011 an ambitious plan for 8400 MWp of solar PV installations until 2030 has been published [14]. The recent IRP’s revision of November 2013 has considered the latest changes in PV costs and further increased the PV capacity target for 2030 at 9770 MWp [15]. In order to achieve this goal the SA government has initiated policies that have rendered the country as the most attractive emerging country on PV installations [16].

The PV solar electricity potential of SA is illustrated in Figure 4, and it is exceptional even compared to the potential of south-European countries. This map has been recently created in the JRC [17] and represents the yearly sum of global irradiation on SA. The data represent the average of the period 1998–2013, and values are given as kWh/m². The same colour legend represents also potential solar electricity [kWh/kWp] generated by a 1-kWp system per year with PV modules mounted at an optimum inclination and assuming system performance ratio 0.75. Moreover, the thematic maps created in [18,19] further support the idea that the proposed scheme can be very efficient in SA.

5.2. Analysis of existing dams in South Africa

In Figure 5 the full range of dams included in the extended dataset is illustrated. The eastern part of the country receives the highest rainfall rates (800–1100 mm annually) and naturally hosts a large number of water reservoirs. In Figure 4 is shown that the peak potential of solar energy production, being larger than 1800 kWh/kWp is uniquely located in the north-western part of the country. However, solar irradiation in the north-eastern part, where most of the dams are located is still offering an excellent potential of about 1650 kWh/kWp.

As shown in Figure 5, a broad correlation between the number of water reservoirs and population density can be observed. Thus, numerous water storage facilities, mostly earth-fill dams, collect water for the local water needs. Considering that earth fill dams have an inclination of 20°–30°, which is identical to the latitude of South Africa, it is easy to guess that this new approach could be very appropriate in SA.

It is important to note that the eastern part of the country has also the lowest electrification rate, especially in rural areas. Therefore, PV installations on the face of dams located in these regions, with a parallel creation of mini-grids can improve the energy access of nearby...
communities. This rationale is not based exclusively on economy of scale, but also adopts principles of the smart grid policy [20], where residential and productive areas are self-sufficient. This approach is expected to be effective and expand the positive impact of the Solar Home Systems (SHS) initiative that delivered energy for the basic needs of the inhabitants of the rural, low-income areas.

6. SOUTH AFRICAN CASE STUDY—GIS-BASED METHODOLOGY

The authors have developed a methodology that supports the selection of the first-rate sites. Accordingly, input data and information on the parameters of the dams (height, slope, length of crest, capacity and depth) have been analysed along with basic hydrological information (catchment area, impounded river and discharge).

6.1. Locating the first-rate sites

Location, geometry and direction of the dam’s face define the orientation and tilt of the solar panel installation and consequently affect the efficiency of the system. The authors extended the harmonized dataset with the dam height and defined the exposure of the abutment of the dam expressed in positive degrees from 0° to 360°, measured clockwise from the north. The analysis initially sorted the studied dams in three categories.

6.1.1. Dam’s height and orientation.

The first category has included low-height dams, indicated in grey colour in Figure 5. Although these dams could also be—under certain conditions—suitable for solar system installations, they impose technical difficulties related to the narrow installation surface. Because the present analysis aims at first-rate locations, dams with a $h > 5$ m have been highlighted, because they offer superior technical and economic terms.

Consequently, dams with a near-optimal direction have been highlighted. Because solar systems in South Africa...
perform optimally when facing north, dams having a north-west to north-east orientation have been considered as first rate locations. Thus, sites with an exposure of less than 60° (north-east) or more than 300° (north-west) have been considered as favourable and are illustrated in blue colour in Figure 5. The number of the highlighted dams in blue colour is 37 and includes dams of different type and size.

6.1.2. Dam’s type and functionalities.

Processing the information of the dams can further increase the knowledge on the examined sites and support the selection of the most suitable locations. Apart from the height, there are additional issues that define how suitable a dam is for the proposed scheme.

The main and secondary purpose of the dams has also been recorded. Exact geographic coordinates and proximity to inhabited areas are important for further analysing the economic viability of the proposed scheme in specific areas. Accordingly, analysing the highlighted locations (37 dams) the number of first-rate dams has been limited to those 10 that facilitate efficient PV installations. The selected dams and the technical characteristics of the installation have been included in Table I.

