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*Research Article*

# Obtaining Maximum Electrical Energy with PV Panel Layout Optimization in Space Truss Roof Systems

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## ABSTRACT

Solar panel is mostly applied in many roof types on buildings. That the angle of solar radiation is different in curved space truss system affects the amount of voltage and current of the solar panels and overall system efficiency. In this study, meteorological information of Isparta city, technical data of various solar panels, intra-year random shadow effect calculations are analyzed. The technic of genetic algorithm is applied, and the process of computerized simulation is performed in order to find the optimal solar panel combination. Based on the simulation results, the highest efficiency will be obtained from the PV panels if PV panels application is made on the curved space truss roof system.

**Keywords:** *Photovoltaic panels (PV), Solar array, Space truss roof, Genetic Algorithm*

# Uzay Kafes Çatı Sistemlerinde PV Panel Yerleşim Optimizasyonu ile Maksimum Elektrik Enerjisi Elde Edilmesi

## ÖZET

Güneş paneli uygulaması genellikle çalışmalarda teras çatı, eğik çatı, cephe üzerine yapılmıştır. Eğimli uzay kafes sistemlerinde güneş ışınım açısının farklı olması, güneş panelleri üzerinde oluşan gerilim ve akım miktarını, toplam sistem verimini daha fazla etkilemektedir. Bu çalışmada; Isparta ilinin meteorolojik bilgileri, çeşitli güneş panellerinin teknik verileri, yıl içi rastlantısal gölge etkisi hesapları kullanılarak en uygun güneş paneli diziliminin bulunabilmesi için genetik algoritma tekniği uygulanmış bilgisayar ortamında simülasyon işlemi gerçekleştirilmiştir. Bu sonuçlara bağlı olarak, eğimli uzay kafes çatı sistemlerine PV panel uygulaması yapılırsa en yüksek verim elde edilebileceği sonucuna ulaşılmıştır.

***Anahtar Kelimeler:*** *Fotovoltaik Paneller(PV), Solar dizi, Uzay Kafes Sistemleri, Genetik Algoritma*

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# I. INTRODUCTION

Today, the rapid increase of the population and the depletion of traditional energy sources increase the demand for renewable energy sources. Among renewable energy sources, solar or photovoltaic (PV) energy is preferred because of its low cost, low operating and maintenance costs and its universal availability. Electricity from solar energy is obtained directly by PV cells. The power obtained from a PV cell is low. Depending on the energy requirement, the module or panel is connected by connecting PV cells in series-parallel configuration, and arrays are formed by connecting modules in various configurations. [1], [2]. Solar energy systems can operate standalone or connected to the grid. [3]-[5]. PV modules are combined with system components; e.g., inverters, batteries, electrical components and installation systems [6], [7].

The most of space truss roof structures are used for large span buildings, particularly gas stations, stadiums and railway stations. The main elements of these building systems are nodes and pipes. Space truss systems give the buildings modern identity with their visuality, though they are perceived and used as roof coverings to a large extent. It is a light roof type due to its ability to work statically in three dimensions. In the space truss systems, the integration points of the pipes are spherical and hot forged shaped steel materials. [8], [9].

Yeşilata and Fıratoğlu [10], investigated the optimum design and operating conditions of the PV system. In this study, they aimed to provide the required power by using minimum number of PV panels. Karatepe et al. [11], in their work, they studied the change of the parameters of the solar cell single diode equivalent circuit for different temperature and radiation conditions and developed a new model based on artificial neural networks. In her work, Mutlu [12], aimed to develop a model proposal that will enable roof systems and roofing material manufacturers and contractors to evaluate all of the alternatives together in the work of renewing existing roof systems as photovoltaic roof system and in the design of photovoltaic roof system in new buildings. Wang and Hsu [13], In their studies, they performed analytical modeling of PV modules with segmented shadow effect and different orientation. Deline et al. [14], presented a simplified analytical model for large PV lattices with constant shading effect. Considered the ratio of shaded PV panels under serial and parallel connections over all PV panels. Balato et al. [15], In their study, they investigated serial and parallel connection states of PV arrays with an algorithm. They tried to solve the mismatches in the different connections with the Monte Carlo algorithm which consists of 24 PV panels.

In this study, the most suitable connection design is obtained and simulated by placing the PV panels on the roofs of vault shaped space truss roof system. For this purpose, firstly the solar radiation was examined and analyzed, then the mathematical model was determined by investigating the factors affecting the working of the solar cells together with the technical characteristics. In the other step of the study, the use of PV panels on building surfaces and roofs was examined and the geometric structure of the space truss systems was analyzed. When the vault shaped space truss roof system was examined, it was determined that different angles would form on the surface of each PV panel. This will result in loss of power and efficiency in the system due to different current or voltage mismatches be-tween PV panels in PV array to be formed by serial or parallel connection. Depending on the type of inverter applied to the input, different serial and parallel connection types would occur. The amount of power to be obtained varies with the connection sequence of the PV panels. Optimization is needed to keep the power at its highest value. By using genetic algorithms as the optimization technique, the application to obtain the most suitable PV array connection has been developed.

