GEOGRAPHIC AND TECHNICAL FLOATING PHOTOVOLTAIC POTENTIAL

by

Giuseppe Marco TINA[a*], Raniero CAZZANIGA[b], Marco ROSA-CLOT[b], and Paolo ROSA-CLOT[b]

[a] DIEEI, University of Catania, Catania, Italy
[b] Koine, Pisa, Italy

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The photovoltaic geographic potential (PVGP) is defined as the fraction of the solar irradiation received on the land available for a photovoltaic facility. The area of this usable land is calculated by a suitability factor which is determined by a variety of different geographical constraints. We extend this kind of analysis to floating photovoltaic (FPV) structures and consider the use of water surfaces with the same definitions and notations used to define the PVGP for systems installed on the ground. Results are very promising because of the large water surfaces available and because of the possibility to build floating structures which are more compact than land based photovoltaic plants. In fact, using just 1% of natural basins areas to install FPV plants, about 25% of the world electrical energy demand (in 2014) can be supplied. The PVGP is evaluated for two PVF raft geometries: one is a typical shed structure, the other is an innovative solution named gable.

Key words: *photovoltaic floating plan, water packing factor, geographic potential*

Introduction

Among renewable non-programmable energy sources, the photovoltaic (PV) is the most rapidly developing one. The total cumulative installations amounted to 242 GWp at the end of 2015. Europe's contribution to the total cumulative PV installations amounted to 40% (compared to 48% in 2014). In contrast, installations in China accounted for 21% (compared to 17% in 2014). However, to evaluate the real impact of PV on national power systems we should use other indexes, such as: capacity per inhabitant (W/inhab) and PV penetration % (PV yearly production/internal demand). The PV technology has now developed to the point where the cost of kWh produced by PV plants is becoming competitive with conventional electricity generation technologies and PV is increasing its share of the energy mix around the world [1]. Notwithstanding the many benefits of using PV plants, there are different types of non-negligible environmental burdens. As it happens for other types of power plants (*e. g.* renewable or conventional), the potential environmental costs of the installation and operation of PV farms are experienced mainly by the local population, while the general benefits accrue to all [2]. The most important impacts are in terms of land use [3]. The installation and operation of PV systems determine a relevant transformation of the territory for various reasons, such as: land use, elimination of the existing vegetation, visual impact on the components of the landscape, microclimate change, glare from the reflection of the direct sunlight. The environmental, terri-

[*] Corresponding author, e-mail: giuseppe.tina@dieei.unict.it

torial and landscape impacts basically depend on the physical extent of the system, which for utility scale PV plants is very large. Given the cost of land, the maintenance problems and the environmental impact, a lot of work has been done in order to manage all these aspects, recently summarized in a useful review by Martín-Chivelet [4]. Also, PV systems may displace food crops and invade cultivable land, which factors contribute to the ongoing *food vs. fuel* controversy [5]. These coupled land and food challenges may seem insurmountable, but through agrivoltaics (*i. e*. the dual use of land for both solar PV and agriculture) they can be partially solved [6]. Another possibility to overcome this problem is by the installation of PV systems on water basins. These systems, named floatovoltaics (FV) can be defined as PV systems floating on any sized body of water. When the concept of floating photovoltaics is combined with aquaculture, aquavoltaics is realized. Its goal is the efficient use of water with the dual purpose of food and energy generation. While solar panels above the water or on its surface provide the electrical energy, the aquatic organisms living within the water below provide a sustainable food source [7].

The main goal of this paper is to extend, by means of a suitable formulation, the potential analysis already developed for ground PV systems [4] to the PV floating structures so as to have an idea of the power that can be installed on a water basin and how much energy can be produced. The potential values are also evaluated numerically for two possible designs of floating systems.

Geographical and technical PV potential

The geographic PV potential, PVGP, is defined as the annual irradiation $I_a(0)$, in kWh/m^2, on a horizontal surface multiplied by the quantity A_s, in m^2:

$$\text{PVGP} = I_a\,(0)\,A_s \tag{1}$$

where A_s has been defined as the area suitable for installing the PV.

