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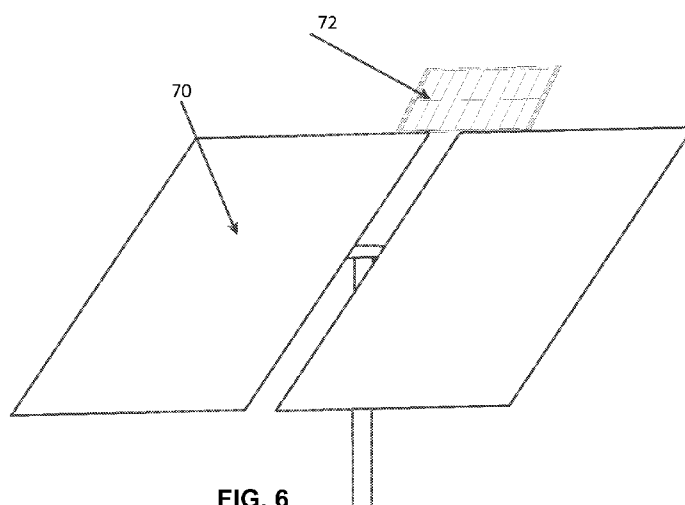


FIG. 6

(57) Abstract: Shading by clouds can affect the amount of flux on a heliostat which in turn can affect the energy generated by the solar device. Real-time monitoring of clouds shading is necessary for efficient operation of the entire solar power system. The output of a photo-sensitive panel attached to a heliostat may be measured in direct unhindered sunlight and at a first orientation. The output of the photo-sensitive panel may then be predicted for a second orientation. Upon measuring the actual output of the photo-sensitive panel at the second orientation, a communication function may be performed when output measured at the second orientation of the panel is below or above the predicted output. A reduced-insolation event is indicated by lower-than-predicted output at the second orientation. Upon indication of a reduced-insolation event, the heliostats may be controlled, i.e., the aiming directions for one or more of the heliostats may be changed.



**METHOD AND APPARATUS FOR OPERATING A SOLAR
ENERGY SYSTEM INCLUDING MONITORING OF CLOUD SHADING**

CROSS-REFERENCE TO RELATED APPLICATIONS

5 The present application claims the benefit of U.S. Provisional Application No. 61/674,630, filed July 23, 2012, which is hereby incorporated by reference herein in its entirety.

FIELD

10 The present disclosure relates generally to solar energy systems, and, more particularly, to operating a solar energy system to monitor for cloud shading.

SUMMARY

15 In a field of heliostats, shading by clouds can affect the amount of flux on a heliostat which in turn can affect the energy generated by the solar device. Real-time monitoring of cloud shading of at least some of the heliostats can allow for more efficient operation of the entire solar power system. Where it is desired to know what the weather conditions are within a large geographic region (e.g., cloud cover over the geographic area) a weather station may be provided in or near the large region. However, weather conditions predicted by the weather station may not be indicative of the path of a cloud that shades only a part of the large area.

20 In some embodiments, a method of operating a solar energy system having a field of heliostats, may include: (i) measuring the output of a photo-sensitive panel attached to a heliostat when the panel is in direct unhindered sunlight and at a first orientation; (ii) predicting the output of the photo-sensitive panel at a second orientation; (iii) measuring the output of the photo-sensitive panel at the second orientation; and (iv) performing a communication function
25 when output measured at the second orientation of the panel is below or above the predicted output. The communication function may include: creating an alarm, communicating data to at least one of a control system and an operator, and recording the data or the alarm. The second orientation is the same or different orientation as the first orientation, but when the sun's position has changed. The difference between predicted and measured output may occur when
30 there is cloud cover. Alternatively, or additionally the difference between predicted and measured output is a function of a parameter of a cloud.

35 The method may further include the steps of monitoring decreased output across the field of heliostats; and in response to the monitoring, optimizing the solar field parameters. The solar field optimization may include changing an aiming direction of at least one heliostat. Further, the movement of the cloud over the solar field may be predicted in response to said monitoring.

In some examples, the photo-sensitive panel is a photovoltaic cell panel or a photochemical panel. The photo-sensitive panel may be used to generate electrical energy to a drive system that orients the heliostat when sun-tracking. In some embodiments, at least a portion of the generated electrical energy is stored in a storage device. The storage device may be a battery or a capacitor. The calibration of the photo-sensitive panel may be accomplished through the use of imaging devices, or through the use of insolation measuring devices

In some embodiments, a heliostat may include: (i) at least one mirror; (ii) at least one drive system; (iii) at least one electrochemical cell configured to provide motive power for the heliostat drive system; (iv) a plurality of photovoltaic or photochemical cells configured to generate electricity to be used to charge the electrochemical cell; and (v) a controller. The controller may be configured to receive a value of an electrical output of the photovoltaic or photochemical cell and calculate the amount of shadowing caused by clouds on the mirror. The controller may be additionally configured to calibrate the orientation of the heliostat based at least in part on the value of an electrical output of the photovoltaic or photochemical cell.

In some embodiments, a method of operating a solar energy system having a field of heliostats, may include: (i) controlling a plurality of heliostats to track the apparent movement of the sun to reflect incident solar radiation on a receiver; (ii) calculating an electrical output of a photosensitive panel and generating a signal indicating a current or impending transient reduced-insolation event; (iii) receiving a signal indicating a change in insolation; (iv) calculating, responsively to the signal, characteristics of a current reduced insolation event or of an impending transient reduced-insolation event; and (v) controlling the plurality of heliostats in response to the calculated characteristics of the reduced-insolation event. In response to the calculated characteristics of the reduced-insolation event the controlling may include changing an aiming direction of at least one heliostat.

Systems and methods for operating a solar energy system to monitor for cloud shading of a solar receiving system are described. At least one photosensitive panel may be attached, or otherwise associated with, at least one solar reflective surface, i.e. a heliostat. Examples of photosensitive panels may be but are not limited to a photovoltaic panel, a photochemical panel, photodiodes and a pyranometer.

According to some embodiments, photosensitive panels are used to power the movement and/or communications of the heliostats either directly or by charging an electrochemical cell such as but not limited to, a battery and a supercapacitor which power the heliostat. Terms such as battery or supercapacitor are used interchangeably herein and may mean any electrical storage apparatus including chargeable chemical storage, mechanical storage such as flywheel or pressure tank, and other means.

Sun-tracking by a heliostat may be enabled by at least one drive. In some embodiments movement of the heliostat is enabled with one drive having one degree of freedom, in which case a maximum output level of a photosensitive panel is sought for calibration within the range of movement afforded by the one degree of freedom without necessarily directly facing the sun.

- 5 In some embodiments, the moving elements of a solar receiving system are driven by two or more drives. Two drives in embodiments are an azimuth and an elevation drive.

According to some embodiments, cloud cover causes a decrease in output level of a photosensitive panel, which causes a decrease in an electrical output parameter from the photovoltaic panel. An electrical output parameter can be, for example, voltage, current, power,
10 power per unit of area, or any other value that can be used to represent a respective output level of a photosensitive panel. The decrease can be analyzed to determine a shading parameter. Based on the shading parameter, an operating parameter of the solar energy system can be changed or maintained. For example, the operating parameter may include aiming directions for one or more of the heliostats. Cloud characteristics in addition to the location of the cloud
15 shadow can be used in determining the shading parameter. Such characteristics can be used in determining if and/or how to change the operating parameter of the solar energy system. As a cloud moves over a field, the decrease in an electrical output parameter moves from one heliostat to another. Conversely, when the output of a photosensitive panel on a particular heliostat increases, for example, to a predicted amount then a cloud is no longer shading a
20 heliostat. If there is a further decrease in an electrical output parameter, then this may be indicative of a thicker cloud or a denser part of the same cloud being overhead of the heliostat. The decrease or increase in the output of a photosensitive panel across at least part of the field can be used to predict the movement of a cloud(s) over other parts of the field. According to some embodiments, the difference between predicted and measured output is a function of a
25 parameter of a cloud.

According to some embodiments, heliostats are aimed in response to instructions generated by a control computer and transmitted to the heliostats through a communication system. The aiming instructions and the optimization methods used to generate those instructions can be responsive to the cloud data obtained through the methods and apparatus
30 disclosed in any of the embodiments herein. This responsiveness may include causing a heliostat to move from an aiming point not on a receiver to an aiming point on a receiver, from an aiming point on a receiver to an aiming point not on a receiver, from one aiming point on a receiver to another aiming point on the same receiver, or from an aiming point on one receiver to an aiming point on another receiver.

A controller may be configured to receive a measured value for an electrical output of the photosensitive panel and use that value in determining the extent to which direct solar radiation potentially impinging on the at least one heliostat is blocked by clouds. The measurement of an electrical output parameter may be obtained, for example, through an electrical connection between the photosensitive panel and a storage medium such as a supercapacitor, or by use of an additional connection such as a shunt current. The controller may additionally be configured to receive a measured value for an electrical output of the photovoltaic or photochemical cell and to use that value to calibrate the heliostat at least once during the installed life of the heliostat.

According to embodiments, the cloud detection and prediction method can be used in conjunction with devices which measure insolation, and/or imaging devices and/or weather information.

Objects and advantages of embodiments of the present disclosure will become apparent from the following description when considered in conjunction with the accompanying drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

Embodiments will hereinafter be described with reference to the accompanying drawings, which have not necessarily been drawn to scale. Where applicable, some features may not be illustrated to assist in the illustration and description of underlying features. Throughout the figures, like reference numerals denote like elements.

FIG. 1 shows a solar power tower system, according to one or more embodiments of the disclosed subject matter.

FIG. 2 shows a solar power tower system with secondary reflector, according to one or more embodiments of the disclosed subject matter.

FIG. 3 shows a solar power tower system including multiple towers, according to one or more embodiments of the disclosed subject matter.

