

## PVT-Biomass-Battery systems optimized with evolutionary algorithms for small and highly shaded environments

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**Abstract.** When the space where we have to build a PV Solar Plant is not enough to satisfy appropriately the user's demand, a geometric problem arises in its design. To find the optimal location of the panels, the distances between them, their tilt, or even the number of panels itself, may result in a complex work; much more in small spaces with obstacles near the modules. In these cases, the economically optimal solution(s) is strongly related to these geometric constraints, in addition to the more common variables considered in this type of problems: like electrical loads, or local temperature and cloudiness.

This work collects two proposals to mitigate the problem: a Photovoltaic thermal hybrid solar collectors (PVT)-Biomass-Battery system which significantly increases the generated energy per square meter; and a computational methodology, based on evolutionary algorithms, to calculate it.

### Key words

PVT, Shading, Simulation, Self-sufficiency, Evolutionary algorithms.

### 1. Introduction

Photovoltaic (PV) technology is developing fast but, in many cases, simple PV systems are not powerful enough for a given area; as may occur inside the cities. Many systems based on PV try to supplement the restrictions by adding other ways of producing energy, like wind turbines or fuel generators, raising the price of the total system and the maintenance, without solving the main issue: the space optimization. Additional power sources are welcomed, but only when the available resources (space) are fully exhausted.

#### A. State of the Art

One of the most famous tool in this area is PVSYSY. In its newer versions, it can compute geometrically defined PV power plants and calculate its electrical output.

Nevertheless, there are some issues that PVSYSY cannot address:

- 1) It only admits pure PV systems.
- 2) Devices and their connections (strings among others) have to be previously pre-defined before simulating. The program is not autonomous and cannot give a design proposal beyond the set parameters (which are very restrictive).
- 3) The obstacles and the photovoltaic area have to be introduced manually for each simulation, which means that every modification has to be implemented by the engineer. This fact, absurdly lengthens the design phase as the same installation is introduced again and again with simple changes like number of modules, orientation or tilt and others not so simple like string connections. Also, the solutions have to be evaluated one by one.

In conclusion, this kind of tools can help to check concise geometries in order to compare the best few known solutions, but it is far from an optimized tool in the design phase where hundred of geometries (and thousands of electrical systems) are possible. It is even worse when more shadows may appear due to surrounding obstacles.

So, to the best of our knowledge, no software covers completely all of the above problems at the moment. Anyway, the comparisons have been made with the PVSYSY package just by convention, because it is one of the most famous programs at the moment solving standard pure PV.

#### B. Objective

The purpose of this paper is to show an improved and advanced methodology based on evolutionary algorithms, combined with a symbiotic system (PVT-Biomass-

Battery). The main purpose is to generate very complex designs, obtained automatically, and extremely adaptable to the final user's real situation (geometry, location and economic parameters) and demands (energy loads). Both, the system and the computation, have been developed in the most general way possible, keeping in mind the main goal: to use common and well-known devices in the best way possible to make easy and profitable installations where current techniques cannot give a good solution.

## 2. The system

The basic idea of the system is to make profitable the heat generated in the PVT modules by heating up the water which will be used later as hot water by the final user. In addition, this effect reduces the silicon temperature, raising the electricity production. This symbiosis between the devices allows us installing substantially more power than standard solar plants (including PV and thermal modules separately). The system is divided in two subsystems: the thermal and the electrical one as shows the Figure 1.

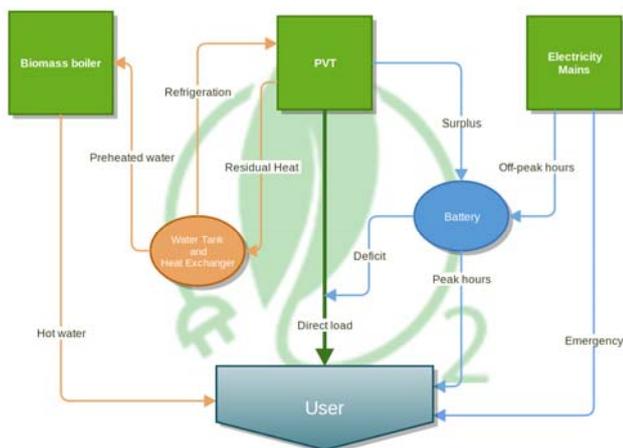


Fig. 1. System scheme. Thermal subsystem in orange and Electrical subsystem in blue.