The ratio between A_s and the total land area under consideration, A_L, depends on many arbitrary elements and for large plants it is suggested to be 1% in agricultural zones and 5% in desert zones [4], or the more conservative European commission percentages [8]. This parameter is very important, so we introduce it explicitly as follows:

$$\alpha_{SL} = A_s/A_L \tag{2a}$$

A similar definition can be applied also to the surface covered by water in a given territory, A_w, that can be partially used for floating PV plants, so we have:

$$\alpha_{SW} = A_s/A_W \tag{2b}$$

The concept of available area is the first input of the technical PV potential that can be calculated in terms of capacity (installed power) or generated electricity (energy): $PVPP_d$ (PV power potential density in kWp/m^2) and $PVEP_d$ (PV energy potential density in kWh/m^2/year) are defined as the PV power per unit of land (water) area and the PV energy per unit of land (water) area, respectively.

$$PVPP = PVPP_d \cdot A_s \tag{3}$$

$$PVEP = PVEP_d \cdot A_s \tag{4}$$

This is the actual usable solar power or yearly energy yield, once it has been transformed into electricity by a PV system.

The $PVPP_d$ depends on some parameters:
- the PV panel efficiency η. This value has been slowly increasing in the last few years and we will assume values ranging from 9% for amorphous silicon to 16% for polycrystalline silicon.
- the generator to system rate (*GSR*) defined as the ratio between the area covered by the PV generator A_{GEN} and the area occupied by the PV facilities A_S.

$$GSR = A_{GEN}/A_s \tag{5}$$

which is assumed to range between 0.7 and 0.85 for a land based PV plant. In floating plants, due to the absence of ad hoc structures. we will assume this parameter to be equal to 0.95.
- the packing factor *PF* taking into account the structure of the ground plant, the modules tilt angle and the necessity to avoid shadows between modules, as well as the necessity to have some space for managing purposes (modules cleaning, grass cutting *etc*.)

$$PF = A_{PV}/A_{GEN} \tag{6}$$

where A_{PV} is the total area of all PV modules.

With these definitions and assuming that the irradiance at standard test conditions G_{STC} is 1 kW/m^2, the $PVPP_d$ density becomes

$$PVPP_d = \eta\, GSR \cdot PF \cdot G_{STC} \tag{7}$$

The most interesting quantity however is not the $PVPP_d$ but the $PVEP_d$. The relationship between these two parameters can be expressed as follows:

$$PVEP_d = PVPP_d \cdot (1 - F_s)(1 + \beta)Y_F \tag{8}$$

where F_S is the shading factor, and Y_F – the yearly final system yield [kWh/kWp] and $(1 + \beta)$ takes into account the gain which can arise if a cooling system is implemented.

Equations (1)-(8) allow us to estimate the land area necessary to install a PV system of a given power. In the next paragraphs we will focus on what changes between a land plant and a floating PV plant.

Suitability factor α_{sw} for floating PV plants

First of all, a general view of what is a floating plant can be useful. Even if it is a new emerging technology [8], many MW have been installed up to now and there is a quick expansion in the demand of new floating plants. These basins can be classified in several different types:
- Industrial basins (sand pits, mines, cooling basins etc) or wastewater treatment basins. In these cases, a full coverage (α_{sw} = 90-95%) is suggested, [9].
- Irrigation basins, pumping reservoirs. The solution can be very different but a coverage in the range α_{sw} = 30-60% is a good option, as shown in fig. 1 where Suvereto (Pisa, Italy) floating plant is shown through Google earth, [10].
- Hydroelectric basins, water reservoirs: in this case the artificial basins, equipped with power plants and already grid connected, can be very large. So the surface use can range from 5% to higher values but is strictly related to the activities induced by the large impact of the artificial basin on the hydrography and on the human activities connected.
- Natural lakes. In this case the use can range from 0-5% depending on the natural landscape and the environmental impact. Appropriate floating structures, with recreational activities, can be integrated advantageously but are strongly dependent on urbanization and human settlements around.