FIG. 4 shows a solar power tower system including multiple receivers in a single tower, according to one or more embodiments of the disclosed subject matter.

FIG. 5 is a schematic diagram of a heliostat control system, according to one or more embodiments of the disclosed subject matter.

FIG. 6 shows a heliostat with a photovoltaic panel, according to one or more embodiments of the disclosed subject matter.

FIG. 7 shows a solar power tower system with overhead clouds, according to one or more embodiments of the disclosed subject matter.

FIG. 8 shows a solar power tower system with a portion of the heliostat field shaded by one or more clouds, according to one or more embodiments of the disclosed subject matter.

5 FIG. 9 shows a later view of the solar tower system of FIG. 8 where a portion of the heliostat field is shaded by one or more clouds, according to one or more embodiments of the disclosed subject matter.

10 FIG. 10 shows a later view of solar tower system of FIGS.8-9 where another portion of the heliostat field is shaded by one or more clouds, according to one or more embodiments of the disclosed subject matter.

FIG. 11 shows an aerial view of a cloud shadow at a first time moving across a heliostat field with multiple solar towers, according to one or more embodiments of the disclosed subject matter.

15 FIG. 12 shows an aerial view of a cloud shadow at a second time moving across a heliostat field with multiple solar towers, according to one or more embodiments of the disclosed subject matter.

FIG. 13 shows the calibration of a heliostat using a photosensitive panel according to one or more embodiments of the disclosed subject matter.

20 DETAILED DESCRIPTION

A central receiver system, such as one with a receiver supported on a tower, can include at least one solar receiver and a plurality of heliostats. Each heliostat tracks to reflect light to a target on a tower or an aiming point on such a target. The heliostats can be arrayed in any suitable manner. For example, heliostat spacing and positioning can be selected to
25 provide optimal financial return over a life cycle according to predictive weather data and at least one optimization goal, such as total solar energy utilization, energy storage, electricity production, or revenue generation from sales of electricity.

Insolation can be used by a solar tower system to generate superheated steam and/or supercritical steam and/or to heat molten salt. In FIG. 1, a solar tower system can include a
30 solar tower 50 that receives reflected focused sunlight 10 from a solar field 60 of heliostats (individual heliostats 70 are illustrated in the left-hand portion of FIG. 1 only). For example, the solar tower 50 can have a height of at least 25 meters, 50 meters, 75 meters, 100 meters, 125 meters, or higher. The heliostats 70 can be aimed at solar energy receiver system 20, for example, a solar energy receiving surface of one or more receivers of system 20. Heliostats

70 can adjust their orientation to track the sun as it moves across the sky, thereby continuing to reflect sunlight onto one or more aiming points associated with the receiver system 20. A solar energy receiver system 20, which can include one or more individual receivers, can be mounted in or on solar tower 50. The solar receivers can be constructed to heat water and/or steam and/or supercritical steam and/or any other type of solar fluid using insolation received from the heliostats. Alternatively or additionally, the target or receiver 20 can include, but is not limited to, a photovoltaic assembly, a steam-generating assembly (or another assembly for heating a solid or fluid), a biological growth assembly for growing biological matter (e.g., for producing a biofuel), or any other target configured to convert focused insolation into useful energy and/or work.

The term "receiver," by itself, is used herein to refer to the portion of the device targeted by the receiver which captures and converts incident flux to heat and which are actively cooled by a heat transfer or working fluid as opposed to portions that are primarily reflective or simply used to re-radiate or convect heat such as thermal tiles or refractory shades. The receiver may be the aggregate of concentrated light-receiving portions of a boiler, heat exchanger, superheater, or other device used for converting sunlight to heat in a fluid.

The solar energy receiver system 20 can be arranged at or near the top of tower 50, as shown in FIG. 1. In another embodiment, a secondary reflector 40 can be arranged at or near the top of a tower 50, as shown in FIG. 2. The secondary reflector 40 can thus receive the insolation from the field of heliostats 60 and redirect the insolation (e.g., through reflection) toward a solar energy receiver system 20. The solar energy receiver system 20 can be arranged within the field of heliostats 60, outside of the field of heliostats 60, at or near ground level, at or near the top of another tower 50, above or below reflector 40, or elsewhere.

More than one solar tower 50 can be provided, each with a respective solar energy receiving system thereon, for example, a solar power steam system. The different solar energy receiving systems can have different functionalities. For example, one of the solar energy receiving systems can heat water using the reflected solar radiation to generate steam while another of the solar energy receiving systems can serve to superheat steam using the reflected solar radiation. The multiple solar towers 50 can share a common heliostat field 60 or have respective separate heliostat fields. Some of the heliostats can be constructed and arranged so as to alternatively direct insolation at solar energy receiving systems in different towers. In addition, the heliostats can be configured to direct insolation away from any of the

towers, for example, during a dumping condition. As shown in FIG. 3, two solar towers can be provided, each with a respective solar energy receiving system. A first tower 50A has a first solar energy receiving system 20A while a second tower 50B has a second solar energy receiving system 20B. The solar towers 50A, 50B are arranged so as to receive reflected solar radiation from a common field of heliostats 60. At any given time, a heliostat within the field of heliostats 60 can be directed to a solar receiver of any one of the solar towers 50A, 50B. Although only two solar towers with respective solar energy receiving systems are shown in FIG. 3, any number of solar towers and solar energy receiving systems can be employed.

More than one solar receiver can be provided on a solar tower. The multiple solar receivers in combination can form a part of the solar energy receiving system 20. The different solar receivers can have different functionalities. For example, one of the solar receivers can heat water using the reflected solar radiation to generate steam while another of the solar receivers can serve to superheat steam using the reflected solar radiation. The multiple solar receivers can be arranged at different heights on the same tower or at different locations (e.g., different faces, such as a north face, a west face, etc.) on the same tower. Some of the heliostats in field 60 can be constructed and arranged so as to alternatively direct insolation at the different solar receivers. As shown in FIG. 4, two solar receivers can be provided on a single tower 50. The solar energy receiving system 20 thus includes a first solar receiver 21 and a second solar receiver 22. At any given time, a heliostat 70 can be aimed at one or both of the solar receivers, or at none of the receivers. In some use scenarios, the aim of a heliostat 70 can be adjusted so as to move a reflected beam projected at the tower 50 from one of the solar receivers (e.g., 21) to the other of the solar receivers (e.g., 22). Although only two solar receivers and a single tower are shown in FIG. 4, any number of solar towers and solar receivers can be employed.

Heliostats 70 in a field 60 can be controlled through a central heliostat field control system 91, for example, as shown in FIG. 5. For example, a central heliostat field control system 91 can communicate hierarchically through a data communications network with controllers of individual heliostats. FIG. 5 illustrates a hierarchical control system 91 that includes three levels of control hierarchy, although in other implementations there can be more or fewer levels of hierarchy, and in still other implementations the entire data communications network can be without hierarchy, for example, in a distributed processing arrangement using a peer-to-peer communications protocol.

At a lowest level of control hierarchy (i.e., the level provided by heliostat controller) in the illustration there are provided programmable heliostat control systems (HCS) 65, which control the two-axis (azimuth and elevation) movements of heliostats (not shown), for example, as they track the movement of the sun. At a higher level of control hierarchy, heliostat array control systems (HACS) 92, 93 are provided, each of which controls the operation of heliostats 70 (not shown) in heliostat fields 96, 97, by communicating with programmable heliostat control systems 65 associated with those heliostats 70 through a multipoint data network 94 employing a network operating system such as CAN, Devicenet, Ethernet, or the like. At a still higher level of control hierarchy a master control system (MCS) 95 is provided which indirectly controls the operation of heliostats in heliostat fields 96, 97 by communicating with heliostat array control systems 92, 93 through network 94. Master control system 95 further controls the operation of a solar receiver (not shown) by communication through network 94 to a receiver control system (RCS) 99.

In FIG. 5, the portion of network 94 provided in heliostat field 96 can be based on copper wire or fiber optic connections, and each of the programmable heliostat control systems 65 provided in heliostat field 96 can be equipped with a wired communications adapter, as are master control system 95, heliostat array control system 92 and wired network control bus router 100, which is optionally deployed in network 94 to handle communications traffic to and among the programmable heliostat control systems 65 in heliostat field 96 more efficiently. In addition, the programmable heliostat control systems 65 provided in heliostat field 97 communicate with heliostat array control system 93 through network 94 by means of wireless communications. To this end, each of the programmable heliostat control systems 65 in heliostat field 97 is equipped with a wireless communications adapter 102, as is wireless network router 101, which is optionally deployed in network 94 to handle network traffic to and among the programmable heliostat control systems 65 in heliostat field 97 more efficiently. In addition, master control system 95 is optionally equipped with a wireless communications adapter (not shown).

According to one or more embodiments of the disclosed subject matter, a photosensitive panel having photosensitive sensor cells can be attached to or associated with a heliostat. The photosensitive sensor cells can contain a photosensitive surface for receiving light. The photosensitive surface can be manufactured from a material in which at least one electrically measurable quantity is changeable under the influence of light and is also capable of being measured either directly via electrodes or via a charge created by the panel. Examples of

photosensitive panels can include, but are not limited to, a photovoltaic panel, a photochemical panel, photodiodes and a pyranometer.

According to some embodiments, the photosensitive panels can be used to power the movement and/or communications system of the heliostats either directly or by charging an electrochemical cell which then powers the heliostats. An electrochemical cell can include, but is not limited to, a battery and a supercapacitor.

According to some embodiments, the heliostat control system can direct the heliostat to an orientation that yields the highest output from the attached photosensitive panel such that it is directly facing the sun in a two drive system. According to some embodiments, if there is one drive, then calibration can be performed by the photosensitive panel seeking the point of maximum unhindered radiation within the range of movement afforded by the one degree of freedom, without necessarily directly facing the sun. A two drive system in some embodiments can include an azimuth and an elevation drive, which can, for example, effect movements such as pitch, roll and yaw.