### A. PVT solar modules

In order to raise the energy production per square meter and the versatility of the conventional photovoltaic panels, refrigerated PV panels with bypass diodes in each row have been used.

On the one hand, silicon cells have an optimal working temperature of 25°C. Each grade higher reduces the production by 0.43%, this means that the reduction can easily reach 15% at the frequent work temperature of 55°C. In a simulation made for a highly dense solar plant in the city of Granada, an average of +10% of the electricity production and a 103.25% of thermal energy (approximately the same quantity as electrical) was obtained using these modules.

On the other hand, placing a bypass diode in each row of the panels which receive more shadows or, in general, in the lower ones (if stacked), allows a reduction of the distance between them, generating lesser losses (Figure 2). Supposed a squared urban roof with 400m<sup>2</sup>, it would be possible to install about 110 modules following the basic procedure to calculate the inter-row distance (4 hours

without inner shades in the winter solstice) but using bypass diodes in the three lowest cell rows of each panel, that number rises to 180. This implies only a 10% of shadow losses and a less than 5% of bypass losses (even less if the modules were stacked or the diodes were placed only in the strictly required positions).

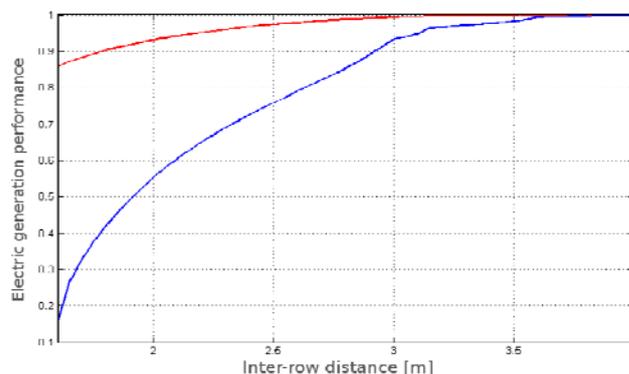


Fig. 2. Performance comparison of a generic photovoltaic installation based on the separation between rows panels. In blue, the electric production performance without taking into account the effect of bypass diodes; in red, the electric production performance taking into account the effect of the bypass diodes.

### C. Electrical subsystem

The elements of the electrical subsystem are: the electric part of PVT modules, the electrochemical battery, the electricity mains and the user (with its particular demands and habits). Combining the electricity extraction of these elements, the system will obtain, on aggregate a year, the lowest external electricity investment possible. Once the price (and different periods, if proceed) are set, the system can work under an established criteria. For example, suppose that the ascending price order is: photovoltaic generated, off-peak hour, battery discharge and peak hour. In this case, the procedure follows these steps:

1. Photovoltaic generated electricity has the highest priority. Surplus charges the batteries.
2. Electricity mains supplement the PV in off-peak hours. Batteries are charged at these hours.
3. Battery supplements the PV during peak hours.
4. When no other options are available, electricity mains provides the user in peak hours.

### D. Thermal subsystem

The elements of the thermal subsystem are: the thermal part of PVT modules, the heat exchanger, the water tank and the biomass boiler.

The water available in a day to refrigerate the solar plant will be exactly the hot water the user uses per day, avoiding waste of water. The pumped heat transfer fluid maintains the modules and the tank at the same temperature, keeping the thermal system balanced. Each time the user requires hot water, the tank sends preheated water to the boiler and introduces cold water from the water mains.

For an installation with a 5000 liters tank and 84 modules, the highest equilibrium temperature registered

in summer in our simulations was 43°C. The temperature reduction in the silicon for that day was about 20°C, generating 116kWh of thermal energy.

### 3. Methodology

The methodology exposed here is currently implemented in a program written in MATLAB™ language and each and every one of its features are original of the authors. The whole process is completely human-independent once the initial data is introduced, which means that there is no need to manually iterate anything at any step of the design process.

