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The Best Architectural Form for BiPV in Tehran

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گزینش مناسب ترین حجم معماری برای بناهای یکپارچه با سامانه فتوولتائیک (BiPV) در تهران

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Abstract

Achieving sustainable architecture may be feasible by using renewable energies. Solar power can be exploited in building via photovoltaic and collectors to produce electricity and heat and it will lead to GHG reduction. Building integrated photovoltaic (BiPV) systems can form a cohesive design, construction, and energy solution for the built environment. PVs produce electricity and have special aspects that can be utilized. The expressive and impressive aspect of a photovoltaic system designed and applied on the envelope of the buildings can not be ignored and the architect should appreciate PV's abilities to perform as an exterior material as well. Designing a BiPV needs a team in which everyone plays his/her own role to reach the maximum output through the system. This paper will analyze the best architectural form and specification of a BiPV in Tehran. In this research diagrams of annual and seasonal total of global radiation in Tehran will be produced. With regard to diagrams the best tilt angle will be discussed. Finally, some basic forms such as cube, prism and box will be analyzed to receive the maximum solar radiation and an isosceles triangle for the best choice.

Keywords: Photovoltaic, Architecture, Form, BiPV, Iran.

چکیده

دست یابی به معماری پایدار با به کارگیری انرژی های تجدیدپذیر مانند تابش خورشید امکان پذیر است که در ساختمان، فناوری فتوولتائیک و کلکتور خورشیدی آن را به ترتیب به الکتروسیسته و گرما تبدیل کرده و با این کار از مصرف سوخت های فسیلی کاسته و باعث کاهش تولید گازهای گلخانه ای و در نتیجه پرهیز از آلودگی محیط می شوند. بناهای یکپارچه با فتوولتائیک (BiPV) که فناوری فتوولتائیک در آن ها به صورت بخش پیوسته و یکپارچه ای از بدنه بنا است، راه کاری جامع برای حصول پایداری در محیط مصنوع است. برای این منظور باید معمار به این فناوری همانند مصالح ساختمان نگرسیسته و وظیفه هر کس در گروه طراحی به گونه ای تعریف شود تا بتوان تا جای ممکن بالاترین بازده از سامانه فتوولتائیک حاصل شود و بنا ساختاری هماهنگ و یکپارچه داشته باشد. این مقاله بر آن است تا با تحلیل احجام مختلف معماری در تهران بهترین آن ها را از نظر دریافت تابش خورشید مشخص نماید. در این راه ابتدا نمودارهای تابش دریافتی سالانه و فصلی ترسیم شده و مناسب ترین زوایای ارتفاع و جهت در شرایط مختلف تحلیل می شود. سپس بعضی احجام متداول معماری از نظر تابش دریافتی مقایسه شده و مشخص می شود منشور با قاعده مثلث متساوی الساقین مناسب ترین حجم است.

واژه های کلیدی: پایداری، انرژی، معماری، بنای یکپارچه با فتوولتائیک (BiPV)، ایران.

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Introduction

Iran not only enjoys vast and valuable deposits of fossil fuels which contribute to her economy, but is also a rich country in terms of renewable energy resources where scientists and researchers have made special efforts in finding and developing renewable sources as well as adopting related technical knowledge in the process (Hagemann, 1996).

In recent years, society has become aware of and therefore sensitive to the destruction of the natural environment with its unforeseeable economic and ecological consequences. With the purpose of conservation, goals have now been set to reduce the consumption of fossil fuels and to utilize energy more efficiently and cost-effectively (The German Solar Energy Society, 2005).

As a result of these goals, specifications and requirements for the construction and design of buildings have also changed. In the centre of interest is the building envelope, the interface between the outside and inside worlds. Owing to the growing expectations of today and tomorrow, the building interface has become a complex, multifunctional component. New technological developments have allowed completely different visions of a conventional facade or roof to be created. Apart from providing protection against the weather and acting as a defense mechanism against intruders, the envelope must increasingly meet society's growing insistence on comfort, the obligation to save fossil energy, the need to avoid the unwholesome effects of a man-made environment such as noise pollution, waste gas emissions or other influences and the demand to make use of active and passive solar design principles and techniques.

All parts of the surface of a building are suitable for the installation of photovoltaic arrays: sloping and flat roofs, and facades. A distinction can be made between additive and integrative solutions (Thomas, 2001). In an additive solution, photovoltaic modules are fastened on top of the roof or onto the facade using a metal structure. As a result, the photovoltaic system

is an additional technical structural element on the building with the sole function of generating power. In an integrative solution, building components of the roof or facade are replaced by photovoltaic components. The photovoltaic system becomes part of the building shell, and in addition to the function of generating power, performs functions such as weather protection, heat insulation, noise insulation, sun shading and safety. This enables further benefits to be derived from the PV and a more aesthetically pleasing solution.

