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Building integrated solar thermal systems presentation and zoom on the solar potential

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Abstract. *This work was realized in the context of the COST Action TU1205 "Building Integration of Solar Thermal System" (BISTS) The objectives for this Action focus on creating a platform from which a working environment is developed that generates methods to further the integration of Solar Thermal System in buildings. This action will be described and some integration examples will be presented. The aesthetic of solar thermal collectors can be an obstacle to their development and limits the growth of the market. Integrating a thermal solar collector in a building improves the aesthetics of the building and allows a best social acceptance of the energy system. But we might ask the question whether as a building integration reduces the choice of the inclination and orientation of the BIST, is there an influence on the solar energy available to be converted into thermal energy? We will try to reply to that question.*

Key words: *Building Integrated solar systems, solar radiation potential*

1. Introduction

The Renewable Energy Framework Directive of the European Union (EU) sets a target of 20% for renewables by 2020. Buildings account for 40% of the total primary energy requirements in the EU and are responsible for 30% of greenhouse gas emissions. The Energy Performance of Buildings Directive (EPBD) requires that RES are actively promoted in offsetting conventional fossil fuel use in buildings. This is further augmented by the recast of the Directive which specifies that buildings by 2020 should be nearly zero energy consumption-producing most of the energy they consume.

Therefore, developing effective energy alternatives for buildings is imperative. Energy in buildings is used primarily for heating and cooling and for the provision of hot water. One way to reduce the dependence on fossil fuels is by the use of renewable energy sources and systems.

Solar thermal collectors are often seen as a foreign element of the building. Many architects, irrespective of the potential benefits, object to this use of renewable energy systems due to this fact alone. It is therefore necessary to develop techniques that better integrate solar collectors within the building envelope and/or structures which should be done in a way that blends into the aesthetic appearance and form of the building architecture in the most cost effective way. In other words, the integration into buildings is the marriage of aesthetics and sustainability (Fig. 1)

Fig. 1. Good and bad solutions.

Integrating a thermal solar collector in a building improves the aesthetics of the building and allows a best social acceptance of the energy system. But we might ask the question whether as a building integration reduces the choice of the inclination and orientation of the BIST, is there an influence on the solar energy available to be converted into thermal energy by the solar collector? The influence of the position of the solar collector is it the same for all latitudes? We will try to reply to that question in this paper.

2. COST Action TU1205: Building Integration of Solar Thermal Systems (BISTS)

As we wrote in the introduction, it is necessary to develop techniques that better integrate solar collectors within the building envelope.

But what we mean by Building Integration? A Solar Thermal System (STS) is "building integrated," if for a building component this is a requirement for the integrity of the building's functionality. If the BISTS is dismounted, dismounting includes or affects the adjacent building component which will have to be replaced partly or totally by a conventional building component.

What are the Benefits of integration? There are many advantages:

- Building envelope: metal, glass or ceramic used in current BISTS roofing designs can last for more than 50 years.
- Thermal and optical performances: different systems can deliver different levels of thermal energy to match the varying needs of building occupants.
- Costs: Significant savings occur by replacing 2 separate systems (wall and collector) with one system that performs both functions.
- Aesthetics: mimic the existing appearance of traditional roofing systems and apply color collectors on façades.

Thus a European framework was created on this problematic. COST (European Cooperation in Science and Technology) is a unique means for European researchers, engineers and scholars to jointly develop their own ideas and new initiatives across all fields of science and technology through trans-European networking of nationally funded research activities [1]. A COST action (TU1205) has been set up on "Building Integration on Solar Thermal Systems" (BISTS) and 22 European countries participate to this action. The chairman of the action is Soteris Kallogirou from Cyprus University of Technology [2]. The main objective is to create a platform from which a working environment is developed that generates methods to study the integration of STS in buildings. The COST partners are working on:

- Development of new novel STS solutions suitable for building integration across 3 generic European regions.
- Definition of a set of key parameters for the BISTS characterization taking into consideration the thermal performance, building functionality and aesthetic aspects.
- Development of standardised range of methodologies for evaluating BISTS.
- Modelling and simulation of STS (optical and thermal) for different building integration scenarios and for the developed solutions.
- Application of developed STS solutions for building integration including fabrication, characterisation and demonstration of prototypes to the extent that own research funding allows.
- Dissemination of Action activities (symposium, conference, website and publications).