The output measured from a photosensitive panel mounted on a heliostat facing the sun and in unhindered sunlight can be used to calibrate the heliostat. Calibration can be performed by using the orientation of maximum electrical output produced by a photosensitive panel measured at a known sun position at the time of measurement and comparing this measurement with the heliostat orientation in relation to its drives. For example, a photosensitive panel can perform an initial calibration of a newly installed heliostat and find the maximum output from the panel for a certain time of the day. The controller can record the orientation relative to the earth's frame of reference, i.e., magnetic north, of the heliostat, the photosensitive panel and the sun. Additionally, the controller can record the relationship between the orientations of the photosensitive panel relative to the orientations of the mirror. It can then be possible to compute these known parameters, and in some embodiments, predict an output from the photosensitive panel for any time of day and heliostat orientation. The precision can increase with multiple one calibration tests. In some embodiments, the calibration can take place when the sun's position is different than its position during the first calibration.

According to some embodiments, the photosensitive panel can be driven by its own motor such that it will always be directly facing the sun, even while the heliostat is positioned such that its surface normal bisects the angle between the sun's rays and a line from the mirror surface to the tower. In this embodiment, the controller can compensate for the varying difference in orientations between the mirror and the photosensitive panel.

The abovementioned calibration can be used to predict an output level of a photosensitive panel at any heliostat orientation and at any time during the day. If the actual

measured electrical output is not the expected/predicted measurement, an alarm may be actuated and/or the data may be communicated to at least one of a control system and an operator. In some embodiments, the data and/or the alarm can be recorded.

According to some embodiments, the actual measured output from the photosensitive panel can be less than the expected/predicted output. This may be caused by a hindrance of direct sunlight being received by the photosensitive panel, for example, by dust, or shading from a neighboring heliostat. In embodiments, a cloud may be hindering the path between the sun and the photosensitive panel. In some embodiments, the reduced output from the photosensitive panel may be caused by a mechanical or electrical malfunction causing the heliostat to be orientated incorrectly

In some embodiments, the actual measurement may be greater than the expected/predicted output. In such instances, it may be necessary to re-calibrate the heliostat and/or photosensitive panel.

FIG. 6 illustrates a heliostat 70 with a photovoltaic panel 72 attached or otherwise associated with the top of the heliostat. In this embodiment where a photovoltaic panel 72 is attached to the top, or anywhere else on or adjacent to the heliostat 70 with access to sunlight, the heliostat is oriented during routine operation at an orientation that is ideal for reflecting sunlight onto the receiving tower. According to some embodiments, the heliostat is oriented such that its surface normal bisects the angle between the sun's rays and a line from the heliostat to the receiver. A photosensitive panel performs most efficiently when it is directly facing the sun. According to some embodiments, a photosensitive panel may be calibrated when it is directly facing the sun, or when the solar reflective surface holding the photosensitive panel is oriented as described hereinabove. According to some embodiments, the angle of the plane of photosensitive panel may be different than the angle of the plane of the solar reflective surface, such as closer to an orientation that would be facing the sun at least some times during the day. According to some embodiments, the photosensitive panel can be driven by its own motor or any other movement mechanism configured to keep the panel directly facing the sun, which is the most efficient orientation for photosensitivity/charging.

According to some embodiments, a PV module/panel's leads may be short circuited in order to measure current generated therefrom. Alternatively, a shunt current may be used to measure the current. As stated above, more irradiance incident on the PV panel will produce more output and less irradiance incident on the PV panel will produce less output. However, the orientation of the PV panel does not have to be directly facing the sun in order to produce sufficient current to either operate a heliostat directly or to charge batteries or capacitors.

Additionally, a PV panel can work without direct sunlight (i.e., via diffused light). In normal

operation in the middle of a sunny day up to over 90% of the electric current produced by the panel may be produced by direct sunlight as opposed to diffused light.

As shown in FIG. 7, the heliostat field can include one or more heliostats, for example, sun-tracking mirrors aimed at a target for heating a material, (e.g., water, molten salt, or any other material), therein using reflected sunlight. Heliostats 70a, 70b and 70c within the field can be aimed at a target, (i.e., solar energy receiving system 500), mounted on tower 50.

According to some embodiments, heliostats are aimed in response to instructions generated by a control computer and transmitted to the heliostats through a communication system. The aiming instructions and the optimization methods used to generate those instructions can be responsive to the cloud data obtained through the methods and apparatus disclosed in any of the embodiments herein. This responsiveness may include: causing a heliostat to move from an aiming point not on a receiver to an aiming point on a receiver, from an aiming point on a receiver to an aiming point not on a receiver, from one aiming point on a receiver to another aiming point on the same receiver, or from an aiming point on one receiver to an aiming point on another receiver.

In operation, sunlight beams 310, 320, 330 from the sun 300 can strike the reflective surface of heliostat mirrors 70a, 70b and 70c respectively. The heliostats can then reflect beams 311, 321, 331 towards the receiver 500. The reflected rays 311, 321, 331, in addition to beams reflected from other heliostats in the field, can heat the receiver 500 to temperatures of between 400°C and 800°C.

When clouds pass between the sun and the heliostats, direct insolation may be temporarily interrupted. As a result, the radiation reflected onto a solar receiver may differ from an ideal or expected flux distribution. This can result in local variations in temperature or flux. The variations in flux can damage the receiver and result in less than ideal operating conditions, for example, a reduction in steam produced or superheating steam temperature.

FIG. 7 illustrates an instance when clouds shadow heliostats. This blocking of insolation can be seen as clouds 192 shadowing sun 300 from heliostats 70a and 70c, while not shadowing 70b.

According to one or more embodiments of the disclosed subject matter, a reduction in output level of a photosensitive panel as caused by cloud cover may cause less charge to be created by the panel or a decreased output level of a the panel. This decrease may be measured and be proportional in some way to the amount of cloud coverage. This measurement may provide an indication of the nature of the cloud cover. In other words, the thicker the cloud the greater the shadowing of the heliostat which leads to a greater reduction of measured output from the photosensitive panel. At least part of the decrease may be due to some other cloud

parameter for example height of the cloud. Measurement of output such as current/charge is known to those skilled in the art and may be done for example by short circuiting or near short circuiting the photosensitive panel.

As a non-limiting example, for a PV panel operating at 12 Volts, the current may fall within the range of 0-1 Ampere, when there is 1000 W/m^2 of solar power incident on the panel. However, when there is cloud shadowing the sunlight from the PV panel, the incident light may, for example, decrease to 400 W/m^2 and the current produced will decrease proportionally. Cloud cover may cause the total incidence to decrease less than 400 W/m^2 .

According to some embodiments, cloud cover causes a decrease in output level of a photosensitive panel, which causes a decrease in an electrical output parameter from the photovoltaic panel. An electrical output parameter can be, for example, voltage, current, power, power per unit of area, or any other value that can be used to represent a respective output level of a photosensitive panel. The decrease can be analyzed to determine a shading parameter. Based on the shading parameter, an operating parameter of the solar energy system can be changed or maintained. For example, the operating parameter may include aiming directions for one or more of the heliostats. Cloud characteristics in addition to the location of the cloud shadow can be used in determining the shading parameter. Such characteristics can be used in determining if and/or how to change the operating parameter of the solar energy system.

The decrease in current when clouds are over a heliostat can be monitored on a higher level in the hierarchy as the cloud/clouds pass over the solar field. As sunlight returns to one PV panel, neighboring PV panels on other heliostats may be hindered by the same cloud as it makes its way across the field. In some embodiments, by monitoring the fluctuations of incident insolation on PV panels in a solar field, the shading parameter, a trajectory of one or more clouds across a field may be computed, for example, as illustrated in FIGS. 8-10. The time series images can help predict a future shadow status with respect to the heliostat field. Accordingly, the shading parameter can include a future shading parameter, and then an operation affecting at least one operating parameter of the solar energy system can be carried out preemptively. In embodiments, the pre-emptive operation can be related to fossil-fuel derived steam. For example, in the event that the cloud image analysis indicates that an evaporator region of the heliostat field (i.e., a region of the heliostat field where the heliostats are aimed at an evaporator section of the receiver) is about to be shaded within a designated period of time, it may be advantageous to initiate a natural gas boiler so that natural-gas-derived steam can be injected into the steam separation drum associated with the evaporator/boiler.

In some embodiments, a pre-emptive operation relates to re-aiming of heliostats. Because heliostats may need a certain amount of travel time to re-aim, it may be advantageous,

in anticipation of predicted or future shade conditions, to re-aim the heliostats before the heliostat becomes shaded.

In some embodiments, a location of a shadow and/or a shape or size of a shaded region at or near ground level produced by a cloud may be determined. As shown in FIGS. 11-12, for example, movement of a shadow 106 as it moves across heliostats 70 in a system 60 with multiple towers 50 can be tracked.

Characterization of such movement can include determining a shape of the shadow, a translational velocity of the shadow, and/or a rotational velocity of the shadow so as to determine and/or predict movement of the cloud shadow with respect to the field of heliostats or other components of the solar energy system. The determined shadow can depend upon a number of factors, including, but not limited to, the position of the sun as determined in advance from astronomical data, such as day of the year, time of day, and geographic location.

In another application (US Publication No. 2011/0220091, filed January 20, 2011, which is incorporated by reference herein) by the instant Applicant, relating to a method and apparatus for operating a solar energy system to account for cloud shading, images taken by imaging devices of the sky and/or the ground and are used to monitor and predict cloud shading. According to some embodiments, both the method described hereinabove of cloud prediction and the method as described in the incorporated US2011/0220091 publication may be used together. Additionally or alternatively, a plurality of devices which measure insolation such as pyroheliometers and pyronameters may be used in or near the field in conjunction with the method described above. Pyrheliometers and pyronameters or any other weather information and/or insolation devices can be situated in or near the solar field.