The paper is structured as follows; in the second chapter, PV is explained. In the third chapter, space truss roof systems are explained. Chapter four describes the genetic algorithm. In the fifth chapter, the developed simulation software is explained. In the sixth chapter, the data obtained with the software is explained. In the last chapter, the results of the study are summarized.

# II. PV SYSTEM DESCRIPTION

In the literature, there are various electrical equivalents of the PV cell. A diode model is one of the most popular models. Single diode models' equivalent circuit is shown in Figure 1. The circuit has a photocurrent (Iph), a diode (D), a parallel resistor (Rp) a series resistance (RS) referring to an internal resistance of the PV cell. [13], [16].

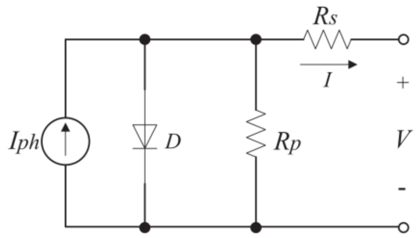



***Figure 1.*** *A photovoltaic array's equivalent circuit* [16]

A PV cell's voltage-current characteristic equation is written as in the following

$$I = I_{ph} - I_0 * \left[exp\frac{q}{kTA}(V + IR_s) \; - 1\right] - \frac{V+IR_s}{R_p} \tag{1}$$

where $I_{ph}$ is light generated current, $I_0$is saturation current of first diode, T is the cell's operating temperature in Kelvin (K), k is the Boltzmann constant (1.381×10−23 J/K), q is the electron charge (1.602×10−19 C) [2], [17].

The power, which a solar cell generates, is between 1-1.5 W. Thus, the solar cells must be connected in series or parallel to obtain the desired power. PV cells must be connected in series parallel configuration on the module to increase the amount of output power and voltage. A PV module consists of a NP parallel cell and a NS series cell. The output current of the PV module is written in the equation 2 [18].

$$I = N_p N_{ph} - N_P I_0 \left( e^{\frac{q\left(\frac{V}{N_S}+\frac{IR_S}{N_p}\right)}{kTAN_h}} - 1 \right) - \frac{\frac{N_p}{N_S}V + IR_s}{R_p} \tag{2}$$

*$I_0$* is cell reverse saturation current, *A* is an ideality factor of diode; *NP* is the number of PV cells connected in parallel; *NS* is the number of PV cells connected in series.

The power-voltage (P-V) and voltage-current (V-I) characteristic curves of the PV panel must be determined. While solar irradiation and PV panel power change in direct proportion, the increase in temperature decreases PV panel power. Under variable temperature, the characteristic curves of P-V and I-V and radiation are shown in Figure 2 (a, b, c, d) [2], [19], [20].