PVs offer enormous potential to building designers but, as an architect has said, "it has to be done right from the start" - they should not be an afterthought. PVs can influence the building's orientation, footprint, layout and form; they will affect the building fabric and will be an important element of the environmental and building systems. They need to be considered as an integral part of the energy strategy of the building and of its functioning. The integration of PVs with the other building elements is critical to success. Appearance and aesthetics are, as ever, especially important (Fadai, 2007). Architects should be aware of PVs limitations and requirements to perform a good design either for system output or building aspect. Each design based on integration not addition of PVs on building needs to determine optimum angle and orientation of PV system for walls, roof and etc. These could affect building form in each region and have influence on building layout, plan and facades. So each architect who integrates PV arrays onto a building have to deal with some information at the first stage of design to reach a proper form for a BiPV. The main questions of this paper are "what is the best form of a BiPV in Tehran?" This research is going to answer if there is any flexibility to choose the best form.

PV Systems and Applications

PV systems can be divided into grid-connected systems and stand-alone systems. For the latter, the

solar energy return needs to be adjusted to the energy demand. As the solar energy yield often does not correspond to the temporary energy demand of the consumer using the system, it is necessary to use additional energy storage (batteries) and sometimes additional sources of energy (hybrid systems).

In the case of grid-connected systems the public electricity network operates as storage for the electricity produced. In general, most of the installed capacity of PV systems in developed countries today is grid-connected, whereby the produced energy is fed into the public electricity grid or consumed in the dwelling (The German Solar Energy Society, 2005).

While PV systems will be installed increasingly throughout the world over the coming years, in the long term it is expected that more and more stand-alone systems will operate, especially in developing countries. However, it should be noted that even today some economically developed countries such as the US and Australia continue to have the bulk of their PV system installations outside of the public electricity network.

Stand-Alone Systems

The first commercial market for photovoltaics was for stand-alone systems. Wherever the energy supply via the grid of the electric utility was neither possible and economic nor desirable, PV systems could be installed economically as stand-alone systems. This operational area continues to grow. There is a great potential for the implementation of stand-alone systems in developing countries, where large parts of the country often still remain without electricity supply. But new potentials are also being created by technical developments and techniques to decrease cost in the field of production in industrialized countries (Markvart, 2006).

Grid-Connected Systems

A grid-connected PV system generally consists of the following main components (Markvart, 2006):

- PV generator (comprising a number of PV modules connected in series and parallel atop a mounting structure)
- DC switch disconnecter
- DC cabling (optional)
- Inverter
- AC cabling, AC switch disconnecter and energy meter.

BiPV design

Benefits

Interest in the building of integrated photovoltaics (known as BiPV), where the PV elements are integral to the building, often serving as the exterior weathering skin, is growing worldwide. PV specialists from some 14 countries have worked within the International Energy Agency's Photovoltaic Power Systems Implementing Agreement over the past several years to optimize these systems, and architects in Europe, Japan, the United States and Australia are now beginning to explore innovative ways of incorporating solar electricity into their building designs (Oliver and Jackson, 2001).

A BiPV has many additional benefits (Prasad and Snow, 2005):

- The building itself becomes the PV support structure.
- System electrical interface is easy - just connect to a distribution panel.
- BiPV components displace conventional building materials and labor, reducing the net installed cost of the PV system.
- On-site generation of electricity offsets imported and often more carbon-intensive energy.
- Architecturally elegant, well-integrated systems will increase market acceptance.
- BiPV systems provide the building owners with a highly visible public expression of their environmental commitment.

Design

A successful BiPV solution requires interaction between building design and PV system design (Prasad and Snow, 2005). The approach can be fully to integrate the PV system in the building, displacing a conventional external building material, such as tiles on a roof or cladding against a façade. An alternative, but equally valid approach is to see the PV system not as an intrinsic building design issue, and to place it onto a building element, such as a roof or other fixture. The integration of PV systems in architecture can be divided into five approaches. According to Prasad and Snow (2005) it can be:

- Applied seamlessly. The PV system is applied seamlessly and is therefore not architecturally disturbing. An example is in Maryland, USA (Figure 1.) where the PV is laminated onto the roof and is barely visible. This solution was chosen because the entire project is of historical significance. A modern high-tech material would clearly not be appropriate for this architectural style (Sick and Erge, 1996).

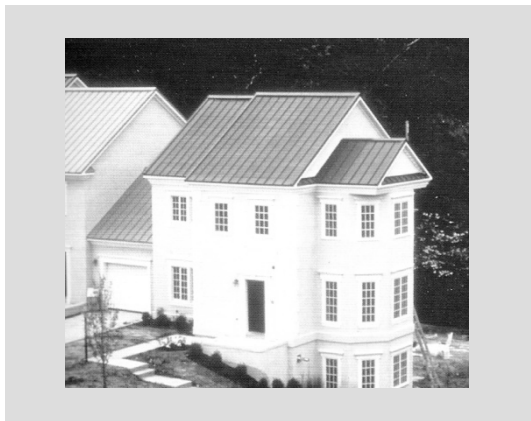


Figure 1. PV on a dwelling in Maryland, USA (Prasad and Snow, 2005).