This tool provides a totally new way to address the design process because it solves the three big issues mentioned in Section 1. The big difference is in the way it faces the problem, the methodology is based on feeding the program's Artificial Intelligent (AI) with technical information, leaving the decision making to it.

Once the raw data input is set (including environment geometry, understood as all the elements that affect the installation by its presence, including the panels themselves), the program will find the most profitable solutions, given by the relation between the initial investment versus Net Present Value (NPV) Pareto Frontier. In other words, the algorithms are made for finding all the best solutions that a problem can admit. Meanwhile, the current tools available in the market only solve designs one by one, without checking if it is optimal or not, this being a source of bad designs.

In this paper, "solution" includes: technologies used from simple PV to PVT-Biomass-Battery through all possible combinations, number of panels, panel positions, panel connections (strings), panel tilt and, if proceed, battery capacity. The rest of the parameters, like water tank capacity or boiler power, can be declared fixed inasmuch as their calculation corresponds to non-continuous or dependant system.

#### A. Important formulation used

Solar cells have been modelled using the characteristic equation of a solar cell:

$$I = I_L - I_0 \left[ \exp\left(\frac{V + IR_s}{nkT}\right) - 1 \right] - \frac{V + IR_s}{R_{SH}} \quad (1)$$

where,  $I$ : Output current (A),  $I_L$ : Photogenerated current (A),  $V$ : Voltage across the output terminals (V),  $R_s$ : Series resistance ( $\Omega$ ),  $R_{SH}$ : Shunt resistance ( $\Omega$ ),  $I_0$ : Reverse saturation current (A),  $n$ : Diode ideality factor,  $k$ : Boltzmann's constant (J/K),  $T$ : Absolute temperature (K).

To solve this equation the Phang et al. analytical method [1] has been used. It includes the series-parallel, the irradiance and the module temperature corrections. Panel temperature estimation has been calculated using the

Normal Operating Cell Temperature (NOCT):  $T = T_a + Ir(T_{ONC} - 20) / 800$ , where:  $T_a$  is the ambient temperature (K),  $Ir$  is the normal irradiation ( $W/m^2$ ).

The main hypothesis used in the simulations is that when a shadow appears, the affected cells (and all connected in series with them) are completely unproductive. The current work is focused on modelling the residual current that comes out.

On the other hand, the thermal part of the PVT modules has been modelled with the next formulation [2]:

$$P = r\alpha Ir - U_i(T_i - T_a) \quad (2)$$

where now,  $P$ : Collectors thermal power ( $W/m^2$ ),  $r\alpha$ : Optical parameters (0.28 has been used [3]),  $U_i$ : Global losses coefficient ( $W/m^2K$ ) (8.66 has been used [3]) and  $T_i$ : Transfer fluid input temperature (K), and the rest of parameters have been defined above.

Finally, battery duration has been modelled with a *Rainflow counting algorithm* [4] by counting and measuring the charge-discharge cycles.

#### B. Data input

There are two kinds of data types in the program, raw technical information and simulation parameters. While the first one is needed to obtain processed and high quality information to send to the program's AI, the second one adjusts the AI behavior.

The generic raw data inputs are:

- Location.
- Irradiation and ambient temperature time series for, at least, a complete year.
- Energy loads time series and hot water demand.
- Environment geometry.
- Economical and investment parameters.
- The surface as a tilted and oriented plane or as a digital elevation model (DEM) matrix (Figure 3).
- The obstacles as composition of vertical parallelepipeds given by two points in a diagonal.

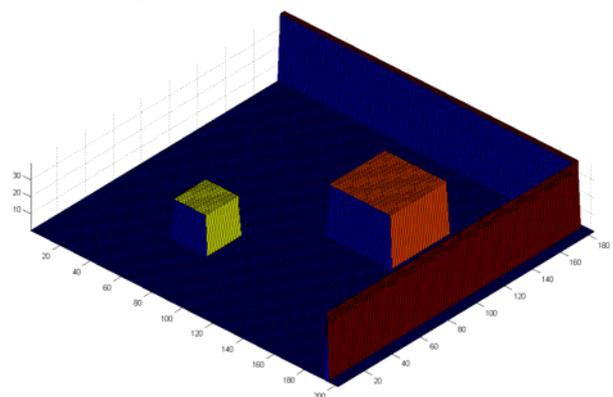


Fig. 3. Example of a simple environment geometry with two

obstacles and a wall introduced in the program.