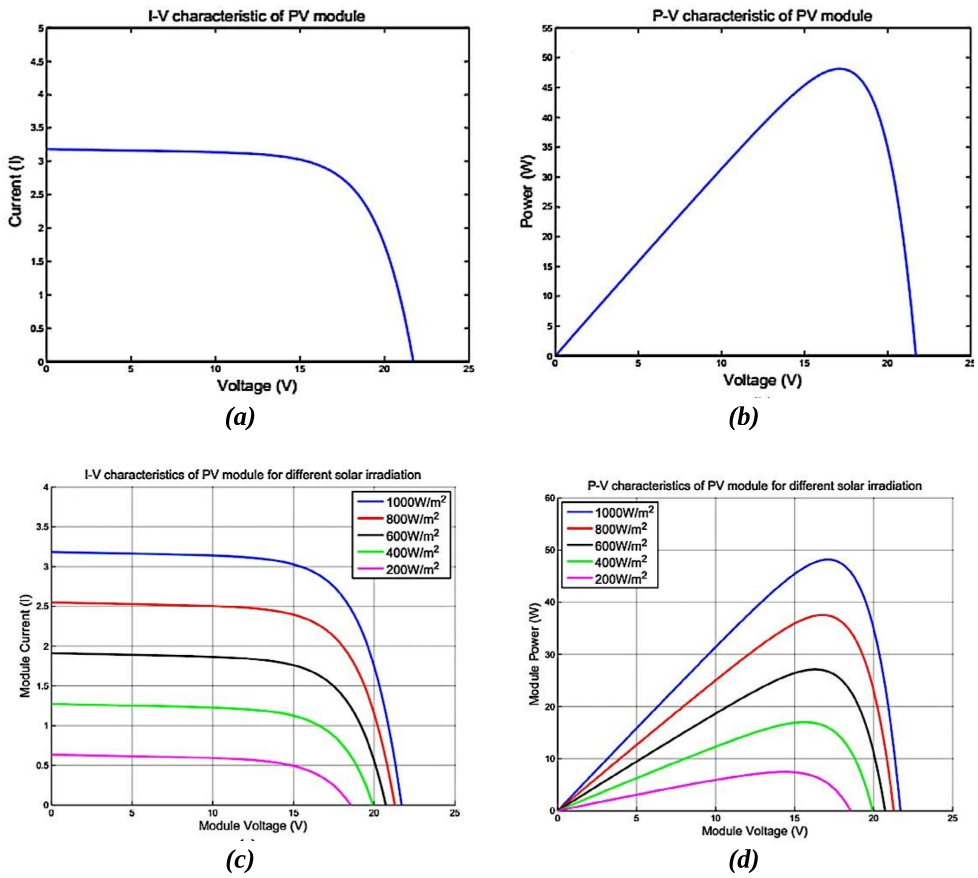



***Figure 2. (a)*** *I-V,* ***(b)*** *P-V characteristic of PV module,* ***(c)*** *I-V and* ***(d)*** *P-V characteristic of PV module for different solar irradiation* [3]

# III. SPACE TRUSS ROOF SYSTEMS

Space Truss systems are very suitable for covering roofs having large spans without using columns or using a small number of columns. The carrier system has two main components: pipes and nodes.
In vault-shaped space truss systems, all the factors that change the geometry of the system, change the system weight. It is possible to collect the main factors that change the geometry under three main headings. These Factors: Span of the arc that gives curvature to the system(L), geometric height of the system (H), are the geometry of the arc that gives the system its curvature. Figure 3 shows an example space truss roof system [21].

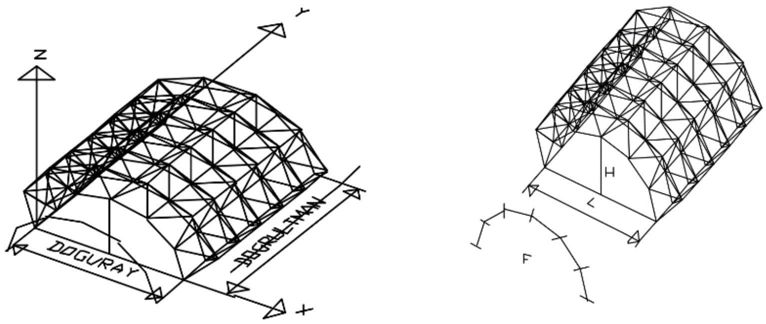



***Figure 3.*** *Space Truss Roof System* [21]

For additions such as integrated systems or PV modules on this surface, the length of the parabola must be calculated. Arc length equation;

$$arc\ length = \frac{1}{2}\sqrt{L^2 + 16H^2} + \frac{L^2}{8H} In\left(\frac{4H+\sqrt{L^2+16H^2}}{L}\right) \tag{3}$$

Figure 4 shows the curve between the point on the parabola and the surface. This angle must be found to find out the angle of PV module which is placed on the surface of parabola. When the angle is found, a vertical line is drawn. The equilibrium of the straight line can be calculated using the point on the parabola. When the line is extended until it intersects the x axis, the angle in between is equal to the angle α. The angle α can be calculated by taking the arctangent of the slope value after finding the slope of the correct balance [22].

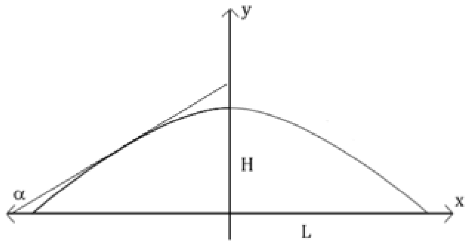



***Figure 4.*** *The curve between the point on the parabola and the surface* [22]

# IV. GENETIC ALGORITHM

In order to obtain an optimum solution of a problem, Genetic algorithm (GA) is a useful optimization technique repeating at different stages such as selection, crossover and mutation. The natural selection process is simulated by Genetic Algorithm by using bio-inspired operators such as crossover and mutation. This theory is based on the survival of the fittest. According to genetic algorithm, solution population is significant. A fitness function against each solution is evaluated and the fitness of each solution is calculated. In the next iteration, the individual's survival relates to the fitness value of the individual. If the individuals have the lowest eligibility value, they will be removed from the population [23]. Genetic algorithms are random search algorithms. The fitness value of a population may remain constant for a certain period of time until the fittest individual appears. Evolution is continued by replacing the new population of offspring produced by natural selection, crossing and mutation with the existing population. The genetic algorithm terminates when the specified number of generations evolves, or when a reasonable solution is achieved at the desired level and the individual with the highest conformity value is considered the most appropriate solution and the transaction is concluded. [24]. Before a genetic algorithm can be run, an appropriate coding for the problem must be designed. A fitness function is also required, which assigns a value to each encoded solution [25].

