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Sun-Spotter: Gravity point displacement as solar-tracking principle

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Abstract
This paper focuses on the design and construction of a floating dual axis solar tracking device. The dynamic floating object is based on a concentrated photovoltaic technology (CPV) with a synclastic mirror facing the incoming sunlight to a photovoltaic element. The dynamic CPV is connected to a kinetic submerged object by four cables. The submerged object suspends below the floating CPV. It is equipped with a water displacement mechanism which creates gravity point displacement, causing the floating object to tilt. In this way the floating CPV is able to follow the path of the sun like a dual axis solar tracker. The measuring of the most optimal angle of the incoming light is regulated by four LDR’s. They are connected to an Arduino-programmed control system driving the water pumps and bringing the floating CPV in the most optimal tilt towards the incoming light.

Keywords: Concentrated photovoltaics (CPV), floating dual axis solar tracker, gravity point displacement, buoyancy, reflective mirror, ETFE membrane, membrane pump, Arduino, four-bar linkage, kinetic cable structure.

1. Introduction
Solar tracking is an increasingly important optimization measure within the world of solar energy. It eventually leads to material reduction and higher efficiency, which makes it a logical step towards sustainable development. Depending on various factors, single axis- tracking or dual- axis tracking can be implemented. Application of these systems, can result in an additional energy yield between 13% and 48%. The most efficient situation is achieved, when the solar panel is perpendicular to the
sun at any given moment of the day if the sun shines. On a cloudy day the tracking of the most incoming light can deviate from the angle of the sun to the altitude.

Increasing land scarcity caused by overpopulation and global warming are two of the biggest problems confronting the world. Countries like Japan, China, India and Bangladesh are battling with these problems. Photovoltaic (PV) energy can help against global warming but needs a huge amount of land. For instance, a PV power plant needs 1 km² for every 20-60 megawatts (MW). For countries with a high population and limited land this is hardly an option. [1]

Efficiency of solar panels is highly dependent on the surface temperature of the panels. Research has proved that the efficiency PV is inversely proportional to its temperature. [2] A typical value for PV efficiency loss with temperature is 0.5% / °C [3]. Generally, passive or active cooling of the panels leads to higher efficiency. Passive cooling requires less energy, but is also less sufficient. Active cooling gives better results, but uses more energy.

Floating solar systems cope with both land scarcity as well as temperature problems. Water has excellent cooling properties, especially when the panels are close to the water. The system can maintain a low operating temperature.

The reflective properties of the water surface also have a positive side effect on the energy output of the PV. Another added value of floating solar systems is that the external forces including the self-weight is supported by the displacement of the structure in the water. Based on the weather and wave conditions of the venue the support structure of the PV elements might be smaller compared to land-based systems. [4]

2. Solar Energy
2.1. Floating solar (tracking) systems
Floating solar systems combines PV plant technology and floating devices. It is a relatively new development can give an alternative for space-consuming land-based systems. Different scale fixed mount projects have been realized, located on irrigation ponds and reservoirs, with the additional intention to decrease evaporation of water. [5]
The orientation of the solar cells is essential for the efficiency of the system. Misalignment is the main reason for output losses. A deviation of 10°degrees initially results in a 2% output loss. A deviation of 20° gives a loss of 10%. A higher deviation will, however, result in more significant losses. The tracking itself, can be done in two ways: by optical sensing and by calculated positioning system. Optical sensing is done through LDR resistors and it is the most precise method when the sky is clear. Cloudy skies, dirt and reflectance of the surrounding decrease the efficiency of optical sensing. Optical sensing functions through light intensity. Unevenly divided or changing light intensity can cause irregular behaviour of
the sensor, which results in constant movement and efficiency loss. A calculated positioning system uses fixed data to direct the panels. Outside influences have no impact on this system. Dual-axis tracking makes it possible to achieve the same output, with less solar cells. The efficiency gain of dual-axis trackers compared to fixed mount systems can even reach 48% [6].