Figure 1. The PVF plant with tracking on the Suvereto (Italy) irrigation basin

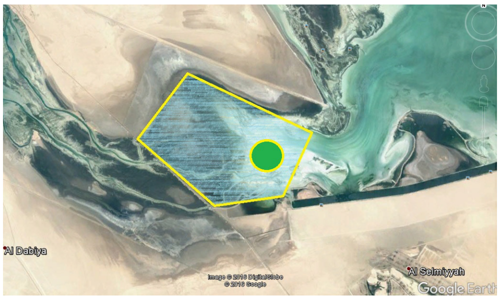

Figure 2. Surface suitable for FPV systems in Abu Dhabi (in green a possible FPV plant)

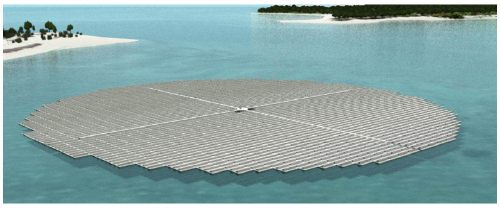

Figure 3. Lakshadweep (India) atoll with a floating plant installed

As far as sea water systems are concerned, there are several possible settlements and we should distinguish between low depth sea inlets or lagoons and off-shore systems.

– If we are in the presence of shallow water (*e. g.* Ijsselmeer basin in Holland or lagoons in the Emirates) the coverage can rise to 10% or more. Figure 2 shows a schematic project relative to a lagoon near Abu Dhabi where a limited surface (15 km^2) of a low depth lagoon deprived of any environmental or touristic interest is outlined and could be used for installing more than 1 GWp of floating PV plants.

– In other cases, such as atolls or low-depth sea near coastlines, it is necessary to consider the impact of waves and the proximity of electrical connections with the grid network. In these cases, the surface being practically unlimited, the size of the floating plant cannot be given as part of the available water surface but only based on ad hoc projects. See for example fig. 3 where an atoll is equipped with a floating platform in order to guarantee the energetic autonomy of the inhabitants.

Water surfaces availability

How extensive are the water surfaces suitable for PV worldwide? We have studied the main world areas and even if a myriad of small irrigation basins and water reservoirs are neglected, the numbers give an idea of the order of magnitude of the available water surfaces. Table 1 shows the values of fresh water surfaces, the installable PV power if only α_{SW} = 1% of these surfaces is used, and the potential energy production for extended regions worldwide in the temperate or equatorial areas [11, 12].

The choice of α_{SW} = 1% is quite arbitrary and is done only in order to get an idea of the possibilities of the floating solution. Further parameters have been used, as follows:

– starting from eq. (8) we have introduced a shading factor of 0% in the equatorial regions, of 5% for the temperate regions and of 10% for regions like Northern Europe and Canada,
– enhancement due to cooling system has been neglected,
– an efficiency η = 16% and a GSR = 0.95 have been used,
– the PF value of 0.8 has been chosen for all the latitudes, and
– finally a value of the yearly average radiation has been taken and values ranging from 1100 kWh/m^2 for Russia and Northern Europe to 1300 for the Middle East have been used.

With these parameters the potential energy is 6.069 TWh, a very high value which covers 25% of the full worldwide electric energy consumption, which in 2015 was 24,215 TWh [9].

The potential technical power is very large, notwithstanding the low value chosen for the parameter α_{sw}, and prompts out the necessity of a more precise evaluation taking into account the details of the available structures and the environmental conditions. We should also note that in these data small basins for irrigation and wastewater treatment are not taken into account. This is a typical case for some countries in a Middle East where the data of zero fresh water surface available corresponds to the absence of natural lakes (*e. g.* the Emirates) but where there are anyway large basins for wastewater treatment or water reservoirs.

Table 1. Technical PV potential in fresh water with α_{SW} = 1%

	Water surface	PVPP	PVEP
	[km^2]	[GWp]	[TWh/y]
Africa	540,030	657	780
America, Central	58,801	72	89
America, South	381,710	464	551
Asia, South-East	153,490	187	233
Asia, South - India	48,320	59	73
Australia	58,920	72	85
Canada	891,163	1,084	1,073
China	270,550	329	375
Europa, North	178,156	217	214
Europa, South	19,612	24	28
India	314,000	382	453
Japan	13,430	16	18
Middle East	140,190	170	222
Russia	720,500	876	867
Turkestan	76,110	93	106
USA	685,924	834	901
Total	4,550,906	5,534	6,069

Sea surfaces available for this purpose should be added to these values. Open ocean with large waves has to be avoided but there are many large basins of salt water. For example in fig. 2 we considered only a small part of the lagoons, whose surface, in Abu Dhabi for example, exceeds 500 km^2. A more important example is the Asian South-East where most of the population lives on houses floating on sea or on large river deltas and where many of the human settlements are based on shallow water areas. This rough estimate suggests that a detailed analysis, taking into account the different local conditions of fresh water available, is necessary. This analysis should also be extended to the salt water domain and in particular to lagoons, or to regions where urban settlements are mainly on water. This could add many other TWh to our list.