- Added to the design. The building may be missing a design function that PV can fill in the form of, for example a practical PV shading device, as shown in a building in Madrid, Spain (Figure 2.). This can occur if the intended purpose of internal spaces within the building changes or the comfort levels required need to be improved. Adding PVs to the building in this situation does not lead to an inelegant outcome (Gyoh, 2000).



Figure 2. IES building in Madrid, Spain (Prasad and Snow, 2005).

- Added to the architectural image. The PV system adds to the architectural image by being integrated into the total design of the building without dominating the project. In other words, the contextual integration is excellent. PV provides a visual statement that can either offer subtle or substantial changes to the architectural dynamics of the building the EMPA building's PV facade and roof canopy gives visual effect to the design without overpowering the original building form (Figure 3).

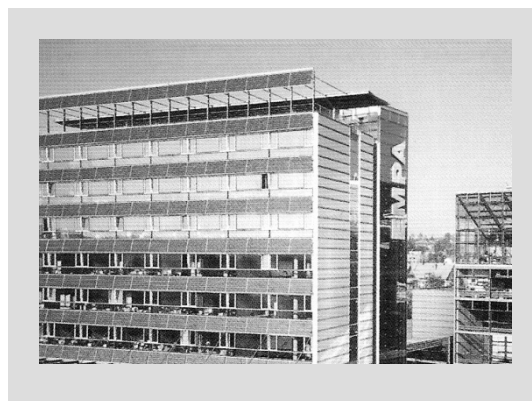


Figure 3. EMPA building in St. Gallen, Switzerland (Prasad and Snow, 2005).

- Used to determine the architectural image. The PV system is used as an integral part of the building envelope and thus shows a harmonic building characteristic. Figure 4 shows dwellings in the Dutch development at Langedijk using PV to dominate the roof aspect and aesthetic feel of the area. The blue colored PV roof, while unconventional, blends effectively with the water and sky vista (Abro, 1999).



Figure 4. Dwelling on the 5 MW site Langedijk, Netherlands (Prasad and Snow, 2005).

- Used to explore new architectural concepts. The application of PV modules, particularly in combination with passive solar design concepts, leads to new designs and new architecture. Figure 5 shows the translucent properties of PV, creating curved or dynamic surfaces as a fundamental construct of the building. Architecturally, this presents new design options, working with a variety of support structure materials and complementary building textures, such as wood and steel. Importantly, the architect can control and experiment with the natural lighting dynamic within the building and transform the color and feel of the internal spaces as the sun's position alters during daylight hours. This creates a new appeal and innovative architectural building form (Abro, 1999).



Figure 5. Interior of conservatory with transparent modules at ECN in Petten, the Netherlands, (Prasad and Snow, 2005).

These categories have been classified according to the increasing extent of architectural integration. However, a project does not necessarily have to be of a lesser quality just because PV modules have been applied seamlessly. PV modules are new building materials that offer new design options. Applying PV modules in architecture should therefore lead to new designs (Oliver and Jackson, 2001).

Material and Methods

PV is a technology to produce electricity from solar power. It is obvious that if electricity output of system is not acceptable it will be a failure for all the system. One of the most important issues in this field is to have the maximum solar radiation on PVs. Each BiPV faces a variety of solar architectural factors and requirements in order to achieve high-quality building integration and solar yield. Three important questions arise:

- What is the best solar yield?
- What is a good solar yield?
- What is an excellent solar yield?

It should be mentioned that architecture deals with a lot of issues and all of them need to be met. Therefore, a BiPV can not always harness maximum solar irradiation, the best solar yield, and like other issues in architecture, solar yield is a scope. This means that, if a BiPV can reach to 90-98% of solar irradiation on certain surfaces like roof and walls, the solar yield will be excellent; figures between 80-90% can be noted as good solar yield. Consequently, a wide range of surface orientations can obtain a very useful solar yield at only a few percent less than the maximum. It is very pleasant to have a wide range of choices in architecture and it provides flexibility that is essential for architecture.

Figure 6 demonstrates a northern hemisphere example for determining the angle of incidence of a tilted PV module relative to the position of the sun at a given location and time of year. The main types of

building integration and associated tilt angles can be distinguished and related to the time/period of production and consumption of solar electricity. These include annual, seasonal and daily/hourly solar energy yield.