Some examples of BISTS are presented in Fig. 2 for new buildings and refurbishment [2].

Fig. 2. Some example of BISTS.

Integrating a thermal solar collector in a building improves the aesthetics of the building and allows a best social acceptance of the energy system. But we might ask the question whether as a building integration reduces the choice of the inclination and orientation of the BIST, is there an influence on the solar energy available to be converted into thermal energy by the solar collector? The influence of the position of the solar collector is it the same for all latitudes? We will try to reply to that question in the continuation of this paper.

3. Solar Potential for BISTS

We will not develop in this paragraph all the equations describing the sun's path around the Earth and about the incidence angle of the sun 'ray on an arbitrary oriented and tilted solar collector. All these equations are available in [3].

When a solar collector is integrated into a building, its inclination and orientation depend on the structure and the design of this building. Then, these BIST are rarely horizontal and oriented toward the south. In these conditions, the solar incidence angle onto the BIST is different to the zenith angle and influences the solar irradiance (and thus the solar irradiation), the sunshine duration and the solar irradiance profile over the day. This constraint due to building integration has therefore consequences on the BIST performances and production.

The sunset and sunrise hours depend on inclination and orientation of the solar collector; particularly during summer, the sun rises behind the collector (and for some latitudes, it stays behind the wall during its entire path) (see Fig. 3). Obviously, some consequences will occur for the BISTS production.

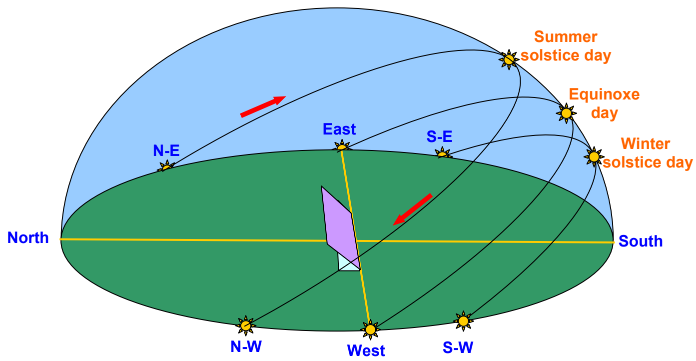


Fig. 3. Illustration of the sun path according to the period of the year.

3.1. First Approach: Extraterrestrial solar radiation: influence of beam radiation

The extraterrestrial radiation is the solar radiation before entering in the Earth' atmosphere (before absorption and scattering by gas and aerosols). This study allows to observe the influence of inclination and azimuth angles on the beam radiation (mainly present by clear skies) but optic length and meteorological conditions are not taken into account.

Fig. 4 shows the influence of the inclination of the solar collector for a site situated at 40° latitude. Similar influences are noted for other latitudes. A 90° inclination (Integration into a wall) improves the energy gain during winter and decreases it during summer, which is interesting for heating purposes because heat is more required in winter, moreover, the overheating is reduced during summer. For cooling purposes with BIST, the integration into a wall is less appropriate.

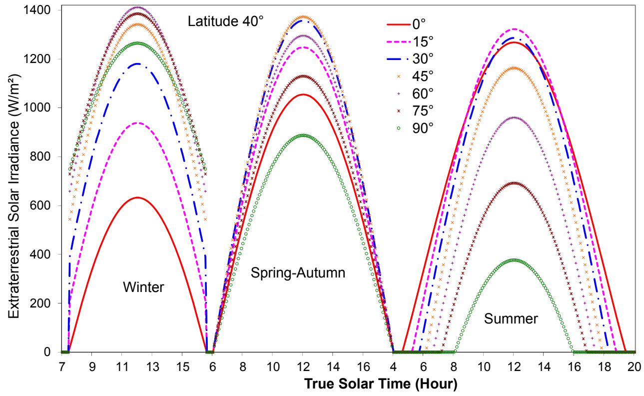


Fig. 4. Influence of STS inclination for a 40° latitude site on extraterrestrial solar irradiance.