Floating PV structures and packing factor PF

There are many possible solutions for a FPV plant and these have been widely discussed in the literature [10]. All these solutions are characterized by the need to be as compact as possible in order to reduce the raft cost and to lower the final price for kWp installed and for kWh produced, so the packing factor of FPV plants is very often higher when compared to the land based solutions.

To give a definite example, we will refer to our own solution which consists in rafts built with polyethylene pipes and galvanized iron, supporting a series of panels with a slope which depends on latitude and on the two possibilities explored up to now: fixed system and

system with tracking [13]. This concept has been developed with the aim to optimize several aspects of the floating structure:
– modularity: large structures have to be built with components on land. Panels should be assembled directly on the raft before the launch,
– robustness: the raft should be built in such a way as to withstand a strong wind load and waves up to one meter. For this reason, we persist in using steel beams supported by large HDPE pipes,
– large size: compatible with logistic problems and useful for optimizing the assembly in water,
– simplicity of launching: the raft should be moved without need of cranes or complex systems, and
– minimum cost: the cost component is not completely defined due to the absence, for the moment, of scale economies, but it is a driving parameter in any case.

This concept is shown in fig. 4. The raft is about 12 meters long and is constituted by polyethylene pipes and galvanized steel beams which can be easily assembled in a suitable area near the basin. This solution has been carefully studied to minimize the costs while maintaining the required flexibility for the panel coupling. A solution for system with tracking where the 12-meter raft supports 8-9 panels with a 15° slope (or more) has been further developed, as well as a solution for fixed systems where the number of panels can be increased to 10-12 using a small slope of only 5-10°.

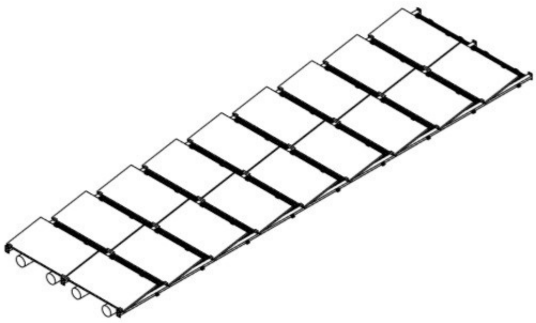

Figure 4. The PVF plant: a raft with catwalk

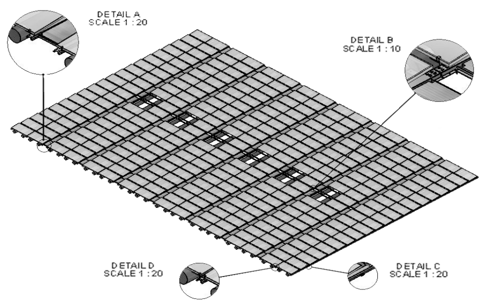

Figure 5. The PVF 100 kWp plant (Tiengeh project)

Figure 5 shows a 100 kWp FPV plant, realized in Singapore in the framework of the SERIS test bed project. To increase the PV packing factor, special solutions can be designed for the geometry of the array, such as the one reported in fig. 6, which is effective in water basins at latitudes lower than 23°.

This technique is aimed to optimize the PF, and the theoretical value should be compared with experimental findings. Unfortunately very few data are published in the literature, even if many papers describe technical solutions for rafts. The only systematic test recently done has been the one in Singapore by SERIS [14]: the scheme of the displacement of the 8 FPV plants installed in this test bed is shown in fig. 7, whereas in tab. 2 the surfaces and power of the 8 plants are given.