In general, one of the most critical factors to be considered is the orientation of the building envelope elements towards the sun. The question is: how does the orientation of the building envelope influence the solar yield? The solar yield for flat and sloped roofs as well as for facades in Tehran can be calculated in different ways:

- Annual solar yield for the building envelope;
- Seasonal solar yield for the building envelope;
- Daily/hourly solar yield for the building envelope.

Best/good daily/hourly solar yields can partly differ from best/good annual and/or seasonal solar yields. Using daily/hourly solar yield for the building envelope can be useful when there is a specific daily/hourly load, for example, before or after noon. In this paper, the annual and seasonal solar yield is discerned for Tehran. All of the calculations were

done by METEONORM version 5.1.2 by METEOTEST. This software has a broad database that supports Tehran Mehrabad weather station and is also simple and user friendly.

After calculating annual and seasonal solar yield, some diagrams were produced; AutoCAD 2007 by Autodesk was used to draw the diagrams. In regard to diagrams and rate of solar irradiation on different orientation and tilt angles the shape of a BiPV plan was concluded. At the end there is an evaluation on the proportion of length to width of rectangles to receive the maximum solar radiation.

Annual Calculation

Solar radiation is unequally distributed on surfaces of different orientation. It is obvious that surfaces oriented to the equator can earn more energy. At a first step, tilt angles 0°, 5°, 10°, 15°... 90° were chosen. To have a precise annual solar yield, it was proposed to calculate radiation for all tilt angles with orientations -90° to 90°. This was done for tilt angle=0° by METEONORM, but the difference between results was negligible. Table 1 shows solar radiation on inclined surface toward the south in Tehran in kWh/m².

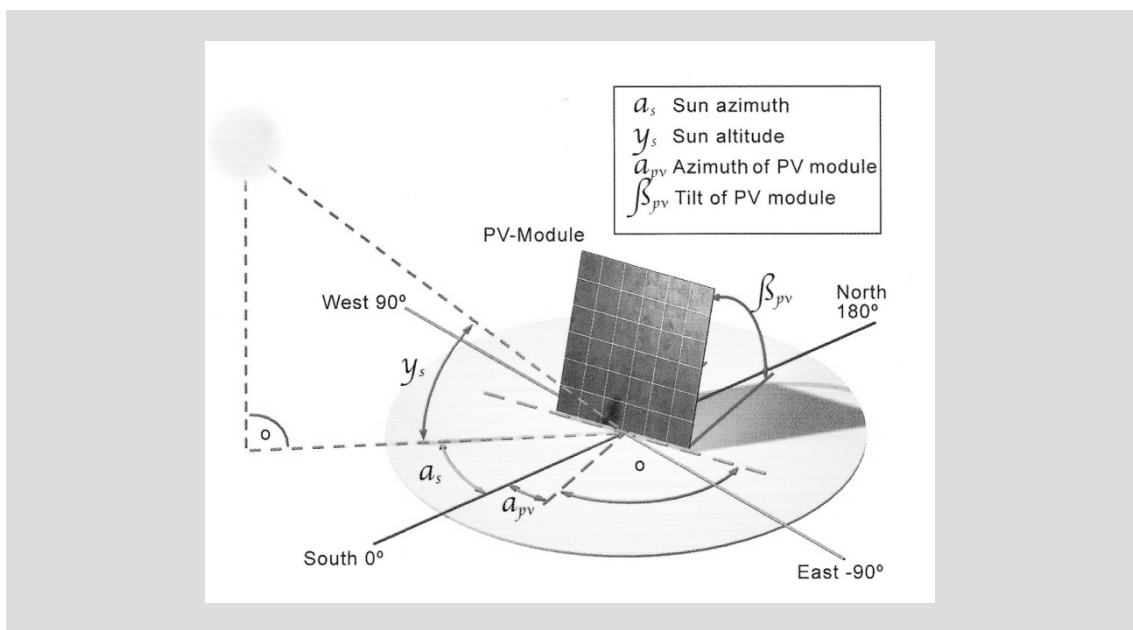


Figure 6. Angle of solar incidence on a tilted PV module, (Prasad and Snow, 2005).

Table 1. Daily irradiation in Tehran (in kWh/m²) for a typical day in every month as a function of the panel inclination in degrees.