A standard genetic algorithm pseudo code is [26]:

```
InitPopulation(P)
Fitness(P)
  while MaxGenerationNotReached do
        for i = 0 to xfactor do
              p1 = Selection(P)
              p2 = Selection(P)
              (o1, o2) = crossover(p1, p2)
              crowding(p1, p2, o1, o2)
        end for
         for i = 0 to dfactor do
```

```
        p = Selection(P)
        Dropping(p)
        end for
        for i = 0 to mfactor do
              p = Selection(P)
              Mutation(p) end
        end for
        Fitness(P)
  end while
SelectBestIndividual(P)
```

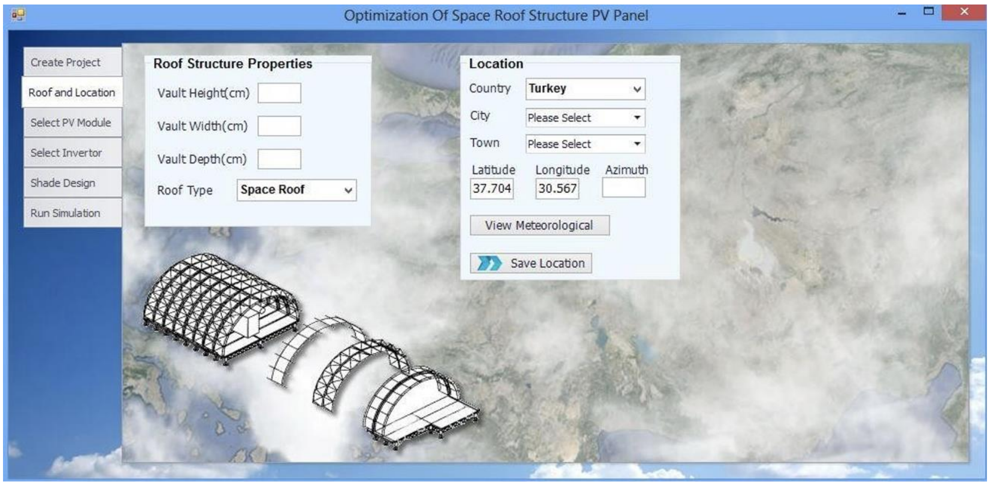
## V. SOFTWARE DESIGN

By the developed software, PV array design which can generate annual maximum energy to roofs with vault shaped space truss system is simulated with genetic algorithm. For this process, each PV module is treated as a gene and the initial population is obtained from these genes by resembling different PV array designs according to the roof size and characteristics. Then new individuals are formed from the population and a new population is established. In order to perform simulation process; PV module, meteorological information, roof system, location information of the region must be saved and read from the system. A database is used in the software to process all this data. The start-up form allows the creation of a new simulation process or shows previously created simulations. Before the simulation process is performed, the main form is opened to add the information about the software to the system and to display the supporting data presented by the system in the application. In order to model the work on the roof of the vault-shaped space truss system, the geometric features data of the structure must be entered to the project. The performance of PV modules is directly related to the climatic and geographical characteristics of the region where it is applied. Therefore, the location data of the simulation must be entered to the project. In the study, real measurement of Isparta province's meteorological information was used and simulated. The software consists of many functions, methods and classes. There are classes in which the optimization process is carried out with the genetic algorithm. One of the methods in these classes is created for the fitness function of the genetic algorithm. Since the annual time interval is considered, it is aimed to find the maximum value by summing the amount of power generated in all hours during the year. Here, the voltage and current values of the PV modules in the PV mesh are calculated according to the connection type on the circuit. Fitness function is written in the equation 4.

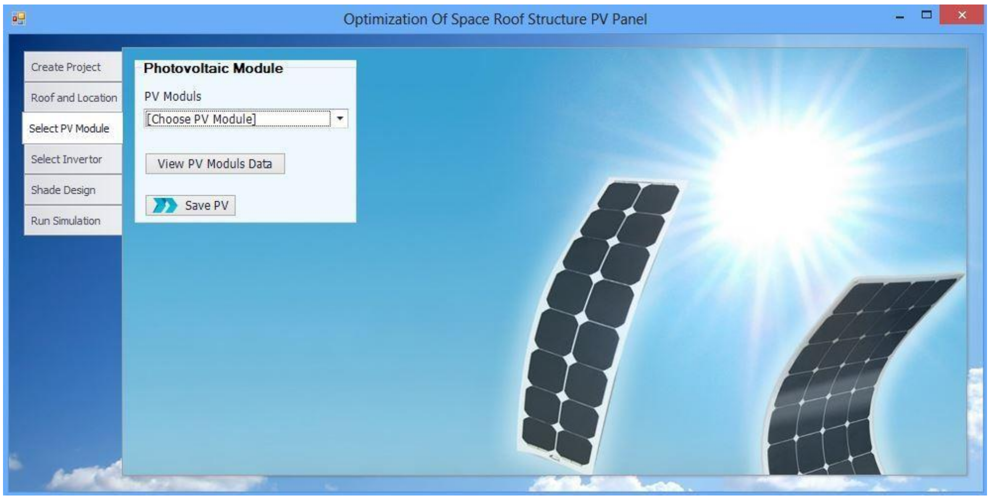
$$PT = \sum_{t=0}^{t=365*24} V_{eq_t} I_{eq_t} \tag{4}$$