In addition, there are useful parameters to adjust important aspects of the simulations such as time intervals, space resolution in the models and roughness of the AI searching for good solutions. Their functionality is oriented to control the time and accuracy of the simulations.

### C. Pre-simulations steps

Once the code is running, but before the simulations start, it is necessary to generate some high quality information. One of the most transcendental ones for the rest of the computation are radiation maps (Figure 4). These are generated simulating the shadows projection, beside meteorological processed time series, supposing that the floor is photovoltaic sensitive and scaling the results from 0 to 1. It includes all the intrinsic characteristics of the environment in one matrix.

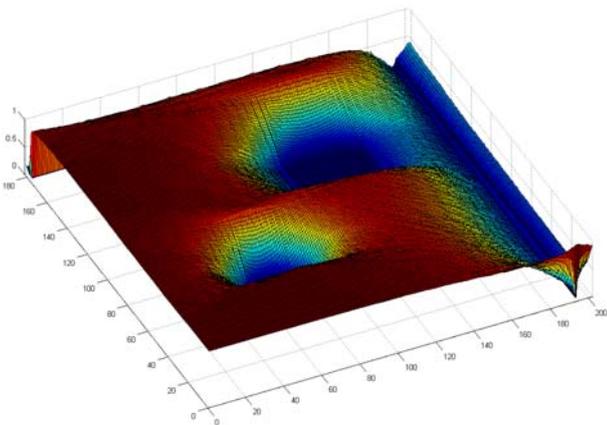


Fig. 4. Radiation maps for the Figure 3 example.

These maps are one of the main AI tools in order that they help it to understand the situation and, consequently, to quickly find the optimal positions for the modules.

### D. Simulation

When the enriched data has been sent to the AI, the simulation process starts. Defining design proposals is the duty of the AI module, firstly with a certain grade of randomness but progressively more accurate, thanks to the acquired “knowledge” of the problem generated in the process. The designs (Figure 5) are sent to the simulator.

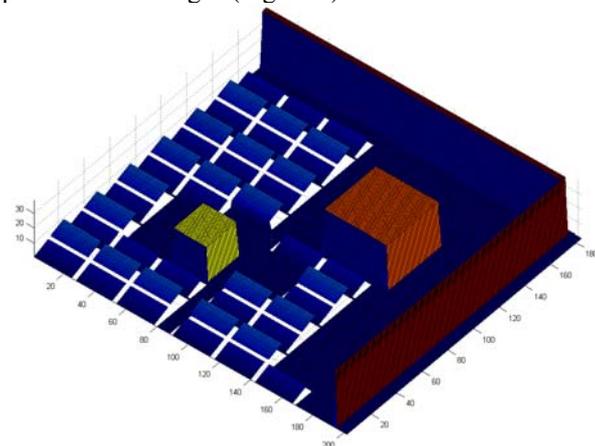


Fig. 5. Example of the design proposal with 45-30° tilted solar

modules for the previous geometry.

The next step is to evaluate the goodness of the proposal: First, shadows over the installation are simulated for a year, including self-produced shadows and obstacles shadows. Using the formulation previously exposed, the gross production is calculated for the whole panels, that is, for the solar cells without considering their connections. The next step is to apply the bypass diodes considerations, which estimate the losses and “switch off” the corresponding series connected solar cells. With the annual distribution of the illuminated cells and their respective production, the evolutionary algorithm obtain the series-parallel connection that most reduces the shadows losses. This step will be discussed in the next section.

The last step is to solve the system. The electrical subsystem is almost fully solved at this time considering that the connections and the production are already known. On the other hand, using the shadows distributions calculated before and applying (2), the program calculates the thermal energy production. The only left are the regulation devices: the water tank and the battery.