Angle	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
0	2.44	3.33	4.08	5.42	6.42	7.64	7.50	6.92	5.75	4.25	2.92	2.25	4.92
5	2.68	3.57	4.26	5.54	6.46	7.63	7.51	7.03	5.98	4.54	3.20	2.50	5.08
10	2.90	3.79	4.41	5.63	6.46	7.57	7.47	7.10	6.18	4.81	3.46	2.73	5.22
15	3.11	3.99	4.54	5.68	6.42	7.47	7.39	7.13	6.34	5.04	3.71	2.95	5.32
20	3.30	4.16	4.64	5.70	6.35	7.32	7.27	7.11	6.45	5.25	3.93	3.14	5.39
25	3.47	4.31	4.72	5.69	6.24	7.13	7.10	7.05	6.53	5.42	4.12	3.32	5.43
30	3.62	4.44	4.77	5.65	6.09	6.89	6.89	6.94	6.57	5.55	4.29	3.48	5.44
35	3.74	4.53	4.79	5.57	5.91	6.63	6.64	6.79	6.56	5.65	4.43	3.62	5.41
40	3.85	4.60	4.78	5.46	5.70	6.33	6.37	6.60	6.51	5.72	4.55	3.73	5.35
45	3.92	4.64	4.74	5.32	5.46	5.99	6.05	6.37	6.42	5.75	4.63	3.82	5.26
50	3.98	4.65	4.68	5.15	5.19	5.62	5.71	6.10	6.29	5.74	4.68	3.89	5.14
55	4.00	4.63	4.59	4.95	4.90	5.23	5.32	5.80	6.12	5.69	4.71	3.93	4.99
60	4.01	4.58	4.47	4.72	4.58	4.82	4.93	5.47	5.92	5.61	4.70	3.94	4.81
65	3.98	4.50	4.32	4.46	4.23	4.39	4.51	5.11	5.67	5.49	4.67	3.93	4.61
70	3.93	4.40	4.16	4.18	3.88	3.94	4.07	4.72	5.39	5.34	4.60	3.90	4.37
75	3.86	4.27	3.96	3.89	3.52	3.50	3.62	4.30	5.08	5.15	4.50	3.84	4.12
80	3.76	4.11	3.75	3.57	3.13	3.04	3.18	3.87	4.74	4.93	4.38	3.75	3.85
85	3.64	3.93	3.51	3.24	2.76	2.60	2.72	3.43	4.37	4.68	4.22	3.64	3.56
90	3.50	3.73	3.26	2.89	2.38	2.17	2.30	2.97	3.97	4.40	4.04	3.51	3.26

After revision, it was decided to select orientations -90°, -75°, -60° ... 0°, 15° ... 90°. So all data were calculated and the results were shown in a diagram (Figure 7.). In this diagram, the x axis represents orientation angles whereby positive numbers are referred to the West and negative ones to the East. Tilt angles are on the y axis and curves show solar yield in kWh/m² unit. As is shown in the diagram, 2000 kWh/m² area is the best tilt angle. At these tilt angles, energy of 2000-2041 kWh/m² is received. Tilt angles 31-33° with an orientation angle=0° can earn the maximum energy. As can be seen there are other choices in the best area, e.g. tilt angle, 30° and orientation angle, -10°. It is very important to have flexible choices because architecture deals with

flexible parameters and needs greater freedom in design. Area 1900-2000 kWh/m² is the excellent area that receives 90-98% solar energy. In this area there are more options for tilt and orientation angles, e.g. tilt=20° and orientation=+45° that receives 1936 kWh/m².

Area 1800-1900 kWh/m² that receives 80-90% solar energy is called good yield. In each building, walls may have a slope. In this paper it is assumed that walls are planes that tilt at 90°. After calculation, it is demonstrated that walls facing towards the East can earn the most energy, 1291 kWh/m², with an orientation angle -26° to -31° while walls facing towards the West receive the most energy, 1301 kWh/m², with an orientation angle 30-36°.

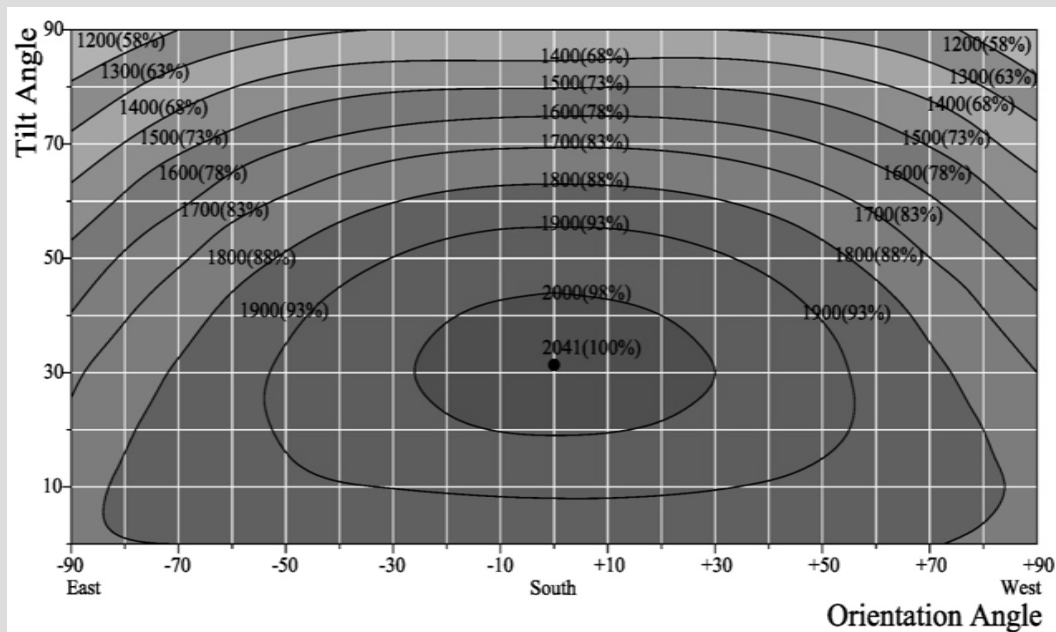


Figure 7. Annual total of global radiation in Tehran.