$V_{eq}$ represents the equivalent voltage and $I_{eq}$represents the equivalent current. The total power can be calculated at all times from hour t = 0 to t = 365 * 24 hours. Our aim in the study is to find the connection type with the highest power value.

Another step in the simulation process is the selection of the PV module which will be used. PV modules can be selected from the software, as well as PV modules can be selected from a different form which shows detailed information. Figure 5(a) shows the form for entering the geographic information and Figure 5(b) shows PV Selection Form.



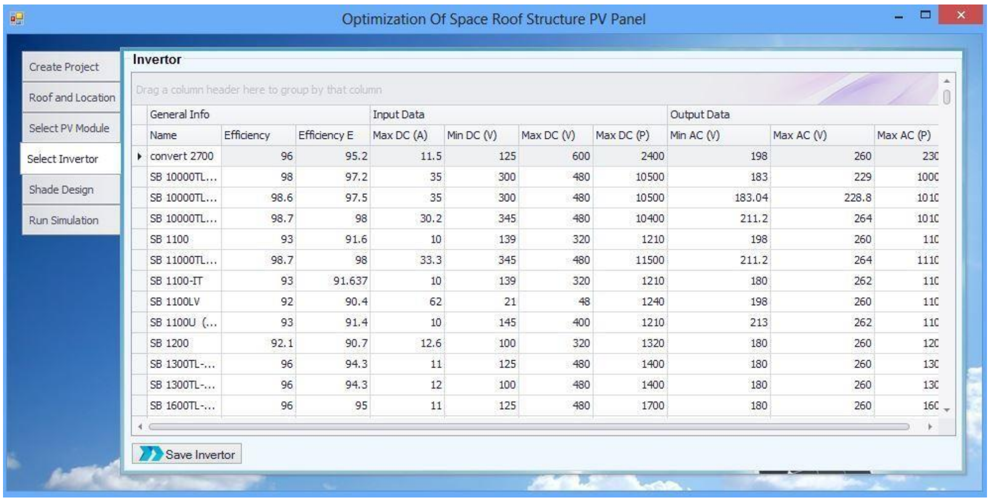

*(a)*



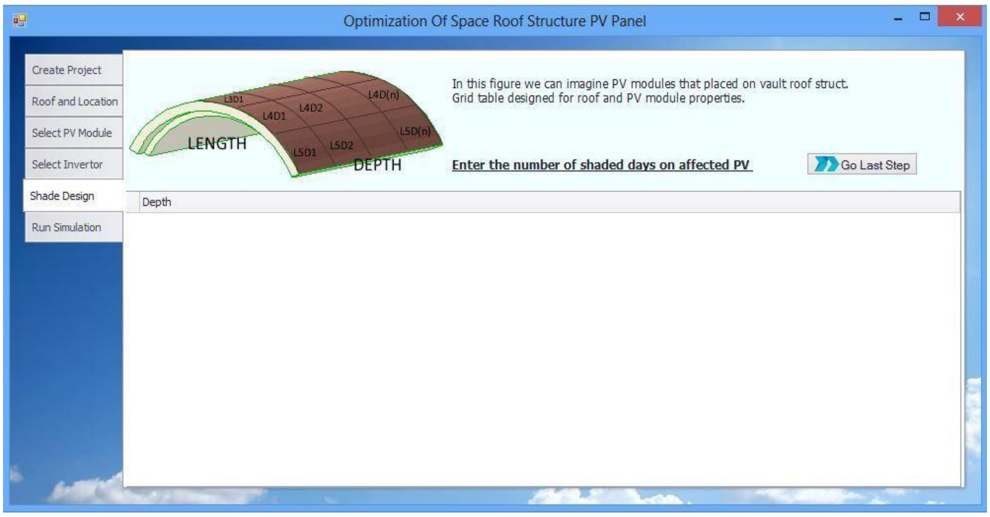

*(b)*

***Figure 5. (a)*** *Geographical information Form* ***(b)*** *PV Selection Form.*

The selected inverter model determines the number of PV panels that can be connected in series and in parallel in the PV panel system. This number varies according to the input current and voltage information of the inverter. In order to design the system, the inverter type must be specified. The form shown in Figure 6(a) helps to make the selection according to the inverter specifications. The last step is the addition of the number of days that the PV modules are shaded. Figure 6(b) shows shading information form. Depending on the length and depth of the roof, the PV module matching the relevant grid cell should be written on average for how many days it will stay in the shadow effect.