According to some embodiments, a photosensitive panel whose position and orientation are known with respect to a first heliostat may be used to calibrate a second heliostat, as shown, for example, in FIG. 13. At any time of day, the position of the sun 300 position is known. The first heliostat 1402 can have attached thereto a photosensitive panel 72 whose orientation and position are known with respect to the first heliostat 1402. According to some embodiments, the photosensitive panel 72 can be stand-alone and not attached to the heliostat. It may be sufficient to only know the azimuthal orientation of panel 72 and its elevation orientation may not be required. To enable this azimuth-only calibration, both panel 72 and second heliostat 1404 need to be approximately in an elevation orientation where reflected sunlight from heliostat 1404 will be detected by panel 72. Heliostat 1404 whose mirror orientation is unknown, for example, and requires calibration, is instructed by a controller to commence rotating on its azimuth axis. When the reflective surface of heliostat 1404 reflects light onto photovoltaic panel 72, photovoltaic panel 72 will have a much higher output than when no sun is reflected from the

heliostat 1404. The output will peak rapidly when the sunshine is reflected directly onto the panel. This orientation of heliostat 1404 in addition to the motor coordinates of heliostat 1404 at this orientation, together with the sun's position and the known position and orientation of the photosensitive panel are recorded. The orientation of heliostat 1404 may then be calibrated with this measurement. Optionally, additional measurements of the same heliostat at different times can be made and added to the calibration data. In some embodiments, multiple heliostats may be calibrated in this way simultaneously.

It is noted that any of the embodiments described above may further include receiving, sending or storing instructions and/or data that implement the operations described above in conjunction with the figures upon a computer readable medium. Generally speaking, a computer readable medium may include storage media or memory media such as magnetic or flash or optical media, e.g., disk or CD-ROM, volatile or non-volatile media, such as RAM, ROM, etc. as well as transmission media or signals such as electrical, electromagnetic or digital signals conveyed via a communication medium such as network and/or wireless links.

It will be appreciated that the methods, processes, and systems described above can be implemented in hardware, hardware programmed by software, software instruction stored on a non-transitory computer readable medium or a combination of the above. For example, the processors can be configured to execute a sequence of programmed instructions stored on a non-transitory computer readable medium in order to control the heliostats. The processors can include, but are not limited to, a personal computer or workstation or other such computing system that includes a processor, microprocessor, microcontroller device, or is comprised of control logic including integrated circuits such as, for example, an Application Specific Integrated Circuit (ASIC). The instructions can be compiled from source code instructions provided in accordance with a programming language such as Java, C++, C#.net or the like. The instructions can also comprise code and data objects provided in accordance with, for example, the Visual Basic™ language, or another structured or object-oriented programming language. The sequence of programmed instructions and data associated therewith can be stored in a non-transitory computer-readable medium such as a computer memory or storage device which can be any suitable memory apparatus, such as, but not limited to read-only memory (ROM), programmable read-only memory (PROM), electrically erasable programmable read-only memory (EEPROM), random-access memory (RAM), flash memory, disk drive, etc.

Furthermore, the disclosed methods, processes, and/or systems can be implemented by a single processor or by a distributed processor. Further, it should be appreciated that the steps discussed herein can be performed on a single or distributed processor (single and/or multi-core). Also, the methods, processes, and/or systems described in the embodiments above can be

distributed across multiple computers or systems or can be co-located in a single processor or system. Exemplary structural embodiment alternatives suitable for implementing the methods, processes, and/or systems described herein are provided below, but not limited thereto.

The methods, processes, and/or systems described herein can be implemented as a
5 programmed general purpose computer, an electronic device programmed with microcode, a hard-wired analog logic circuit, software stored on a computer-readable medium or signal, an optical computing device, a networked system of electronic and/or optical devices, a special purpose computing device, an integrated circuit device, a semiconductor chip, and a software module or object stored on a computer-readable medium or signal, for example. Moreover,
10 embodiments of the disclosed methods, processes, and/or systems (e.g., computer program product) can be implemented in software executed on a programmed general purpose computer, a special purpose computer, a microprocessor, or the like.

Embodiments of the disclosed methods, processes, and/or systems (or their sub-components or modules) can be implemented on a general-purpose computer, a special-purpose
15 computer, a programmed microprocessor or microcontroller and peripheral integrated circuit element, an ASIC or other integrated circuit, a digital signal processor, a hardwired electronic or logic circuit such as a discrete element circuit, a programmed logic circuit such as a programmable logic device (PLD), programmable logic array (PLA), field-programmable gate array (FPGA), programmable array logic (PAL) device, etc. In general, any process capable of
20 implementing the functions or steps described herein can be used to implement embodiments of the methods, processes, systems and/or computer program product (software program stored on a non-transitory computer readable medium).

Furthermore, embodiments of the disclosed methods, processes, and/or systems can be readily implemented, fully or partially, in software using, for example, object or object-oriented
25 software development environments that provide portable source code that can be used on a variety of computer platforms. Alternatively, embodiments of the disclosed methods, processes, and/or systems can be implemented partially or fully in hardware using, for example, standard logic circuits or a very-large-scale integration (VLSI) design. Other hardware or software can be used to implement embodiments depending on the speed and/or efficiency requirements of
30 the systems, the particular function, and/or particular software or hardware system, microprocessor, or microcomputer being utilized. Embodiments of the disclosed methods, processes, and/or systems can be implemented in hardware and/or software using any known or later developed systems or structures, devices and/or software by those of ordinary skill in the applicable art from the function description provided herein and with a general basic knowledge
35 of solar energy systems and/or computer programming arts.

Features of the disclosed embodiments can be combined, rearranged, omitted, etc., within the scope of the invention to produce additional embodiments. Furthermore, certain
5 features can sometimes be used to advantage without a corresponding use of other features.

It is thus apparent that there is provided, in accordance with the present disclosure, methods and systems for operating a solar energy system, including monitoring of cloud shading. Many alternatives, modifications, and variations are enabled by the present disclosure. While specific embodiments have been shown and described in detail to illustrate the application
10 of the principles of the invention, it will be understood that the invention may be embodied otherwise without departing from such principles. Accordingly, Applicant intends to embrace all such alternatives, modifications, equivalents, and variations that are within the spirit and scope of the present invention.

CLAIMS

1. A method of operating a solar energy system having a field of heliostats, comprising:

measuring an output of a photo-sensitive panel attached to a heliostat when the panel is
5 in direct unhindered sunlight and at a first orientation;

predicting the output of the photo-sensitive panel at a second orientation;

measuring the output of the photo-sensitive panel at the second orientation; and

performing a communication function when output measured at the second orientation of
the panel is below or above the predicted output,

10 wherein the communication function is one of: creating an alarm, communicating data to at least one of a control system and an operator, and recording the data or the alarm.

2. The method according to claim 1, wherein the second orientation is the same or different orientation as the first orientation, but when the sun's position has changed.

3. The method according to claim 1, wherein the photo-sensitive panel generates
15 electrical energy to a drive system that orients the heliostat when sun-tracking.

4. The method according to claim 3, wherein at least a portion of the generated electrical energy is stored in a storage device.

5. The method according to claim 4, wherein the storage device is one of a battery or a capacitor.

20 6. The method according to claim 1, wherein the difference between predicted and measured output occurs when there is cloud cover.

7. The method according to claim 1, wherein the difference between predicted and measured output is a function of a parameter of a cloud.

8. The according to claim 1, further comprising the steps of monitoring decreased
25 output across the field of heliostats; and in response to said monitoring, optimizing the solar field parameters.

9. The method according to claim 8, wherein the solar field optimizing includes changing an aiming direction of at least one heliostat.

10. The method according to claim 8, further comprising the step of predicting the
30 movement of the cloud over the solar field in response to said monitoring.

11. The method according to claim 1, wherein the photo-sensitive panel is a photovoltaic cell panel or a photochemical panel.

12. The method according to claim 1, further comprising the step of using one or more imaging devices for calibrating the photo-sensitive panel.

13. A method of operating a solar energy system of claim 1, further comprising using one or more insolation measuring devices for calibrating the photo-sensitive panel.

14. A heliostat comprising:

at least one mirror;

5 at least one drive system;

at least one electrochemical cell configured to provide motive power for the at least one heliostat drive system;

a plurality of photovoltaic or photochemical cells configured to generate electricity to be used to charge the at least one electrochemical cell; and

10 a controller configured to receive a value of an electrical output of the photovoltaic or photochemical cell and to calculate the amount of shading caused by clouds on the at least one mirror.

15 15. The heliostat of claim 14, wherein the controller is additionally configured to calibrate the orientation of the heliostat based at least in part on the value of an electrical output of the photovoltaic or photochemical cell.

16. A method of operating a solar energy system having a field of heliostats, the method comprising:

controlling a plurality of heliostats to track the apparent movement of the sun to reflect incident solar radiation on a receiver;

20 calculating an electrical output of a photosensitive panel and generating a signal indicating a current or impending transient reduced-insolation event;

receiving a signal indicating a change in insolation;

calculating, responsively to said at least one signal, characteristics of a current reduced insolation event or of an impending transient reduced-insolation event; and

25 controlling the plurality of heliostats in response to the calculated characteristics of the reduced-insolation event.

17. The method according to claim 16, wherein, in response to the calculated characteristics of the reduced-insolation event, the controlling includes changing an aiming direction of at least one heliostat.