Seasonal Calculation

Seasons are a product of the tilting of the earth's axis as it orbits around the sun. The sun's height consequently varies according to the season and is more significant at higher latitudes. Some basic principles and trends for BiPV and seasonal solar yield can be drawn. The higher the tilt of the surface :

- The higher the solar input in winter.
- The lower the solar input in summer.
- The tighter the azimuth spread for areas obtaining good solar yield.

The seasonal solar yield is strongly correlated with surface orientation. Excellent or good annual solar yields can differ from excellent or good seasonal solar yields. Roof surfaces of higher tilts and facades oriented slightly away from North in the southern hemisphere and South in the northern hemisphere,

achieve better solar yields in winter, such as in areas of moderate latitudes.

All the previous calculations help to have corresponding diagrams for summer and winter semesters. For this, it is enough to add solar radiation in summer or winter months together. Figure 8 shows the total global radiation in Tehran in the summer semester. In that diagram all the characteristics are similar to Figure 7, but numbers on the curves represent solar yield in the summer semester. According to the diagram, the best tilt angle is 19° while the orientation angle is 0°. At this position, annual solar yield solar yield in the summer semester are, respectively, 2000 and 1277 kWh/m² while the best tilt angle according to annual diagram is 31°.

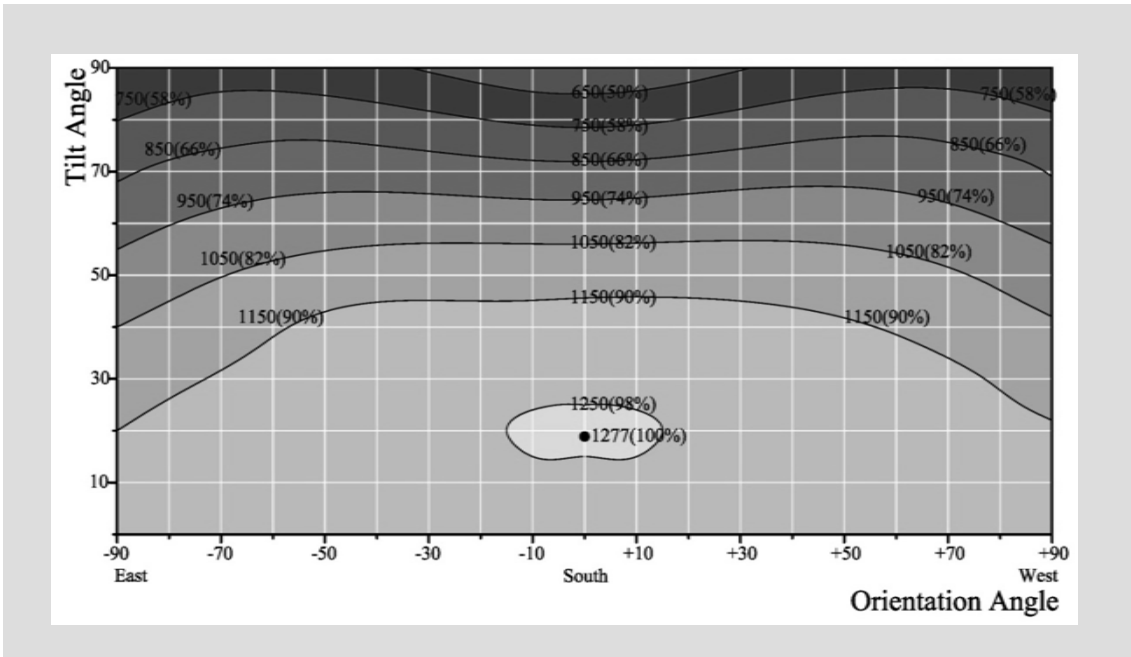


Figure 8. Total global radiation in Tehran in the summer semester.

Figure 9 shows the total global radiation in Tehran in the winter semester. The best tilt angle is 51° while the orientation angle is 0°. At this position, annual solar yield in the summer and winter semesters are, respectively, 1947 and 863 kWh/m² while the best tilt angle according to annual diagram is 31°.