Fig. 5 illustrates the influence of orientation toward the South of a STS on the extraterrestrial solar irradiance. As a symmetry exists around midday, we only presented a wall oriented toward East (similar curves are obtained for West façades).

When the solar collector is oriented toward East, the solar irradiance is higher during morning than for a South STS and the sun rises earlier during summer even though the solar day length is reduced; moreover, the daily solar irradiation is lower than for South orientation. But, there may be advantages:

- In an office building, it is more interesting to heat in the morning when the workers arrive than in evening when the desk rooms become empty; then, a partial east orientation is preferred.
- In a hotel, the hot water requirements occur the morning, an east orientation is a good solution.

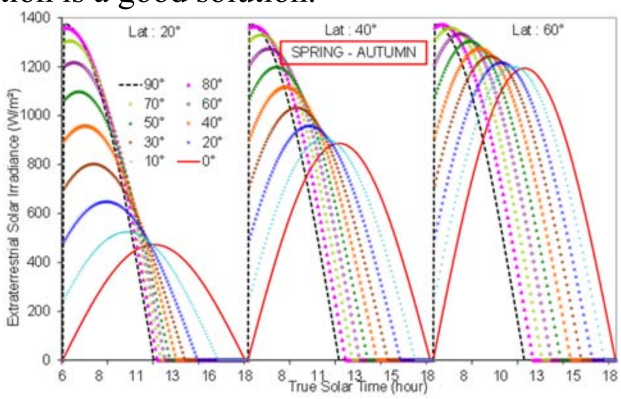


Fig. 5. Influence of STS orientation for 3 latitudes in Spring-Autumn on extraterrestrial solar irradiance.

This study allowed to understand how the solar position influences the energy received directly by the sun, it does not however take into account the meteorological conditions and their variability. For this reason, we extended the study to the solar radiation received at the ground level.

3.2. Second Approach: solar radiation at ground level

When solar radiation enters the earth's atmosphere, a part of the incident energy is removed by scattering and a part by absorption. The scattered radiation is called diffuse radiation. A part goes back to the space and another one reaches the ground. The radiation arriving on the ground directly from the solar disk is called beam radiation (Fig. 16).

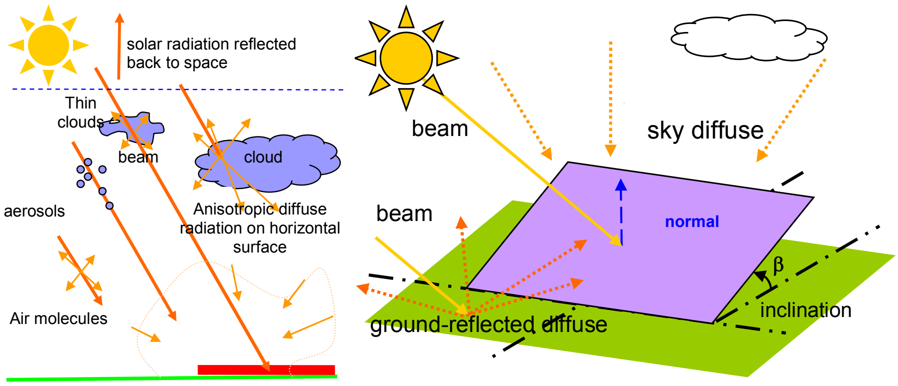


Fig. 6. Radiations arriving on the ground and on a tilted surface.

The total radiation received on a tilted surface is expressed by:

$$I_\beta = I_{b,\beta} + I_{r,\beta} + I_{d,\beta} \qquad (1)$$

where $I_{b,\beta}$ is the beam radiation on the tilted surface;

$I_{r,\beta}$ is the diffuse reflected radiation on the tilted surface;

$I_{d,\beta}$ is the sky diffuse radiation on the tilted surface.