In conclusion the $PVPP_d$ can reach values ranging from 30 to 125 W/m^2. This should be compared with the values in [4] where values around 1 MWp/ha are suggested but where the

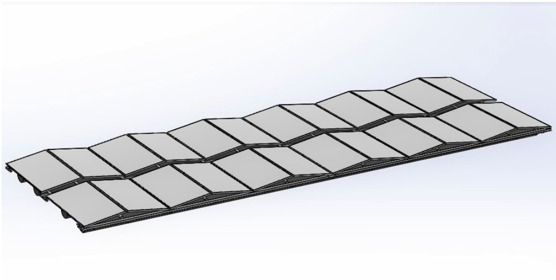

Figure 6. New concept of floating rafts for low latitude |lat| < 23°

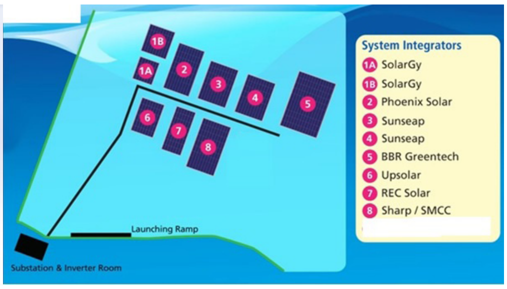

Figure 7. Floating PV plants displacement in Tiengeh (Singapore) [8]

data on real existing plants are always below 70 W/m^2. This is due to the fact that a floating plant is intrinsically more compact that a land based plant and on water we do not need all the infrastructures necessary on land for access to the PV field and for grass cutting and cleaning. The last line of tab. 2 summarizes the theoretical values for the new project shown in fig. 6 where the packing factor can reach values very near to the unity.

Table 2. Tiengeh surface and power of the 8 installations [8]

		A_{GEN} [m^2]	Modules (n)	Power [kW]	$PVPP_d$ (kWpm^{-2})
5	BBR GreenTech	3000	320	100	0.033
2	Phoenix	1028	384	99.84	0.097
7	Rec Germany	975	420	116.4	0.119
8	Sharp Solar	1228	374	100	0.081
1a	Solargy	676	180	51.2	0.076
1b	Solargy	484	180	51.2	0.106
3	SunSeap	1200	324	102.06	0.085
4	SunSeap	1200	324	102.06	0.085
6	Upsolar	788	308	98.56	0.125
	New project	788	384	122.88	0.156

FPV energy yield for different design of PV arrays

To maximize the PVEP, *i. e.* the yearly energy production of a FPV plant, we need to accurately design the layout of the PV array, which is normally deployed in sheds. The main geometrical parameters of sheds are: number of sheds (n_S), PV module width (Wpv), tilt, pitch, top and bottom inactive band. The area occupation is greatly dependent on the PV module tilt. For acceptable shadings, the limit shading profile angle, θ_{Sh}, should be kept below about 20°, whereas the minimum tilt should be some degrees (2-3°) for module cleaning by the rain. At this low tilt angle, the use of PV modules with frames can produce the accumulation of dirt and mosses on the bottom side. If the pitch increases (reduction of number of PV modules in a raft) and the tilt angle decreases, the losses due to shading can be reduced greatly. The shading losses are defined as the ratio between the yearly radiation that strikes the PV modules when they are in sheds and the radiation that strikes the modules when they are on a single plane (*e. g.* pure transposition).

To provide the numerical impact of the design choices on a real FPV plant, in fig. 8, a simulation for a 12 meter long raft structure, installed in Palermo (Italy), lat. 38.13° long. 13.34°, is reported: four cases are analyzed, that is 8 or 10 PV modules (which correspond to 8 or 10 sheds) and 5° or 15° tilt angle. The adopted PV module is a polycrystalline one whose dimensions are 1m width and 2 m length. This information is crucial for the evaluation of the electrical losses. This analysis is performed under the hypothesis of unlimited sheds so the effects of