Comparison

In some systems, e.g. grid-connected ones, the paramount consideration is to collect the maximum energy over the year. It can be seen that the optimum panel angle which maximizes the yearly average irradiation is 31-33°. In general, it is usually close to

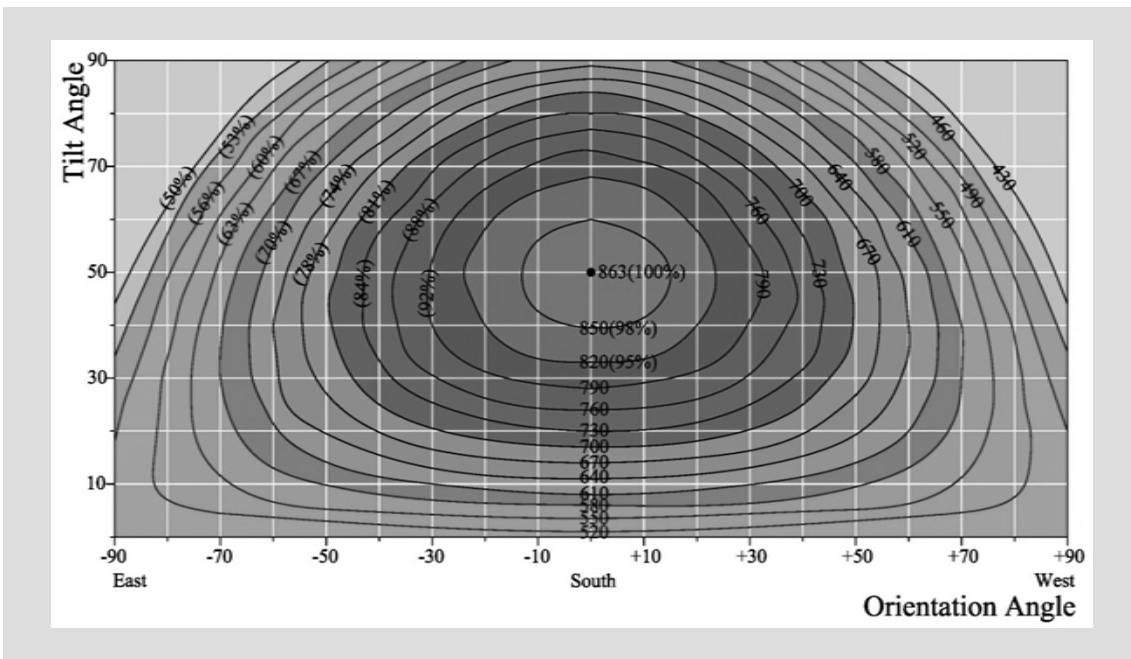


Figure 9. Total global radiation in Tehran in the winter semester.

the latitude angle. Solar electricity is best suited for applications where peak consumption occurs during the summer, e.g. crop irrigation or buildings that need to produce more energy in the summer or winter for cooling or warming. In fact, using an annual or seasonal diagram directly depends on the proposed function of the PV system. It is very important that the output of the PV system in each design has to be calculated at the first step and the use of that energy must be specified. So, the output of PV systems must not be distributed to electrical appliances except that extra amount of energy that could sometimes be produced. For example electricity produced in PVs may be utilized for special lighting purposes such as desks or offices.

On each curve in Figures 7-9 there is a number that shows the solar yield in that orientation and tilt angle as a percentage of the maximum solar yield. This value helps to have a precise estimation of solar yield in each tilt and orientation angle.

Results

All of the analysis in this part is based on the annual total of global radiation in Tehran because it is assumed that energy produced by PVs needs to be used throughout the whole year for a specific purpose. Analysis is based on geometric shapes like triangles, rectangles and circles and other shapes that are

combination of those geometric shapes are ignored. All the shapes have constant area and height (Figure 10.). In fact, they have same volume.

For each shape, there is no PV on the North facade because of lack of sufficient solar radiation. The orientation angle is important for rectangles and is calculated for +45, +40 ... 0 -5, -10 ... -45, but the orientation angle is not so essential for circles or triangles and is ignored. A rectangle is the most usable shape in architecture and the proportion of its length to width can be changed variously. So, rectangles with 3:1, 2:1, 1.5:1 and 1.2:1 length to width proportions have been chosen.

All energy that a shape can harness is the sum of solar radiation on each wall and roof. So solar radiation is calculated for each wall of a shape and the sum of these is shown below every shape (Figure 11.). The area of the roof is the same for each shape and if it is tilted 31-33°, the best tilt angle, the result would be the same. So, the amount of energy that is earned by roofs has been omitted in calculation.

Here, a question may be raised: what is the characteristic of the triangle and how is it selected among lots of triangles? As mentioned before, walls with orientation angles 30-36° and -26° to -31° toward the West and East can receive the most energy. Therefore, orientation angles 30° and -30° were selected and an isosceles triangle created.