6.2. Integration with the PVGIS tool

The developed methodology also estimates the solar electricity potential of the studied locations, by coupling the analysis to the PVGIS tool. PVGIS [21] offers solar irradiation data and information regarding daily profiles of clear-sky and real-sky irradiances during a chosen period, for a selected module inclination and orientation.

PVGIS provided an estimation of the expected annual solar energy production (in kWh) of a 1 kWp PV system on the face of the selected dams. These values are included in Table I, Column 8 and correspond to an optimal installation, with optimal orientation and inclination. However, dams’ surface provides limited flexibility and optimal installation are not always possible. Thus, column 9 includes the expected energy production assuming that the installation adopts the fixed orientation and inclination of each dam.

Often, inclination data of the dams were missing. Accordingly, missing information on the dams’ inclination was estimated based on dams’ type and geographical information on their height and width.

6.3. Available area for PV solar system installation

An important task of the methodology is the estimation of the available area for PV module installation. This leads eventually to the estimation of the installed power capacity, and it is a crucial parameter to evaluate the investment.

The authors estimated the available area of the selected dams, which has been included in Column 6 of Table I. They used the geometrical parameters of the dams based

| ID | Dam         | River          | Nearby city     | Height [m] | Estimated area [m²] | Exposure [degrees] | Estimated solar electr. (optimal) [kWh/kWp] | Estimated solar electr. (potential) [kWh/kWp] | Share [%] | Act./Opt. |
|----|-------------|----------------|-----------------|------------|---------------------|-------------------|----------------------------------------------|-----------------------------------------------|-----------|-----------|
| 1  | Midmar     | Umgeni         | Howick          | 32         | 20 300              | 22                | 1570                                         | 1550                                          | 99        | 99        |
| 2  | Middle     | Letaba         | Givani          | 34         | 44 200              | 34                | 1470                                         | 1440                                          | 98        | 98        |
| 3  | Hans Stroid | Mopl          | Ellias          | 55         | 11 000              | 260               | 1700                                         | 1680                                          | 99        | 99        |
| 4  | Heyskraam  | Mopl          | Hans Stroid     | 29         | 8 410               | 22                | 1650                                         | 1630                                          | 99        | 99        |
| 5  | Assigaei   | Olifants       | Heyshope        | 33         | 24 988              | 27                | 1700                                         | 1680                                          | 99        | 99        |
| 6  | Flag Boshielo | Olifants     | Moplo           | 27         | 31 000              | 338               | 1750                                         | 1730                                          | 99        | 99        |
| 7  | Peraasrivier | Olifants     | Moplo           | 31         | 3 720               | 360               | 1770                                         | 1750                                          | 95        | 95        |
| 8  | Pilgrims Rest | Olifants    | Moplo           | 31         | 3 860               | 360               | 1770                                         | 1750                                          | 95        | 95        |
| 9  | Ohrigstad  | Olifants       | Moplo           | 52         | 3 653               | 360               | 1770                                         | 1750                                          | 93        | 93        |
| 10 | Molatedi   | Olifants       | Moplo           | 29         | 35 533              | 360               | 1770                                         | 1750                                          | 85        | 85        |
on technical descriptions (e.g. crest length, height) and measurements by GIS tools (geo-referenced data and image interpretation). The approximated area was calculated as equal to the area of the orthographic projection of the dam, as a trapezoid. This estimation has taken into consideration all natural or artificial obstacles that hinder PV module installation. Moreover, it ensured that the designated areas will not disturb the typical water-related functionalities of the reservoirs.

7. RESULTS

The created GIS-based decision tool successfully supported the selection of the most suitable dams as shown by the high ratio between the expected annual energy production and the production of an optimum installation. The expected annual energy production of the selected dams for installations with ideal orientation and tilt ranges between 1470 and 1780 kWh/kWp, which is very favourable. The estimated actual energy production is close to these values, and the ratio of the expected production to the maximum is generally >90%, proving that SA dams offer a significant potential for solar system installation. Notably, Hans Strijdom dam (Table I, nr. 3) offers optimal conditions for a PV installation with a ratio equal to 100%. Thus, PV panels placed parallel to its face will have optimal direction/tilt and maximum energy production. The Molatedi dam (Nr. 9) offers the least favourable setting, still with an annual production of 85% compared to the optimum installation. As a gravity dam it has a steep slope. Therefore, although it faces the true north its large tilt results to reduced energy production.