The water tank regulation is much simpler than the battery because the tank size is fixed, and given by the hot water consumption, consequently, the program computes the steady state equilibrium temperature for each time interval considering the physical characteristics of the interval itself and the equilibrium state for the previous interval (Figure 6).

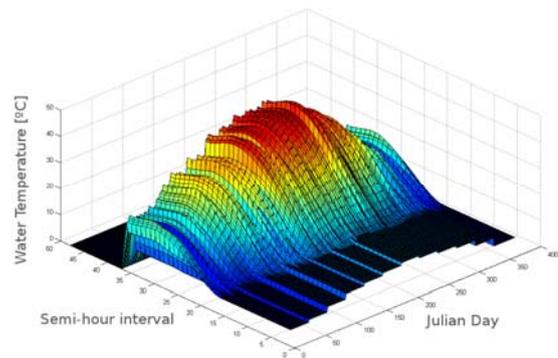


Fig. 6. Simulation of the equilibrium temperature evolution for the Figure 5 installation.

On the other hand, there are some important aspects in the electrical regulation which define the solutions:

- Maximum discharge permitted. The best choice here is to pay attention to the manufacturer recommendations.
- Battery fatigue endurance.
- The charge/discharge criteria given by the price of the different sources and hours.
- Battery capacity.

Usually, the three first aspects are fixed for a specific user, the battery characteristics and the electric market, so the best solution is that which finds the optimum battery capacity. Following a similar procedure as above, the electric subsystem behavior (offer, demand and regulation) is simulated with interval steady state computations.

### E. Evolutionary Algorithms for string connections

When a complete design study is running in the program and hundreds of proposals have to be evaluated, it is not possible to interrupt it just to manually insert the desired strings connection for each simulation. To solve that problem, an additional AI module, based on evolutionary algorithms, has been implemented.

The objective of the EA is to find the strings connections that implies less shadow losses. To achieve that, once the program knows the production of each solar cell in all time intervals for an entire year, a determined number of individuals are created. These individuals correspond with possible combinations of the connections, in consequence, each has an electric output for each associated interval.

Specifically, the EA implemented is a genetic algorithm with three phases. The first one is a generational genetic algorithm where a great number of individuals are defined and are rewarded to massively recognize the field solutions with a rough precision.

The second phase is an analysis of the solutions previously found. The goal of this step is to prepare a good and diverse enough representative sample of all the individuals in order to concentrate the valuable information in a reduced population.

Finally, the third phase is a stationary genetic algorithm with the objective of polling the rough information obtained previously.

The evolutionary algorithms implemented are not only based on trial and error. They have subroutines that accelerate the process, for example, by evaluating similarity between panels. Since it is too complex to go into detail in this paper, the only thing to emphasize here could be that this tool is the key element that allows the process to be fully automated.

In order to easily understand the process, another design is proposed in the Figure 7, while in the Figure 8 three individuals of the EA with different evolutionary development are shown. These three examples are marked in the context of the whole evolution process learning curve (a total of 3000 individuals have been proposed and evaluated).

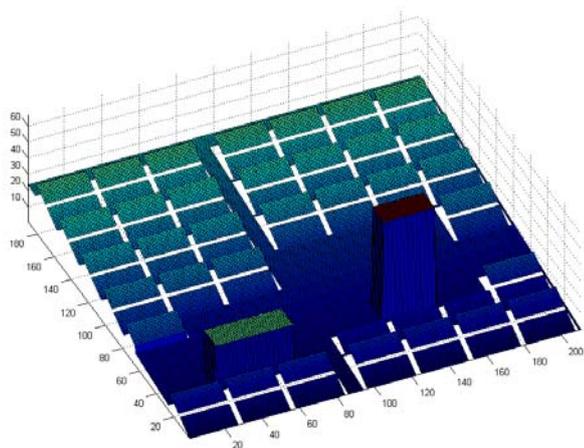


Figure 7. Geometry for the Figure 8 EA individuals.