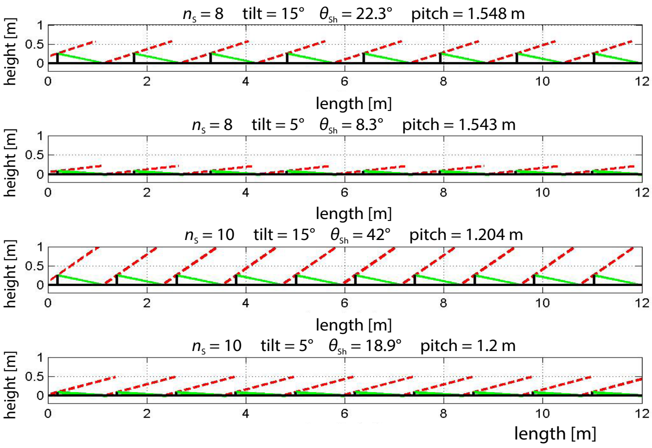

Figure 8. Shadow angle as function of number of PV panels (ns) and tilt angle

the lateral irradiation are neglected. Also the electrical effect of the shading is considered and in this regard the presence of three bypass diodes per PV module is considered as well. Actually, when there are 8 PV modules and the tilt angle is 5° the shading losses are very small, just 0.2% (there is no evident difference between irradiance and electrical losses). In fact during the year the shading effect will be present for few hours when the solar height angle is lower than 8.3°. If there are 10 panels, the shadow angle is 18.9° and this can bring the losses to 0.4% (0.5% electrical). The worst situation is with 10 PV modules and tilt angle of 15°, in this case the losses rise up to 3.9%, the sun limit angle to 41° and the electrical losses would be 6.42%. So the yearly electric energy production of the raft would be only 2% more than the production of a raft with all the modules in a horizontal position. To check the impact of position, two other sites are considered: Oslo (Norway), lat. 59.53° long. 10.41°, and Bamako (Mali), lat. 12.45° long. –7.48°. Table 3 reports the results of shading analysis for the 4 cases under consideration (8 PV modules at 5° and 15° tilt angle, and 10 PV modules at 5° and 15° tilt angle). For each case, three normalized annual energy values, with respect to the case when the PV modules are in horizontal position, are evaluated by means of the software PVSyst, using the Clear day model (this model only depends on the geographic coordinates and the air mass, *i. e*. the solar geometry). Therefore, you can calculate the values for any time:

– e_{PT} (PT – pure transposition. So all PV modules are supposed to be on one plane),
– e_{IL} (the Irradiance Losses are proportional to the shaded active surface, *linear shading*, and
– e_{EL} (electrical losses).

In tables 3 and 4, the variations of these quantities are given in percentage (referred to the horizontal displacement of PV modules). The $H_{y,h}$ and $H_{y,cs}$ are respectively, for a horizontal unitary surface, the yearly solar radiation and the solar radiation under clear sky model. It is worth noticing that in the case of 8 PV modules, apart from places very near the equator line (*e.*

Table 3. Analysis of the impact of pitch and tilt angle in three sites for shed configurations

				Oslo $H_{y.h}$ = 987 kWh/m² $H_{y.cs}$ = 1500 kWh/m²			Palermo $H_{y.h}$ = 1690 kWh/m² $H_{y.cs}$ = 2132 kWh/m²			Bamako $H_{y.h}$ = 2153 kWh/m² $H_{y.cs}$ = 2274 kWh/m²		
Config. name	Tilt [°]	n_S	Pitch [m]	e_{PT} [%]	e_{IL} [%]	e_{EL} [%]	e_{PT} [%]	e_{IL} [%]	e_{EL} [%]	e_{PT} [%]	e_{IL} [%]	e_{EL} [%]
Shed I-L	5	8	1.57	4.7	4.4	3.5	3.6	3.6	3.5	1.4	1.2	1.2
Shed I-H	15	8	1.57	12.7	9.7	7.5	9.1	9.1	7.5	2.4	1.2	0.8
Shed II-L	5	10	1.22	4.7	3.7	3	3.6	3.4	2.7	1.4	1	0.8
Shed II-H	15	10	1.22	12.7	6.2	3.1	9.1	5.5	2.9	2.4	0	–1.1

g. Bamako), it is always convenient to adopt a higher tilt angle (15°), as the smaller electrical losses are not compensated by the reduction of the incoming global radiation when the tilt angle is smaller.

Finally, the double shed configuration, that we name *gable*, proposed in section 5, is analyzed. The gable is made of 2 rows of 12 PV modules per raft, the raft will be east-west oriented. From the electrical point of view two strings made of 12 PV modules in series can be considered, each string groups the PV modules that have the same orientation. The geometry of the system is reported in fig. 9. The pitch between two consecutive modules that have the same tilt is 2.0 m.

Following the same approach used to get the results in tab. 3, another comparative analysis of four configurations of the PV array is reported in tab. 4. It is worth noticing that in Shed I-L and Shed II-H the PV modules are south oriented, whereas in Gable I and Gable II they are east (or west) oriented. Three new places are considered: Copenhagen (lat. 55.72°, long. 12.38°), Trapani (lat. 37.92°, long. 12.5°) and Khartoum (lat.15.6°, long. 32.55°). The gable configuration with lower tilt angle (5°) is surely less efficient than the Shed II-H, but in places at low latitude (such as Khartoum) it has an e_{EL} lower than just 3.2% compared with Shed II-H. On the other hand, the density of power (considering the raft area) for Gable I is 50% higher than Shed II-H and 20% more than Shed I. Approximately the same percentage can be considered for the energy density.