30

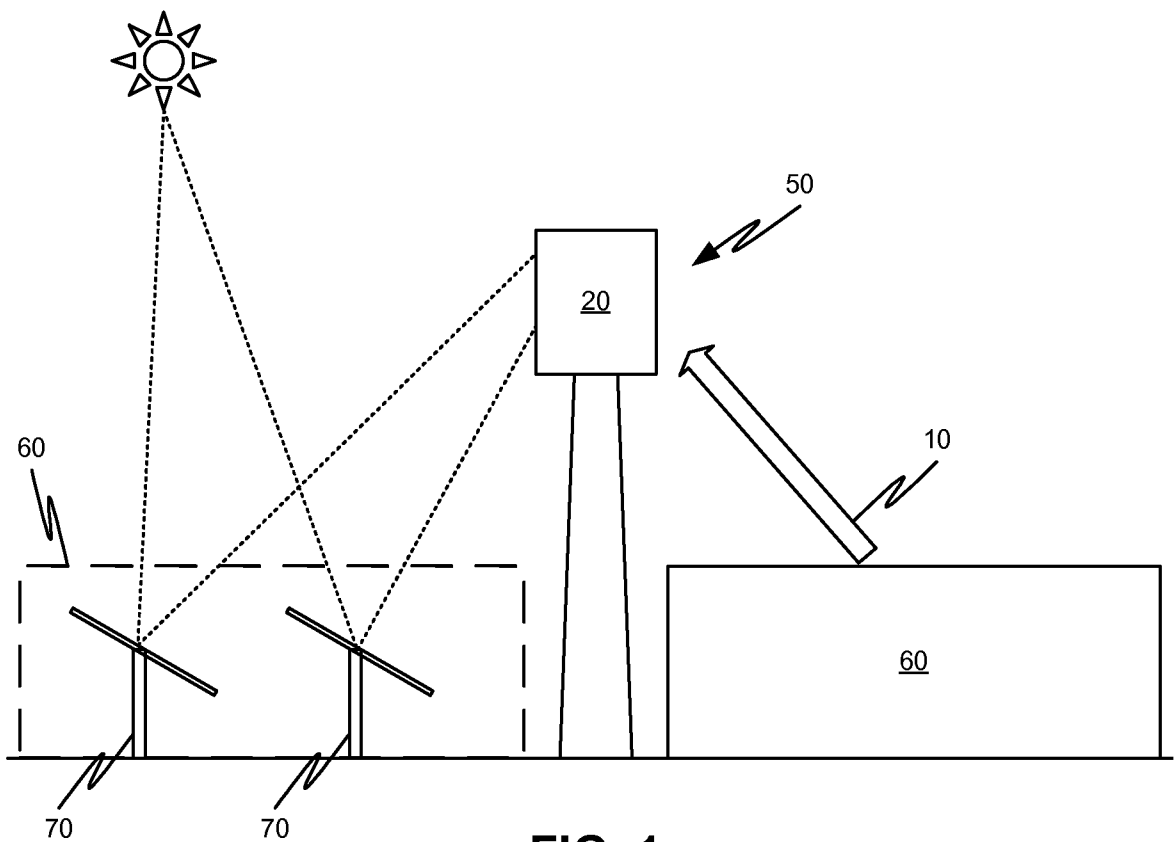


FIG. 1

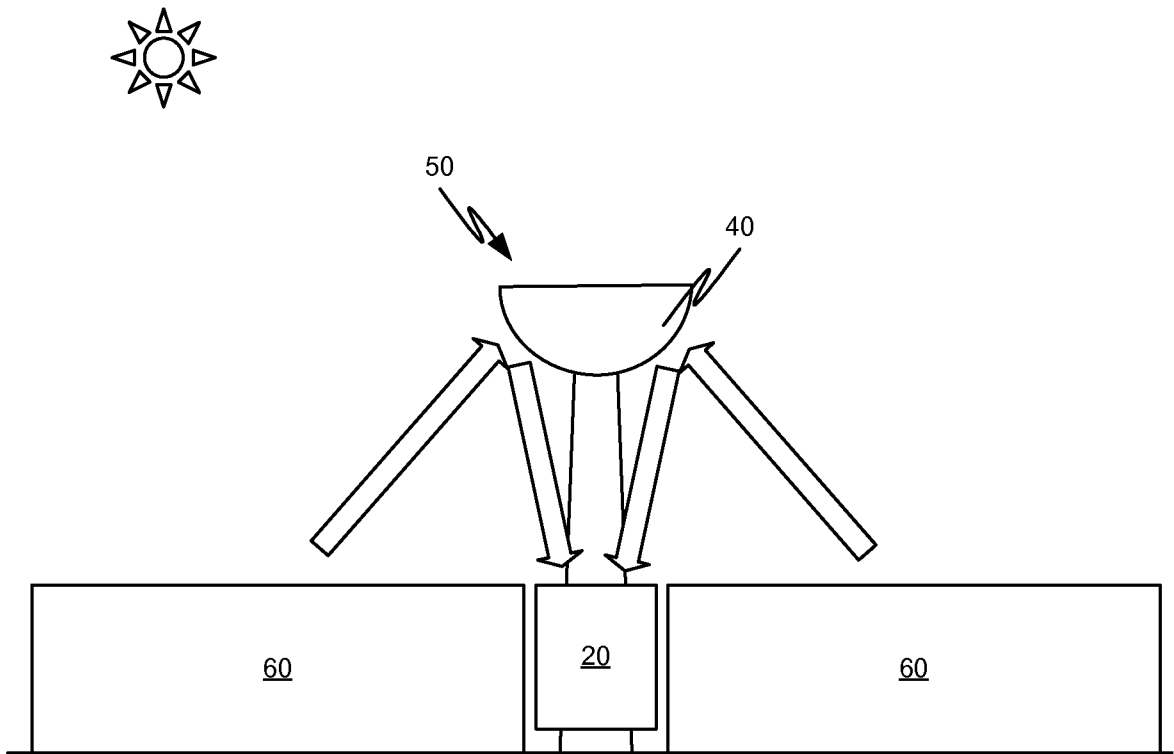


FIG. 2

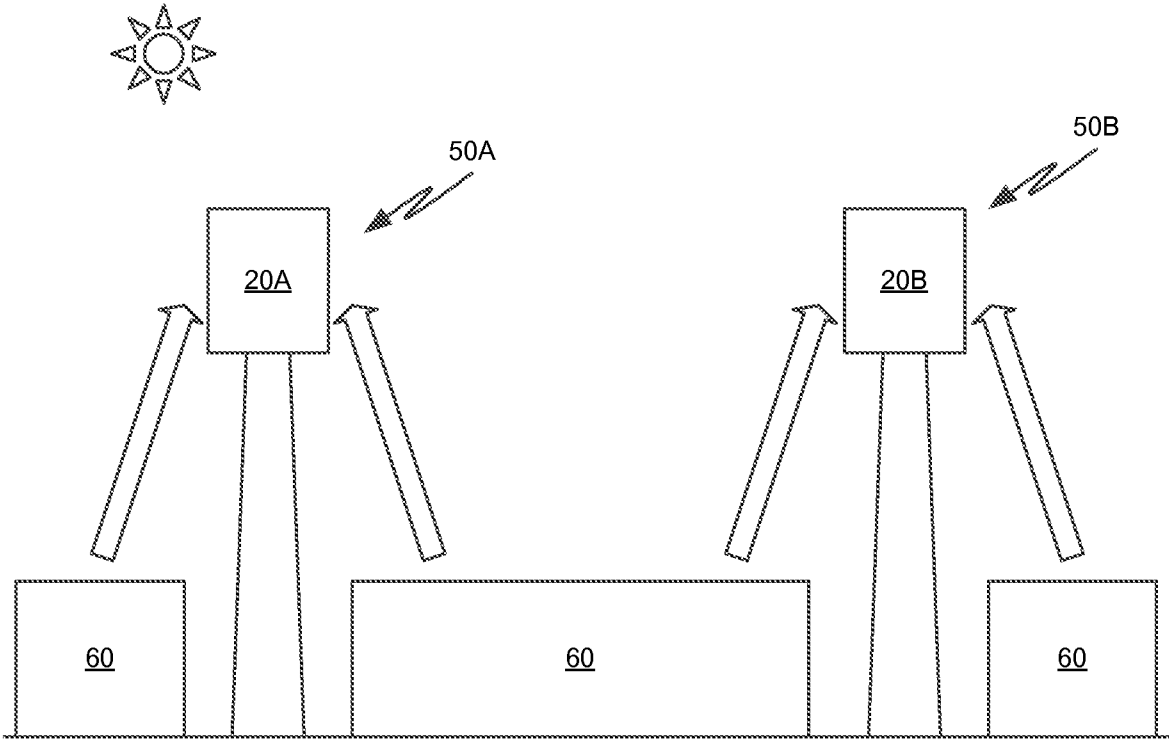


FIG. 3