Floating dual-axis solar trackers require less weight and no heavy support structure, because of the buoyant force of the water. This kind of floating PV plants consist of floating system, mooring system, PV units and underwater cables. Furthermore, the increased efficiency of floating PV plants is strongly reinforced through the cooling effect of the water. A 100 kW plant was realized in Hapcheon, Korea. It has a fixed tilt of 33° and consists of 414 240 W modules. This system was compared to a bigger, land-based system of 1 MW in Haman-gun, 60 km from Hapcheon. The power output of the 1 MW plant was converted to the Hapcheon 100 kW. As the result, the coefficient of utilization of the 100kW and 1MW were 17.6% and 15.5% respectively, which means that Hapcheon 100kW floating PV system’s value is 13.5% higher than that of Haman 1MW system.[5] The results of the test are shown in figure 2. The upgrade to floating solar trackers naturally gives even higher power outputs. Different solar tracking projects have been realized and have generated higher outputs, even reaching up to 60%. The company Pyron solar introduced a dual-axis floating solar tracker, combined with a Fresnel lens-based CPV technology. The system has an additional module efficiency of 22%.

2.2. Concentrated photovoltaics (CPV)

“The key principle of CPV is the use of cost-efficient concentrating optics that reduces the area of expensive, high efficiency cell required, potentially allowing for a competitive levelized cost of electricity (LCOE) compared to Concentrated Solar Power and standard flat-plate PV technology in certain sunny areas.” [7]

The general division of CPV systems, according to the concentration level:

i) High concentration (>300 X, HCPV) point-focus systems with highly efficient III–V cells (>35%) and with a high specific cost.

ii) Low or medium concentration (2–60 X) with silicon cells of up to 20–22% efficiency and at low cost.

CPV optics can be divided into reflective and refractive. This project uses a low concentration reflective technology, in the form of a paraboloid.

The choice of using reflective, instead of refractive is based on the scale of the project and the product development of the mirror. Even more important is the fact that the tracking with the reflective
technology is less complicated. Perhaps the main reason to use CPV is that it requires less material to generate more energy. The surface area of the Si solar cells, used in CPV systems, is drastically lower than with regular PV systems.

3. **State of the Art of Floating Solar Trackers**

Compared to fixed mount projects, the amount of floating solar tracker projects is significantly lower.

**3.1. Single axis solar tracker, Petra Winery project (Italy), Terra Moretti Holding**

The 200 kW Petra Winery project was designed by the Terra Moretti Holding in conjunction with the company SCINTEC, which was responsible for the tracking system. It is a structure almost entirely made of metal struts, with hollow buoyant elements underneath. The structure was designed to hold the crystalline panels at an optimal angle of 40°, while tracking the solar motion. [9]

The tracking is realized through rotational movement of the platform. A central vertical column is rotating the platform. Inside of this column, a horizontal slew drive is located, which rotates the platform.

**3.2. Single-axis solar tracker, Lake Colignola (Italy), Terra Moretti Holding.**

A second similar project was realized by the same company at Lake Colignola, Italy in 2011. It was a smaller scale project, 30 kWp, with the same rotation principle as the Petra Winery. Interesting aspect of this project is the utilization of mirrors to reflect additional solar radiation onto the panels. Another difference is that the panels are placed horizontally, and the mirrors under an angle of 60° and -60° with the expectation to double the amount of solar radiation falling onto the PV panels. In combination with the cooling effect of the water, an annual increase of 60% - 70% was documented during the tests.

**3.3. Single-axis solar tracker, Sunflower Plant, Hapcheon (South-Korea), Solarpark**

Figure 6: Sunflower plant in Hapcheon, South-Korea by the company SolarPark [10].
The biggest floating solar tracker yet, is the Sunflower plant in Hapcheon, South Korea. The Korean company SolarPark created a floating power plant which covers 8000 m² and produces 465 kWp. Once again the movement method is rotational slewing drive, located in the centre of the platform. According to the company, the system uses a very small amount of energy exclusively to run the rotation mechanism. [9]

3.4. Dual-axis solar tracker, Liquid Solar Array, Australia, Sunengy

A floating solar tracker project, based on a different type of dynamics, is the Liquid Solar Array (LSA) by the company Sunengy from Australia. A very innovative and unique pilot project, which uses very light plastic concentrators, mounted on anchored rafts. A thin plastic concentrator lens rotates to track the sun, daily and seasonally. In this case, the concentrators are moving simultaneously and the supporting structure is static. Collectors rotate tracking the movements of the sun by both a light sensor and a pre-programmed path. A minimal amount of silicon (or other types of) photovoltaic cells are housed in a PV container that sits in the water where the cells are kept cool and efficient, through convective heat flow to the surrounding water. During bad weather, every unit has the ability to protect the lens by rotating and submerging under water. A wind sensor is connected to the sun tracking software to submerge each unit into the water should winds rise above a predetermined force and return the lens to its tracking position once the winds have abated. [11]