Apart from the local solar irradiation the power capacity of the installation depends on the available area. Installation is possible on the entire dam’s face excluding spillways, gateways and any machinery with its surrounding area. Taking into account the required distance between modules and the needed walkways for maintenance, a coefficient of 80% has been applied to estimate the net area. In Table II the outcome of the PV system installations in the selected dams is illustrated. The developed capacity through the application of the proposed scheme will be almost 42 MWp with an annual energy production of about 70 GWh. Sterkfontein dam (Figure 6, Nr. 10) offers a significant potential of 22.5 MWp, because of its length and height. Although the selected dams are the most favourable

| ID | Estimated area [m²] | Net area [m²] | Capacity [kWp] | Estimated annual solar electr. [MWh] |
|----|---------------------|--------------|---------------|-------------------------------------|
| 1  | 20 320              | 16 000       | 2400          | 3700                                |
| 2  | 44 200              | 35 000       | 5250          | 7500                                |
| 3  | 11 000              | 9000         | 1350          | 2300                                |
| 4  | 8410                | 6500         | 975           | 1600                                |
| 5  | 24 998              | 20 000       | 3000          | 5300                                |
| 6  | 31 050              | 25 000       | 3750          | 6500                                |
| 7  | 3720                | 3000         | 450           | 750                                 |
| 8  | 9888                | 8000         | 1200          | 1900                                |
| 9  | 2553                | 3000         | 450           | 650                                 |
| 10 | 195 300             | 150 000      | 22 500        | 40 000                               |
|    | 362 430             | 275 500      | 41 325        | 70 200                               |

Table II. Characteristics of installations in the selected dams.

Figure 6. Aerial view of the selected dams, South Africa.
for this approach, there are numerous dams where the installation would be advantageous. Expanding this scheme to more installations can effectively support the target of South African government for increased share of renewable energy sources by 2030. According to [15], new PV installations in South Africa will have an annual rate of 300 MWp additional capacities until 2024 which will be then increased up to 1000 MWp/year until 2030. It is thus obvious that similar installations could support this plan, because South Africa has a significant dam network that offers substantial potential for this novel approach.

It is interesting to note that all 10 selected dams are non-powered. Six of them collect irrigation water, while the remaining four supply with drinking water nearby cities. Thus, apart from partially covering dam’s energy needs, the solar system installation will also support the interrelationship between energy and water.

Increasing the overall capacity of the installation in order to enhance energy production can also be achieved by expanding the PV installation to the surrounding areas of the dams. Accordingly, the planning in the Kotani dam has predicted module installation in the area near the dam’s toe (Figure 7a). Property or environmental issues are not expected to occur, because such areas are supervised by the reservoir operator authority. Some of the selected South African dams offer a similar possibility. Indicatively, the installation in Sterkfontein dam (Figure 7b) can be expanded to surrounding areas.

8. CONCLUSIONS

In the present paper a novel, innovative approach for renewable energy production, the development of PV systems on the downstream face of existing dams has been presented and discussed. The proposed scheme can be applied either to powered or non-powered dams. In the first case it provides energy independence to existing dams. Combined installations with hydropower dams enhance efficiency because of the hybrid system operation.

Following the creation of the datasets, a purposely developed GIS-methodology was used to detect the first-rate locations in South Africa. PVGIS tool supported the methodology by providing information on solar insolation and estimations on energy production. Accordingly, 10 dams have been selected, and the total capacity of the installation is estimated at 42 MWp, and this additional capacity is expected to produce an annual electricity of 72 GWh, only from exploiting the surface of the selected dams.

It is, thus, shown that the proposed scheme offers a substantial potential for renewable energy production. This approach is perfectly suited to countries with an advanced solar electricity potential and abundance in non-electrified irrigation dams. It is required to investigate the necessary policies that support the development of similar installations. In this way a framework defining this approach will be created and safeguard water reservoirs’ operation, promoting increased PV solar system penetration in the energy market.

The analysis developed here is expected to be extended in the near future to other Sub-Saharan countries, provided that robust data would become available.

9. DISCLAIMER

The views expressed in this paper are purely those of the writers and may not in any circumstances be regarded as stating an official position of the European Commission.

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