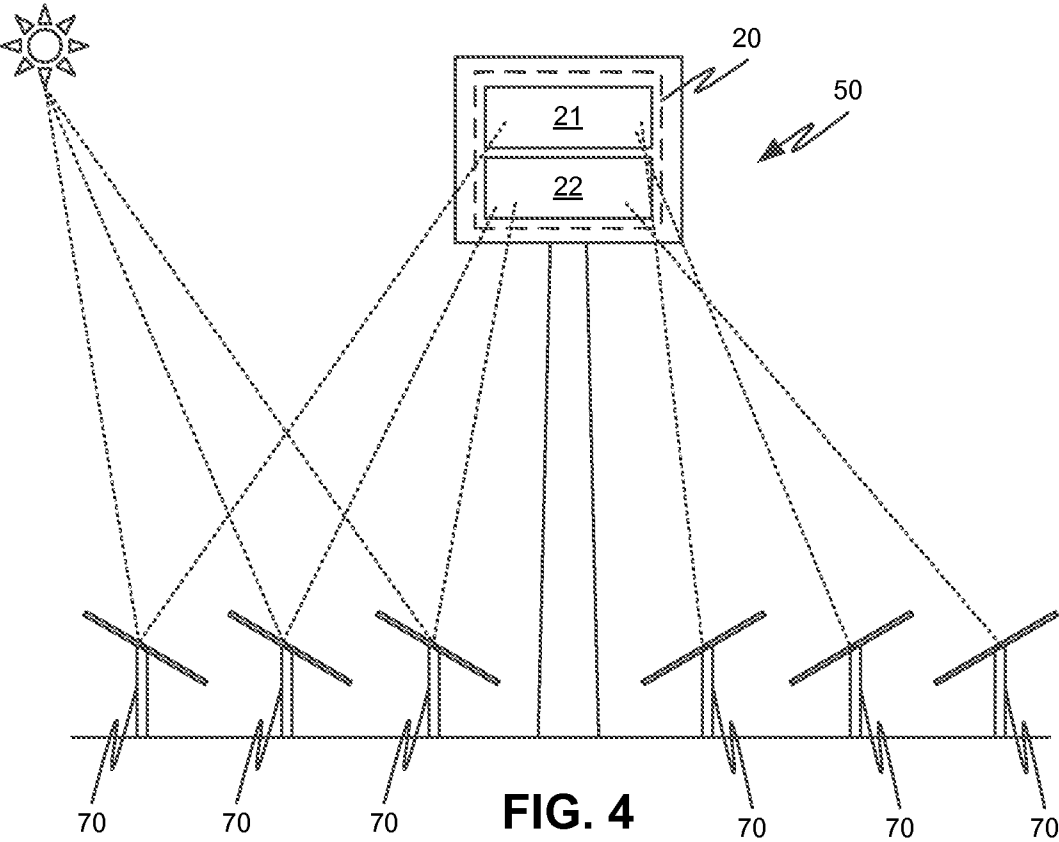


FIG. 4

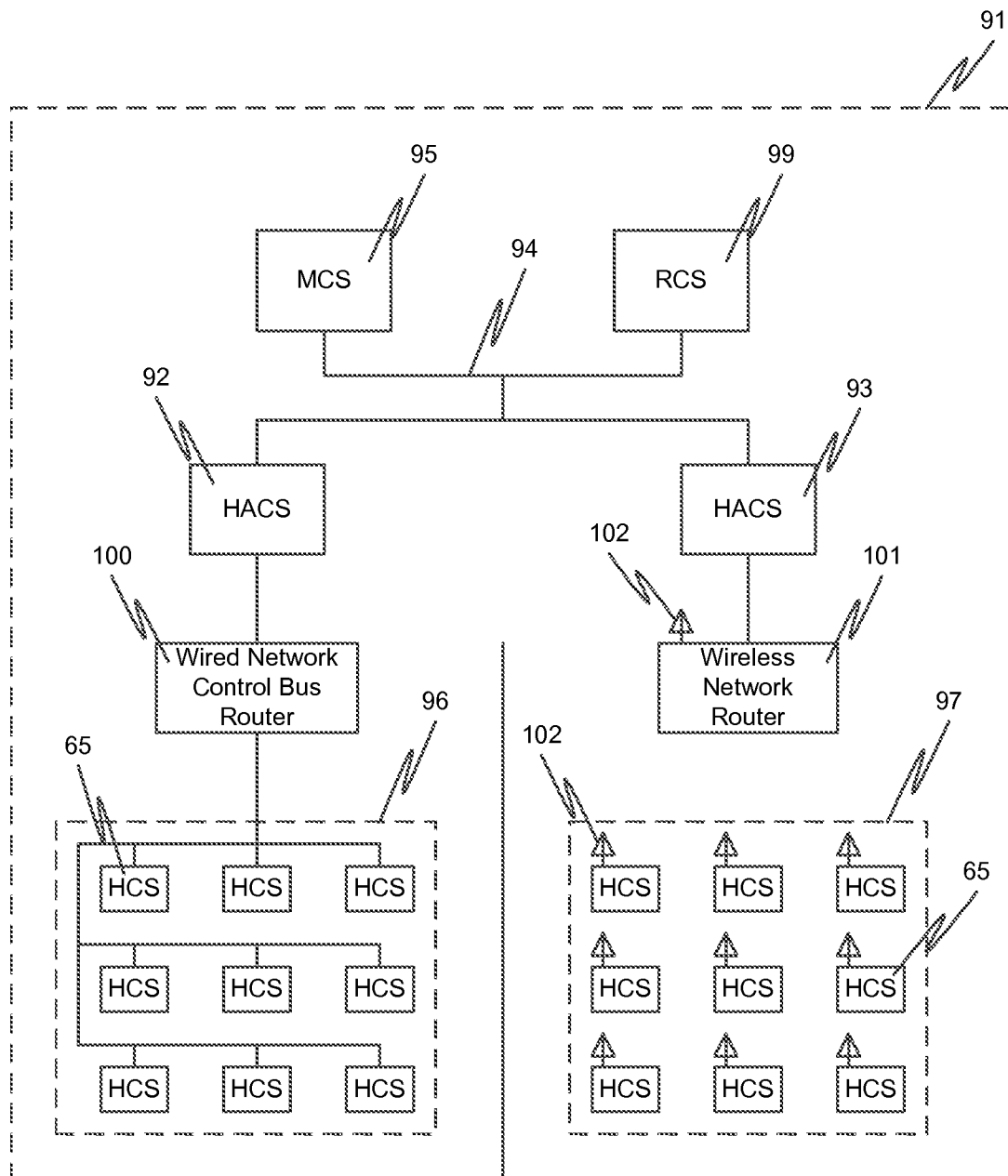
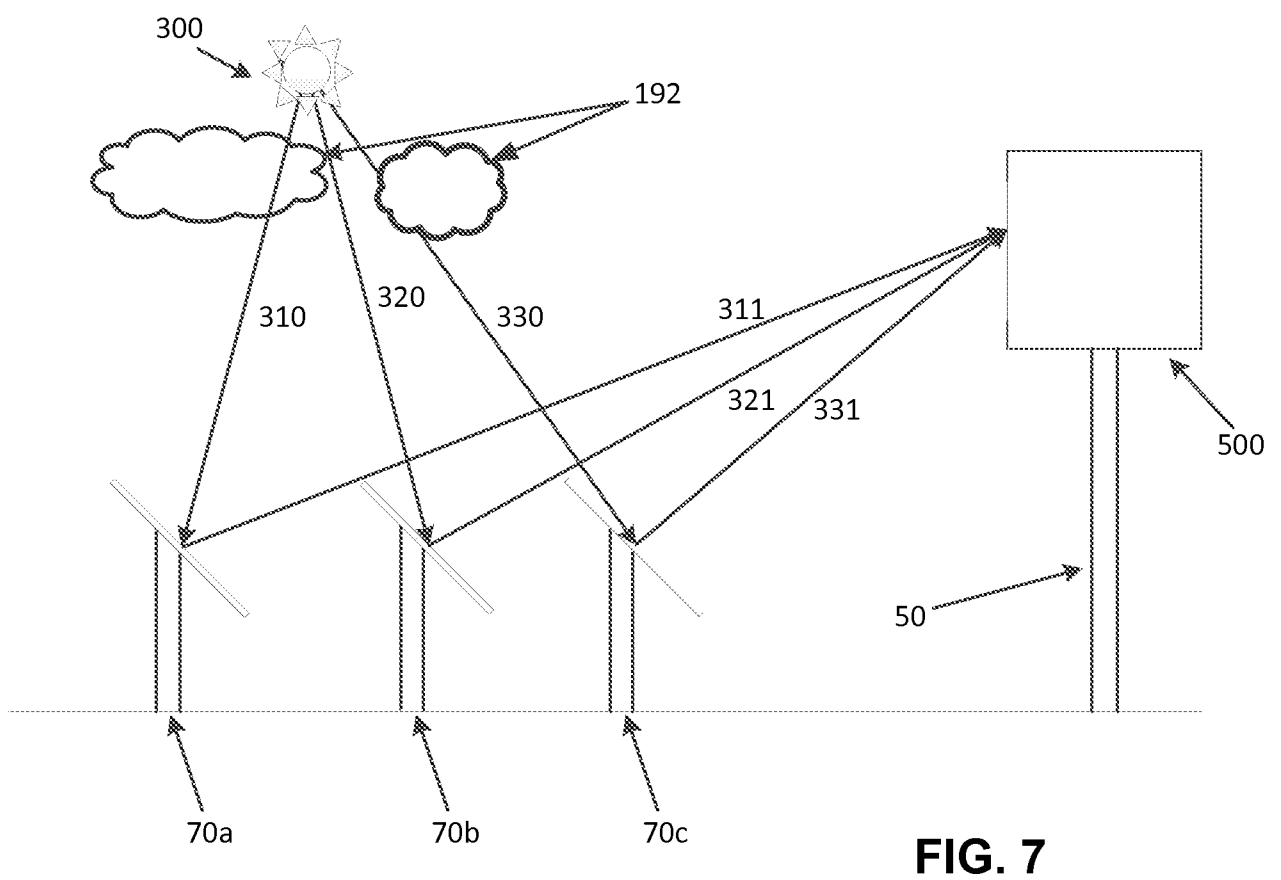
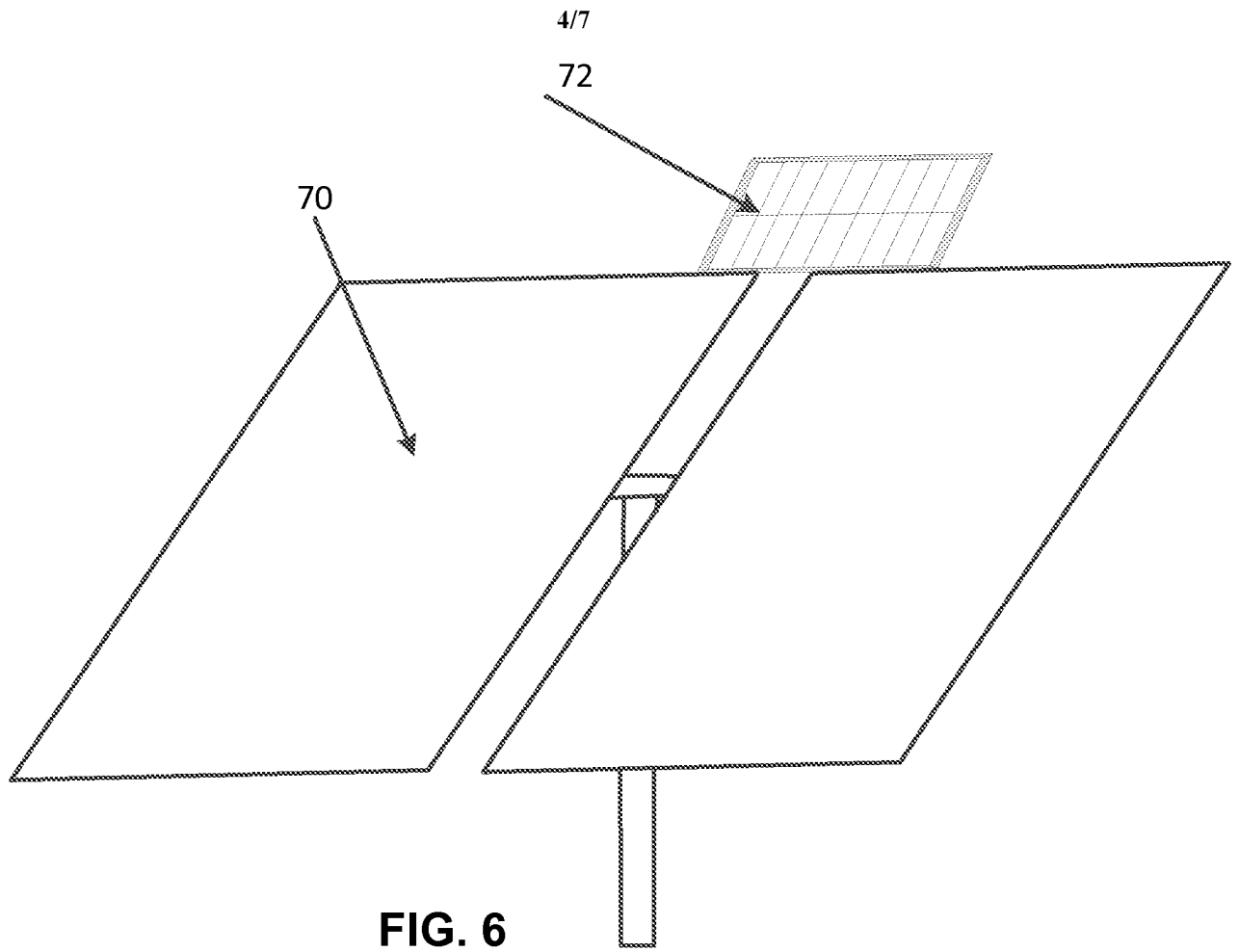