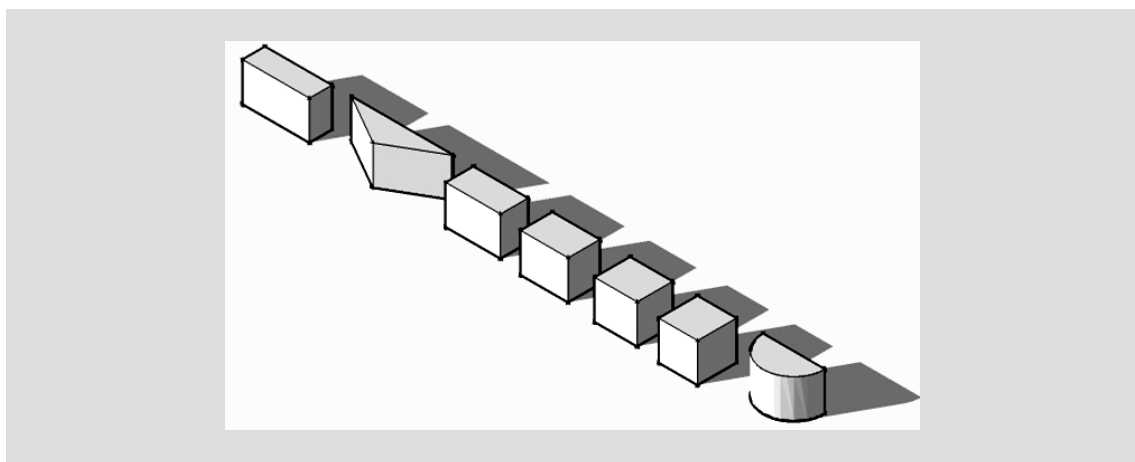


Figure10. Selected forms

Figure 11. Solar radiation analysis for different shapes

Conclusion

With regard to the above analysis, it can be concluded that there are annual, seasonal and daily/ hourly solar yield for Tehran and each of them has its own use. Using annual solar yield is suitable when PV systems have to be used all the year. Seasonal solar yield is used when peak of energy demand is in the summer or winter. Daily/hourly solar yield is used when there is an energy demand before or after noon each day. Based on annual total of global radiation in Tehran diagram, the best tilt angle is 31-33° towards the South. The best orientation angles for walls are -26° to -31 towards the East and 30-36° to the West. However, according to the total global radiation in Tehran in the summer and winter diagrams, the best

tilt angles are respectively 19° and 51° with orientation angle, 0°. According to form analysis, the best form is an isosceles triangle with a roof tilted 31-33° (Figure12).

Table 2 shows the result of form analysis for PV integration in Tehran. As it is observed the best form is triangle. Rectangles with a 3:1 proportion of length to width is next and the third place is occupied by the square. These priorities are only a scheme for PV integration and there are lots of issues that are important in building design. These forms are basic and each architect should manipulate all the disciplines to create a comfortable building for occupants.

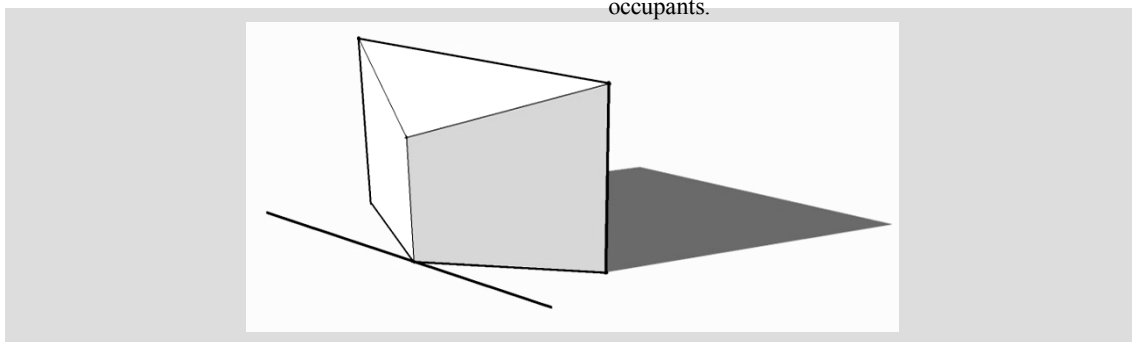


Figure 12. The best form for PV integration in Tehran

Table 2- Priority of forms for PV Integration

	Priority	Length to width proportion	Amount of energy yield (kWh / year)
Triangle	1	-	16716
Rectangle	2	3:1	14773
Square	3	1:1	14737
Circle	4	-	14443
Rectangle	5	1.2:1	14442
Rectangle	6	2:1	14256
Rectangle	7	1.5:1	14247

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