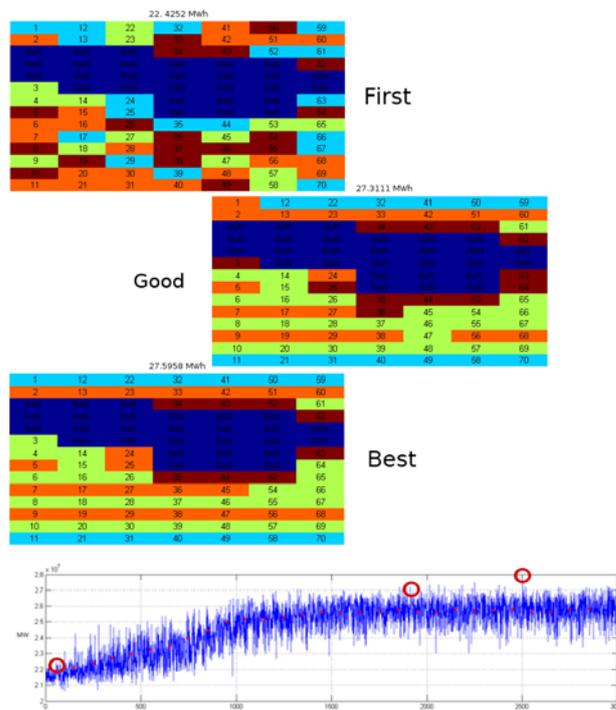


Fig. 8. Three individuals extracted from different instants of the evolution process for geometry in Figure 7 referenced in the learning curve of the whole process. The dark blue zone is where there are no panels, and the color scale indicates the four strings admissible for this simulation. It is immediately appreciated that EA groups the first and the last row, in blue, (shadeless in the whole year) in one string; the panels surrounding obstacles, the dark red, in other and the rest mostly separated by height, green for panels at the ground level and orange for in height ones.

### F. Output information

All the technical information is available after the program finishes all the computations referred to the system performance. Beyond that, the most conceptual and important information, and where the problem really shows its unique characteristics is in the Figure 9.

Thank to it, it is really easy to economically compare different technologies applied to the same problem with the certainty that the process has included all plausible solutions. Consequently, the final user can take the best decision depending on the investment, benefits and technology while the engineers handle the technical data.

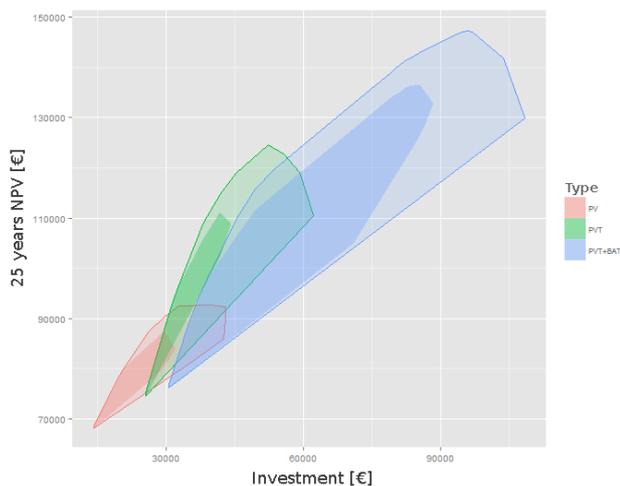


Fig. 9. Regions of the solutions field, in economical parameters, for the three kinds of systems computed for the same final user.

High density solutions (more shadow exposed panels) are in semi-transparent colors while mid or low density are in semi-solid colors. This chart compiles hundreds of designs solved.

## Conclusion

The state of the art has been overtaken. The methodology proposed can face entire complex problems autonomously, including:

- Systems form pure PV to PVT-Biomass-Battery.
- The possibility of studying multiple of them simultaneously is also available.
- It is not necessary to pre-set the string connections before the simulations.
- The geometry is strongly taken into account in the designs and, together with the final user's habits (electricity loads), the solutions are highly personalized. This makes optimization process much more refined compared to generic initial data.
- In view of the results (Figure 9), it is totally recommended to properly study the real needs and the actual conditions of every problem. For the PVT-Battery system exists more than 10000€ of benefits for the best highly dense solution compared with to the best midly dense one.
- This kind of installations makes profitable solar technologies in places where currently is not, because of lack of appropriate calculation tools or because it is using the incorrect technologies.

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