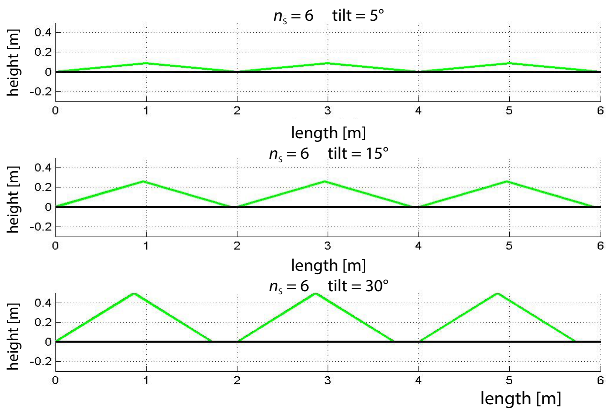

Figure 9. The FPV gable configuration for two possible tilt angles: 5° and 15°

Table 4. Comparative analysis of shed and gable configurations in three sites

				Copenaghen $H_{y.h}$ = 977.4 kWh/m² $H_{y.cs}$ = 1533 kWh/m²			Trapani $H_{y.h}$ = 1832 kWh/m² $H_{y.cs}$ = 2154 kWh/m²			Khartoum $H_{y.h}$ = 2227.6 kWh/m² $H_{y.cs}$ = 2362 kWh/m²		
Config. name	Tilt [°]	n_S	Pitch [m]	e_{PT} [%]	e_{IL} [%]	e_{EL} [%]	e_{PT} [%]	e_{IL} [%]	e_{EL} [%]	e_{PT} [%]	e_{IL} [%]	e_{EL} [%]
Shed I-L	5	10	1.22	4.8	3.3	2.9	4.3	3.5	2.9	2.2	1.7	1.7
Shed II-H	15	8	1.57	12.9	9.7	9.2	11.1	9.5	9.3	4.6	3.2	3.2
Gable I	5	6	2	0	0	0	0.1	0	0	0	0	0
Gable II	15	6	2	–0.2	–1.9	–2.1	–0.8	–2.1	–2.9	–1.1	–2.2	–3

Since the raft has not a negligible cost, the plant optimization will depend on the following parameters:

– raft cost compared with PV panel and CIT (cable, inverter, transformer) costs,

- latitude: in the equatorial region, a very low slope for panels is suggested whereas in the Mediterranean area a higher slope is preferable,
- fixed system or with tracking: the optimal slope is higher if we propose vertical axis tracking, and
- shadow angle: the reduction of solar radiation harvesting which is acceptable in a given plant.

The last point depends on both the technical solutions and the latitude. The electrical characteristic of PV modules is relevant: the presence of bypass diodes reduces the impact of power losses. Recently the distributed electronics (at the level of a single PV module) associated with modified PV modules (where all substring terminals are available in the connection box) offer a solution for the reduction of the impact of partial shadowing on the energy production of the string [15]. Notwithstanding these improvements, it is clear that the packing factor decreases at high latitude and the shadowing increases. These two effects, together with the lower solar irradiance at high latitudes have been taken into account in tab. 1.

Conclusion

The large spread and use of PV systems of the last years indicate that we have only just begun to explore the potentialities of such technology. Although over one century has passed since Einstein's interpretation of the PV effect (Einstein, 1905), its implementation has not yet reached its maturity. The enormous need for renewable energies (especially PV), and the strong and vocal approach of opinion-makers have pushed the market towards more trivial and simple solutions: roof and flat lands. These solutions are important but intrinsically limited and inadequate to take up the challenge of climate change, air pollution, and the depletion of stocks of fossil fuel. The high compact factor and the unlimited availability of water surface (fresh water or salt water) suggest that the transition to floating plants in the PV technology scenario can have a dramatic impact on RES and can be the winning solution in the next few years. We are convinced that such a transition can increase the impact of solar PV to a double-digit percentage of the total electricity production. The new PV systems will be floating, located near urban areas, integrated and equipped with appropriate storage systems: they will merge smoothly into the existing structures with a minimum environmental impact.

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