The sky diffuse radiation is maximal for a horizontal surface because a horizontal plane sees the totality of the sky dome.

Our objective is to calculate the solar global irradiance on the ground for various inclinations and azimuths of the plane from only the measured horizontal global irradiance. There are numerous models available to estimate global radiation on inclined surface from horizontal radiation, but these models require information at the same time on the global and the beam or diffuse radiation on a horizontal surface. Our method consists in coupling two types of models as illustrated on Fig. 7: a model for the estimation of horizontal diffuse solar radiation from the horizontal global one and a model for computing the global solar radiation on tilted planes from horizontal global and diffuse radiations.

94 combinations were tested from experimental hourly global irradiations in Ajaccio by Notton *et al* [4] using 7 horizontal diffuse solar irradiation models [5] and 15 tilted diffuse solar irradiation models [6]. The RRMSE obtained with these combinations are around 10% and the best combination conduces to a RRMSE of 8.11% for 45° and 10.71% for 60° [7]. Thus, we use the combination of two models:

- The Climed2 model [7] calculates the horizontal diffuse irradiance I_d from the horizontal global irradiance I:

$$\begin{cases} f = 0.995 - 0.081\,M_T & \text{if} \quad M_T \le 0.21 \\ f = 0.724 + 2.738\,M_T - 8.32\,M_T^2 + 4.967\,M_T^3 & \text{if} \quad 0.21 < M_T \le 0.76 \\ f = 0.180 & \text{if} \quad M_T > 0.76 \end{cases} \qquad (2)$$

with $f = I_d/I$ and $M_T = I/I_0$ M_T is the clearness index, I_0 is the extraterrestrial irradiance.

- The second step consists in computing the tilted global irradiance from the horizontal global and diffuse ones by equation (1):

$I_{b,\beta}$ is the beam solar radiation on the inclined plane and is calculated by [3]:

$$I_{b,\beta} = (I - I_d)\left(\frac{\cos\theta}{\cos\theta_z}\right) \quad (3)$$

θ is the incidence angle and θ_z the zenith angle [3].

$I_{d,gro,\beta}$ is the diffuse solar radiation reflected by the ground [3]:

$$I_{d,gro,\beta} = \frac{1}{2}\rho I(1 - \cos\beta) \quad (4)$$

where ρ is the ground albedo often taken equal to 0.2.

$I_{d,sky,\beta}$ is the diffuse solar radiation coming from the sky and it is the more complicated component to estimate. We chose to use the Klucher'model [5-6,8].

$$I_{d,sky,\beta} = I_d\left[0.5\left(1+\cos\left(\frac{\beta}{2}\right)\right)\right]\left[1 + F\sin^3\left(\frac{\beta}{2}\right)\right]\left[1 + F\cos^2(\theta)\sin^3(\theta_z)\right] \quad (5)$$

with $F = 1 - (I_d/I)^2$

The sky diffuse component is maximum when $\beta = 0$ because when the plane is horizontal, it sees the totality of the sky dome.

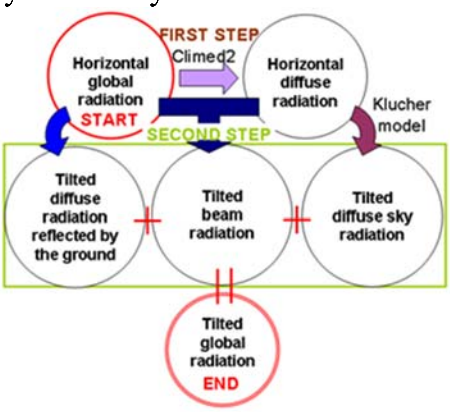


Fig. 7. Method for determining the solar radiation on an arbitrary oriented and tilted surface from horizontal one.

Using this model, it is possible to calculate the solar irradiance incident on a tilted surface not facing to South. Fig. 8 illustrates the influence of inclination on the daily profile of solar irradiance for three particular days (clear, partially cloudy and cloudy sky). The data were measured and collected on the site of our laboratory (Ajaccio, France, latitude 41°49').