*(a)*




*(b)*

***Figure 6. (a)** Inverter selection **(b)** Shading Information Form*

Once all these operations are performed, the optimization can be started via the Run Simulation tab. In Run Simulation tab, first of all, a form is designed to enter values such as elitism criterion, number of iterations, mutation probability related to genetic algorithm. Once all values are entered, the calculations are started, and the results are obtained. Genetic algorithm results can be checked from other tabs in the same section. Detailed information of each PV module can be seen on the different tab. Clicking on PV modules opens the details and shows in detail the angle where the PV module is located. A calendar shows the power the PV module will generate at any time of the year. Figure 7 shows the details of PV panels.

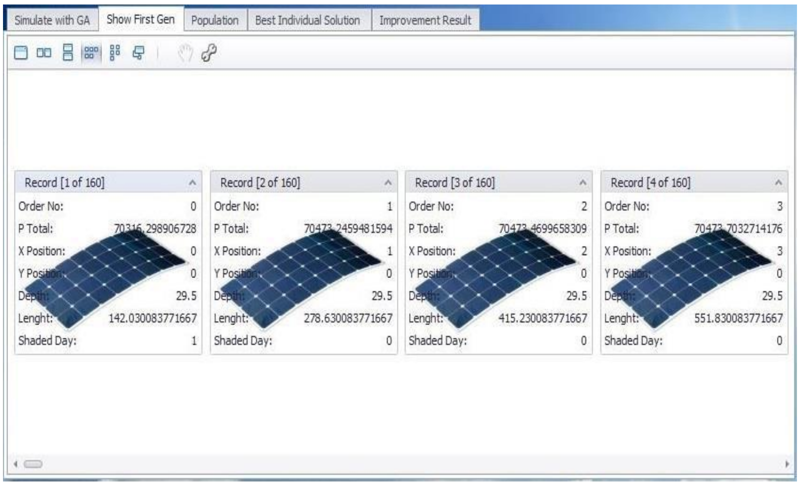
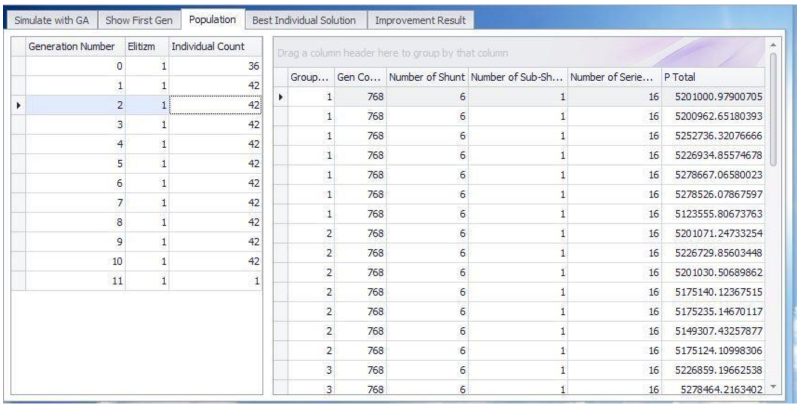
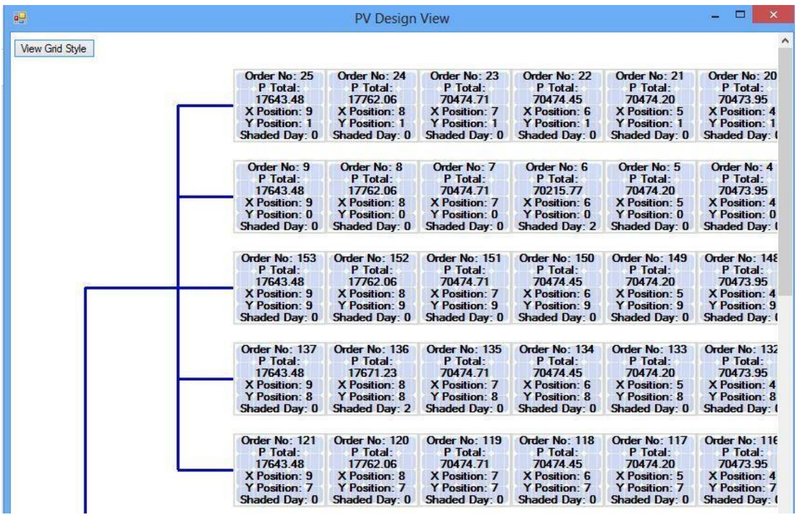



***Figure 7.*** *PV Simulation Details.*

In the Population tab, information of all individuals created during the simulation process can be seen. PV array design, circuit diagram and PV module can be seen with general information by clicking on individuals. PV grid design can be viewed as grid list on this form. Figure 8 (a) shows population tab, Figure 8 (b) shows the details of the PV modules.