It is a very promising project, tested in more than 10 countries, focusing on benefits such as low material use and high energy output. One of the test locations is India, where a 1.2 m² fresnel lens per unit was implemented. The company claims to have achieved a 230 W of electrical output per single unit.
3.5. Dual-axis, CPV technology, San Diego (USA), Pyron Solar

In 2004 the company Pyron Solar designed a double-axis floating solar system based on a CPV principle. A rotating platform with solar modules, also capable of tilting to a variable angle. It is a 90 kWp DC CPV generating system with dual-axis solar tracking. It includes three, ideally spaced, 30 kWp DC arrays 15 m in diameter, all floating in water. A prototype was developed, but the product never reached commercial level. [12]

3.6. Conclusion SOTA

After analyzing the state of the art of the floating solar trackers, it becomes clear that most systems are pilot systems on a utility scale, located on calm water surfaces such as reservoirs and ponds. Each project consists of multiple arrays of PV modules. These modules are generally placed on a rotating platform and are using single-axis tracking. The rotation of this type of platforms around a mechanical pivot is beneficial in terms of the amount of PV modules that can be used, as up- and downscaling is possible.

The downside of these systems is that they are mostly suitable for calm water surfaces and most of them have a static position in the vertical direction. Water level fluctuation and changes in the overall water dynamics, could result in damage and efficiency decrease. Another restriction is the fact that the single-axis tracking nature of these systems does not result in less material being used.

From these limitations, the idea of the Sun-spotter has emerged. It is based on the following conditions:

- Applying dual-axis tracking through vertical movement;
- Downscaling of the system to a modular size;
- Increasing the efficiency and decreasing the amount of material used;

The configuration of this new system will be covered herinafter.

4. Tracking with Gravity Point Displacement

4.1. Structures & balancing

4.1.1. Form stability of floating objects

The metacentric height (GM) is a measurement of the initial static stability of a floating body. It is calculated as the distance between the centre of gravity (G) of a floating object and its metacentre (M). The center of Buoyant (B) moves as the object is tilted. Because the system is floating the structure has upward pressure preventing it from sinking and if the weight is corresponding with the upwards forces creating a stable position and depth. The buoyancy [13] of the floating body depends on the weights and the density of the fluid. A larger metacentric height implies greater initial stability against overturning.
The stability of a floating body is influenced by the shape of the body. In a rectangular object the metacentric height increases in the beginning. At a certain angle it becomes lower as the body is tilted further more. This is called “form stability”. 

In case of circular or spherical objects the measurement of metacentric height is fixed for all angles. The further the floating body is turned over, the bigger the distance between gravity point and the vertical M-B line. The bigger the distance of G to the MB line, the higher the force to turn over the floating body. In case the M, G and B point are close to each other, the tilting of the object becomes almost without any resistance. For the Sun-Spotter a half sphere is ideal because the center of buoyant and the meta center will be at the same vertical centerline of the sphere. The center of gravity will also be at the same line and has to be under the metacenter to avoid falling over. By adding an extra load at the bottom of the sphere the gravity point can be lowered to increase the stability of the sun-spotter if necessary.

4.1.2. Underwater structure – Kinetic cross
Under the floating sun-spotter hangs a suspended kinetic cross in the water. The cross is connected with four cables to the floating sun-spotter. The cross is moving based on the displacement of the weights between the four spheres. To keep the cross horizontal in the neutral position the fluids and dead load of the cross have to be evenly divided over all containers; only a small difference causes the structure to tilt. The air will automatically divide itself because the containers are all connected on top. To achieve a limited tension in the cables the cross was designed to be almost weightless in the water. (see figure). Underwater the air inside the spheres will give upthrust; this has to be almost equal to the gravity from the mass of the
4.1.3 Kinetic nature of the structure

From a purely kinetic point of view, the structure behaves according to the four-bar linkage principle. It consists of four bodies, called “bars” or “links”, connected in a loop by four joints. Generally, the joints are configured so the links move in parallel planes, and the assembly is called a “planar four-bar linkage”. [14]

Because of the equal length of the ‘bars’ and ‘links’ parallel movement, the structure belongs to the parallelogram configuration. Maintaining the parallelism is essential for the solar tracking properties of the structure.