FIG. 5



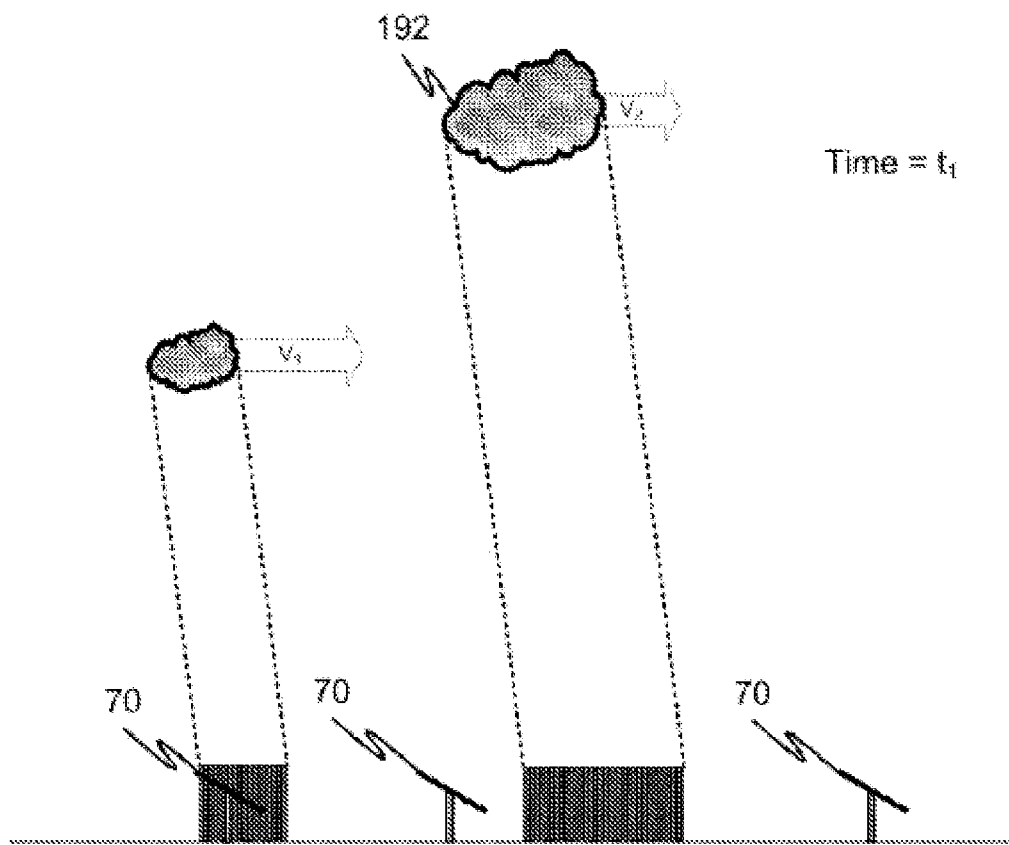


FIG. 8

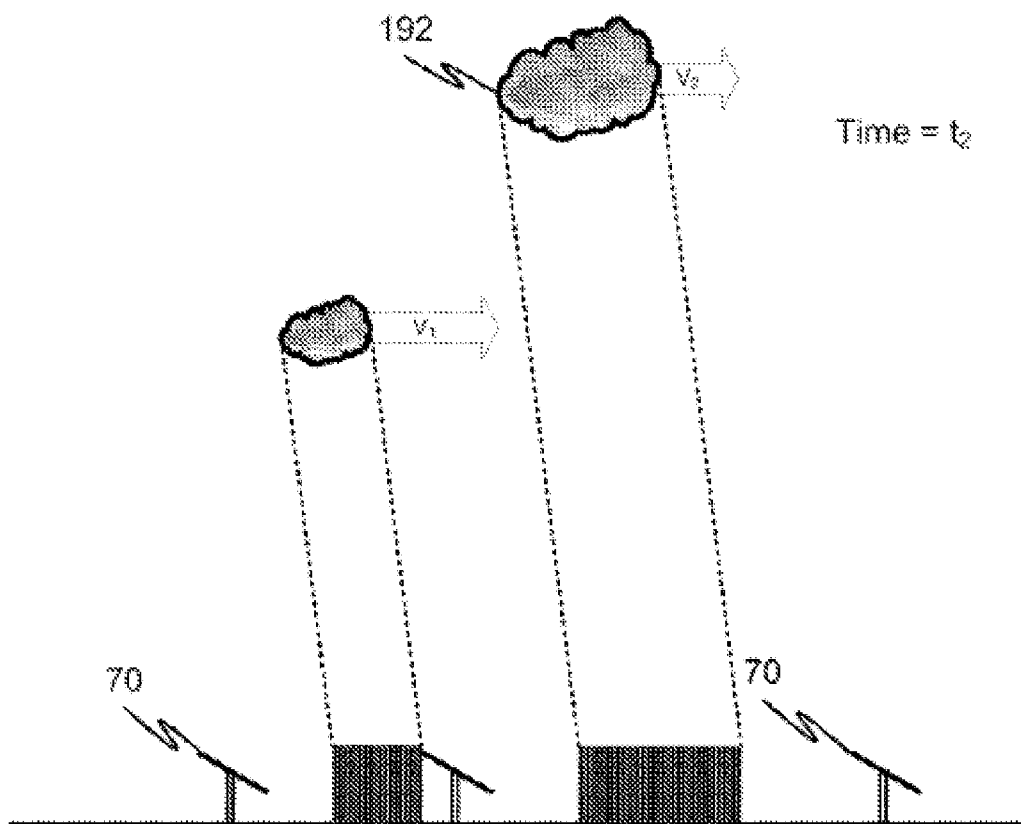


FIG. 9

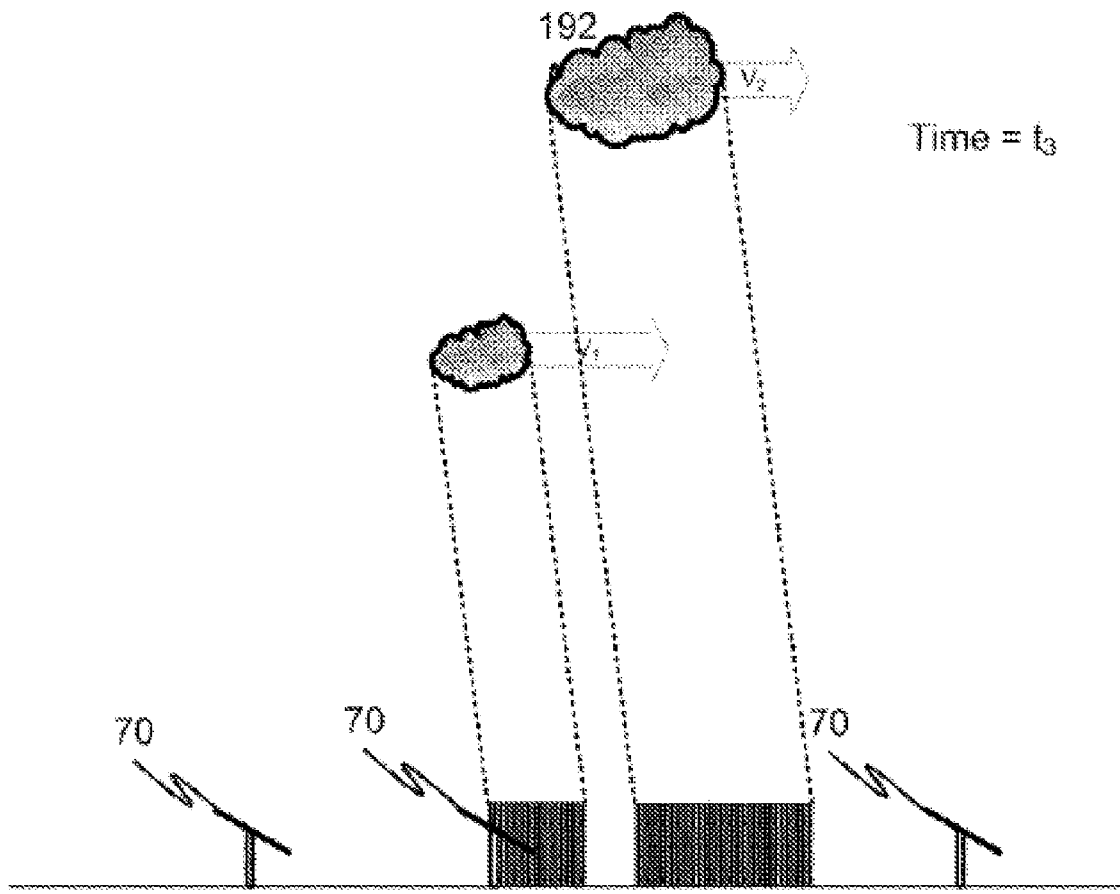