***(a)***




***(b)***

***Figure 8. (a)*** *Population Tab* ***(b)*** *PV Modules Details*

As a result of the simulation, the most appropriate solution can be seen. The individual in the list is created PV mesh design that produces the highest power and efficiency. The tab shown in Figure 9 is arranged to compare the best result with other results and to see how much the system has been improved. The ratio of the highest power generating design to the least power generating design and the success rate of the optimization process can be easily seen and examined.

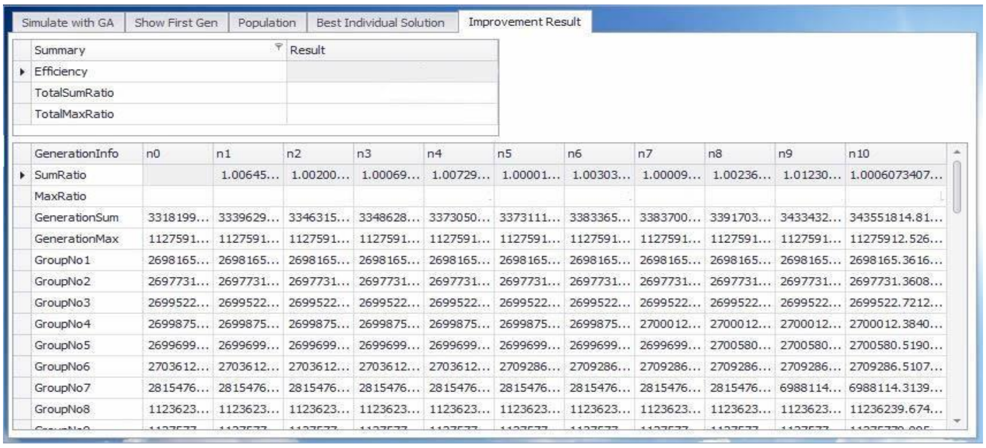
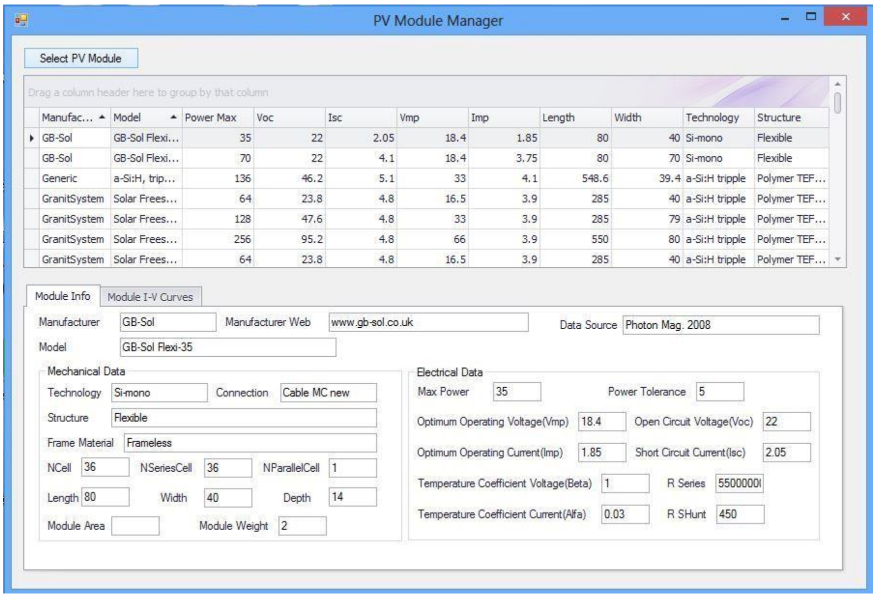