In this configuration, the cables function as struts with tensile load. This tensile load is created by the weight of the submerged cross. The buoyant force of the floating part of the structure prevents the structure from sinking and partially enables the movement of the upper link (q). The anchor point functions as a fixed link and a tipping point. The cables are connected with the upper and lower link, through a sliding joint. These sliding joints are lying in two plane surfaces, perpendicular to each other, connected to the main hinge point. This makes movement in the xz and yz direction possible. The upper q and the lower link l vary in length, 1480 and 1740 mm. Links s and p have the length of 1000 mm. This results in only horizontal parallelism, needed for the tracking application of the object. Because of the deviant composition of this four-bar mechanism, it cannot be classified as a regular drag-link connection.

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4.2 Gravity point displacement method
Tracking the sun is done by a direct interaction of the underwater cross and the floating structure. Every action that is performed under water directly steers the floating structure in the same direction. There is a direct connection between the gravity point under the water surface and above the water surface. A small displacement in the movement cross directly tilts the floating structure in the same direction.

The needed components are four containers, half-filled with water or other liquids and air that are connected in pairs with two two-directional or four one-directional pumps in between. The containers also have to be connected from top to top to transport the air and to prevent high pressures in the spheres. This is the base of the system. The technique to move the gravity point is fairly simple, moving the fluids/weights from balanced to the desired tilted position, corresponding with the angle of the sun to the altitude.
Moving the weights is a continuous interaction between pumping water and a corresponding flow of air. Between the containers preventing the pumps from creating high pressure (uses more power) and creating up thrust on the inverse side.

The water in the four containers moves in the X and in the Y-direction, so as the air. This interaction makes the containers move separately in the Z-direction, making the cross tilt and therefore tensioning the cables and tilting the floating structure in the same direction.

The movement of the Sun-Spotter is based on two different parameters. Together these parameters define the angle of which the Sun-Spotter will tilt.

- **Rotational points:**
  - O1: The radius of the spherical part of the Spotter make the rotational point, this point stays in place when the Spotter tilts.
  - O2: The rotational point is the lowest point of the center. This is where the cross is attached to an anchor cable.

- **Center of gravity / gravity point:**
  - CG1: This point represents the center of mass of the floating structure and is the balanced middle point of all weights that are attached to the structure.
  - CG2: When all containers are filled evenly the gravity point is in the middle of the movement cross.

- **Angles in °:**
  - \( \alpha \): The angle of the floating structure.
  - \( \beta \): The angle of the movement cross.
Displacing the gravity point is a direct interaction between the center of gravity (CG) and rotational points (O) underwater and above water. Moving fluid underwater displaces the gravity point/center of gravity (CG2) and makes the cross tilt around the rotational point (O2). Corresponding to this displacement, the gravity point of the floating structure (CG1) also directly follows the displacement of the movement cross gravity point, resulting the floating structure to tilt around the rotational point (O1). This means that CG1 and CG2 of both the movement cross and the floating structure are always directly above each other while the only one that is controlled is the one underwater (see figure). Due to this the angle that the movement cross creates (α) is equal to the angle that the floating structure creates (β).

6. Prototyping Sun-Spotter

The Sun-Spotter [16] consists out of two components; the floating structure and the underwater structure combined with a smart electronic system.

For the prototype the floating part is made out of a rounded polyester bowl with steel attachment eyes, right above the rounded part to prevent the cables from touching the polyester when tilting and to prevent from tilting too far. The top part is made out of RVS and aluminum to keep the top lightweight.

To control the tracking an Arduino-programmed system was developed. This system tracks the sun with a light sensor consisting of four LDR’s (light-dependent resistor) corresponding with the four membrane pumps. When one LDR has a lower resistance the voltage will change and the corresponding pump will be activated by the software programmed on the Arduino until every LDR is equally lighted.
7. Conclusion
After analyzing the state of the art of floating solar trackers, it can be concluded that most of the systems are based on a rotational movement. This movement is created mechanically through slew drives. The Sun-spotter distinguishes itself from other systems, through the type of movement that it uses. Displacing the gravity point to create movement is ideal for tracking the sun. Another achievement of the Sun-spotter is the combination of the CPV technology, which requires less solar cells to generate more power.

This floating kinetic sun-tracker based on the four-bar linkage system combines the positive properties of different systems such as:

- It is applicable as long as there is water;
- Low-energy use for tracking due to integration of natural laws such as gravity and buoyancy;
- The fact that it can have a large tilt angle makes the Sun-Spotter applicable in northern regions up to 60 degree northern latitude;
- It is a simple and efficient technology;
- The CPV technology, requires less solar cells to generate more power;
- Dual-axis solar tracking is the most efficient way to generate sun power;
- The availability of water gives the opportunity to cool the PV cells.

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