FIG. 10

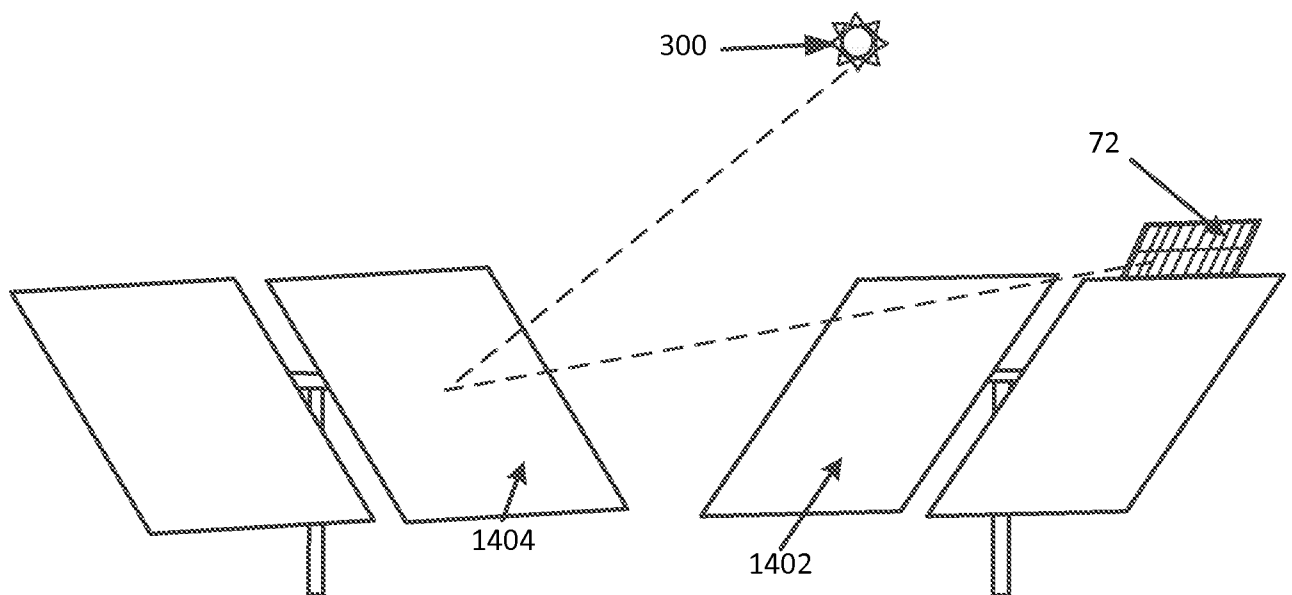


FIG. 13

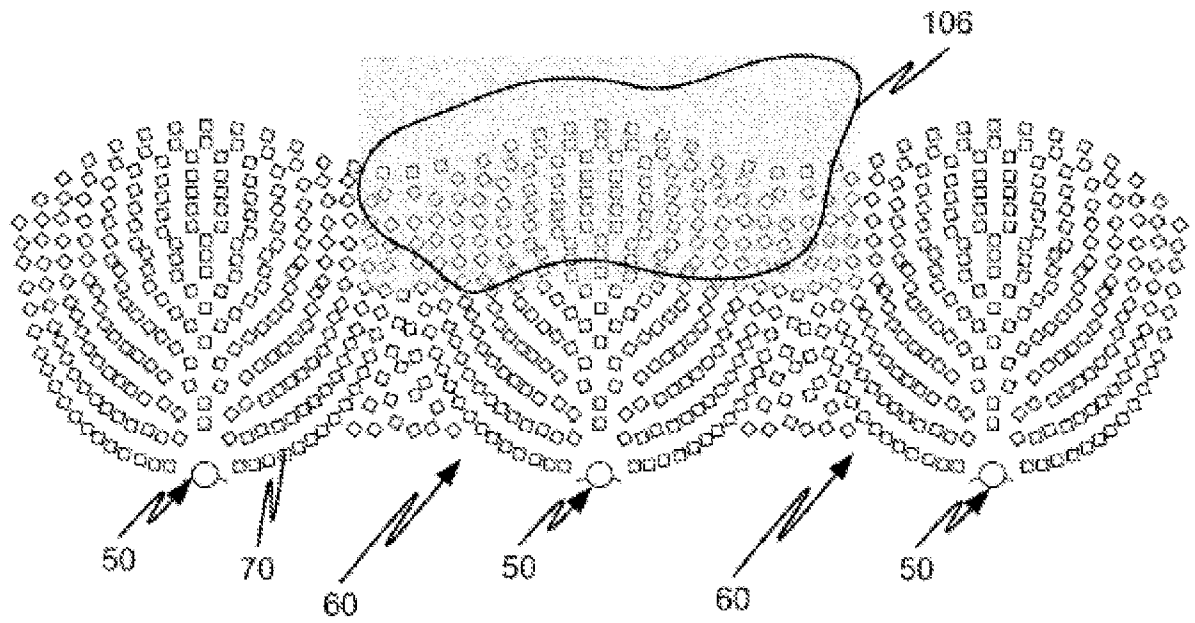


FIG. 11

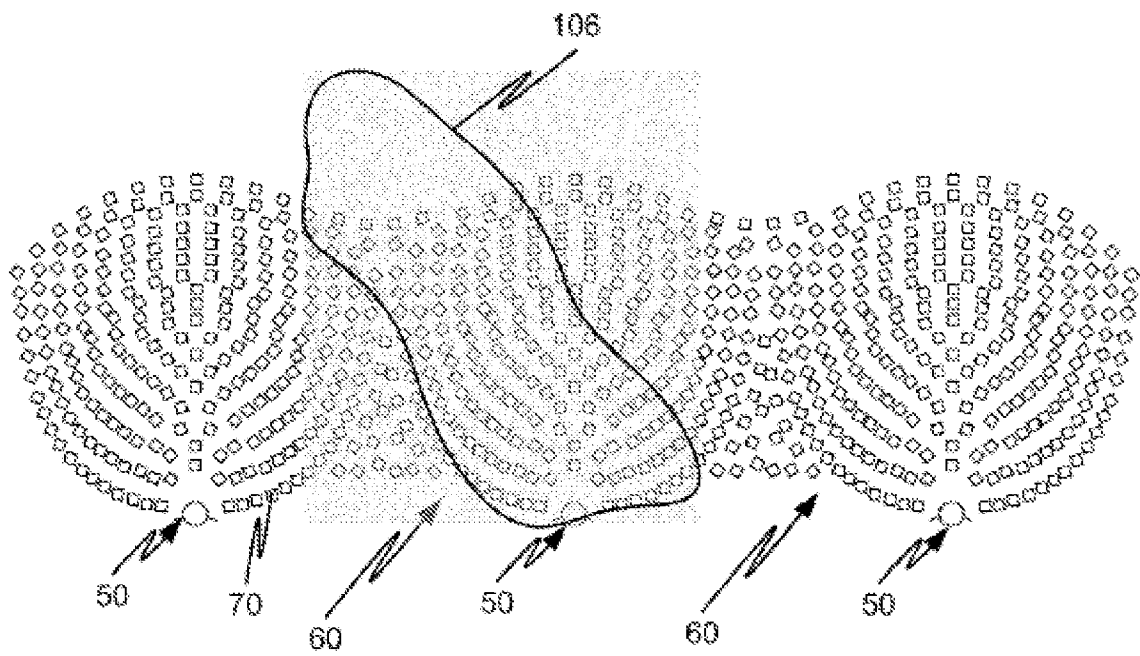


FIG. 12