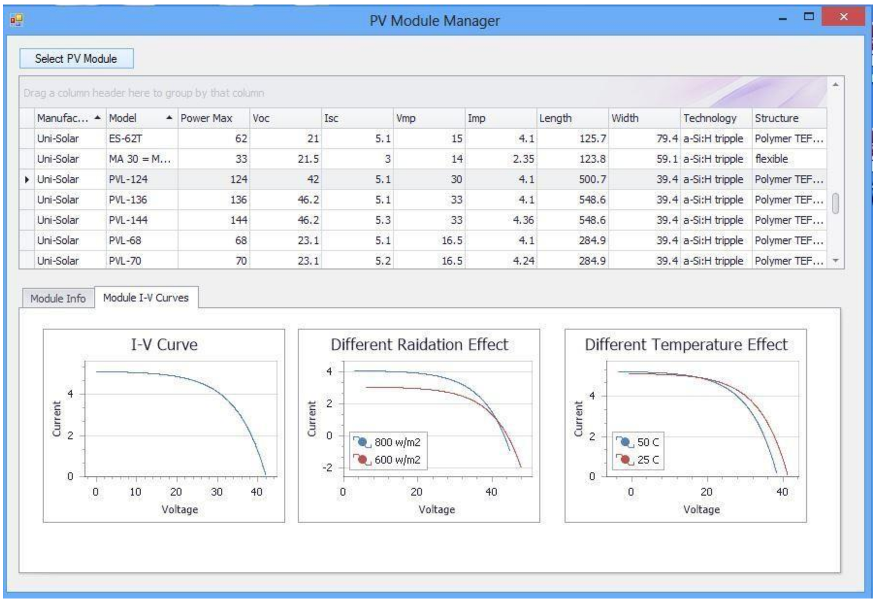

***Figure 9.*** *Improvement Result Tab*

## A. PV MODULE FORM

The most important factor determining the power of the system in the simulation process is the PV modules where PV array is formed. There are thousands of PV panels produced by many companies on the market. The user must see the PV panel data provided by the manufacturer when making the selection. In the study, the data of PV panels were provided from manufacturers' datasheet, Photon magazine and other PV panel applications. Only the flexible PV panels are shown to the user. Other type of PV panels cannot be used in vault-shaped space truss roofs. In applications where the roof type can be changed, all PV panels can be shown to the user. Manufacturers, models, electrical and mechanical information of PV panels, current-voltage graph, current-voltage graph under different temperature and radiation can be seen on the form. Comparison with other PV panels can be made. The user can select the desired PV panel from this form and add it to project. Figure 10 (a, b) shows the PV module form interface.




***(a)***




***(b)***

***Figure 10.*** *PV Module Form and Module List*

# VI. RESEARCH FINDINGS AND DISCUSSION

In this study, the placement of PV modules on the space truss roof system is calculated according to inverter selection, the amount of power that PV modules will produce in different connections by using genetic algorithm and a PV array is obtained to calculate maximum energy. The evaluation of the Genetic Algorithm process and its results according to two different simulation procedures, the comparison of the connection patterns of PV array was analyzed and interpreted. The climatic characteristics of the region to be simulated are very important. In this study, solar radiation information of Isparta province is used from data provided from TÜMAŞ data access center of General Directorate of Meteorology. Radiation, temperature and sunshine data are available hourly over a period of one year. The US-32 model of the Uni-Solar manufacturer was chosen for the PV module to be installed on the roof surface. The maximum power of this PV module is 32 W, open circuit voltage is 23.8 V, short circuit current is 2.4 A. In addition, there are 22 PV cells in the PV module, 11 series and 2 parallel connections. In the first simulation, the inverter, which determines the PV module connection type, was selected as SB3000 (3.2 kW) with a 95% efficiency value. This inverter supports 12 A current, 268 V-480 V voltage range according to input specifications.

## A. EVALUATION OF CONNECTION TYPES IN PV ARRAYS ACCORDING TO INVERTER SELECTION

PV modules used in PV braids can be connected with each other while serial or parallel connection methods are used. The characteristic that determines the connection type is the inverter that applied to the input. It was calculated that 768 PV modules should be used in both simulations. The connection types of these PV modules and the obtained power values are shown in Table 2.

***Table 2.*** *Connection types and associated power ratings*

| Inverter Type | Invertor Count | Parallel Line | Serial PV Module Count | Total Power with GA Optimization *(W)* | Total Power without GA Optimization *(W)* |
|---|---|---|---|---|---|
| **SB3000 (3.2kW)** | 8 | 6 | 16 | 5382297.52 | 5019983.15 |
| **SB 6000US 11-277VAC (6.5kW)** | 4 | 12 | 16 | 5389954.0 | 4914342 |

In two different simulations realized according to 768 PV modules, connection methods are designed in 2 different combinations. It was observed that the obtained power value increased when the number of parallel connections between PV modules increased. In the case of the SB3000 inverter type, an improvement of 7.2% was obtained when the genetic algorithm was applied, and in the case of the SB 6000US 11-277VAC inverter type, an improvement of 9.678% was obtained when the genetic algorithm was applied.

# VII. CONCLUSION

In this study, genetic algorithm technology applied computerized simulation process was performed in order to find the optimal solar panel combination with using the meteorological information of Isparta, technical data of various solar panels, and intra-year random shadow effect calculations. Depending on simulation results, if PV panels application is made on the curved space truss roof system, the highest efficiency will be obtained from the PV panels. By using genetic algorithms as the optimization technique, the application to obtain the most suitable PV array connection has been developed. The highest amount of power and efficiency to be produced throughout the year is calculated using the genetic algorithm. For the future works different algorithms and optimization technics can be applied.

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