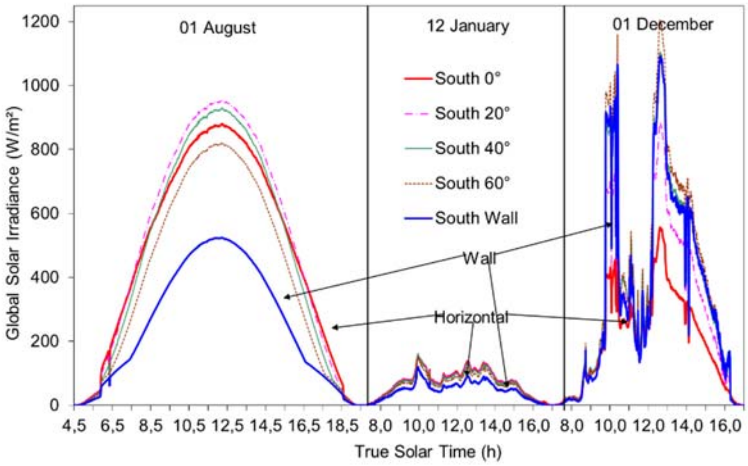


Fig. 8. Influence of the inclination for three typical days in Ajaccio.

The corresponding solar irradiation are given in Table 1.

Table 1

Influence of BISTS inclination: Daily solar irradiation (kWh/m²)

Date	South 0°	South 20°	South 40°	South 60°	South Wall
01 August	7.17	7.61	7.15	6.12	3.83
12 January	0.68	0.69	0.66	0.59	0.45
01 December	2.02	2.93	3.53	3.78	3.38

We note that:

- A similar behavior for clear sky and extraterrestrial solar irradiance (01/08)
- For cloudy skies, a small influence as the sky is totally cloudy, the diffuse radiation stays small and decreases a little when the inclination increases.
- For partially cloudy skies, the influence depends partly on beam and diffuse components.
- A similar work was realized for the influence of the orientation (Fig. 9 and Table 2).

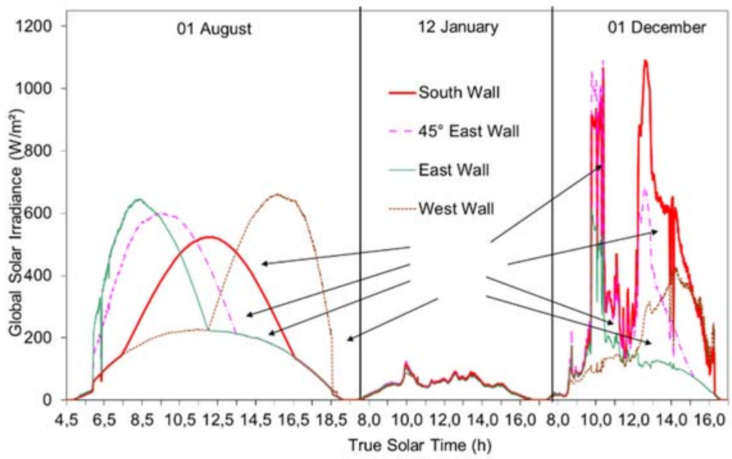


Fig. 9. Influence of the orientation for three typical days in Ajaccio.

Table 2

Influence of BISTS Orientation: Daily solar irradiation (kWh/m²)

Date	South Wall	45° East Wall	East Wall	West Wall
01 August	3.83	4.18	4.05	4.44
12 January	0.45	0.44	0.42	0.42
01 December	3.38	2.27	1.15	1.63

We see that:

- Clear sky: differences with extraterrestrial irradiance, an East wall receives again solar radiation in the afternoon (sky diffuse and ground reflected). More energy is captured by an East wall in summer because the sun rises earlier (the sun rises behind a south wall).
- Cloudy sky: no influence.
- Partially cloudy sky: the influence depends on the percentage of diffuse and beam radiation and on its repartition over the day

After this analysis of the daily profile of the solar irradiance, we will see the influence on the annual and monthly mean of the daily solar irradiation. We choose four meteorological stations spread over the Earth (Table 3).

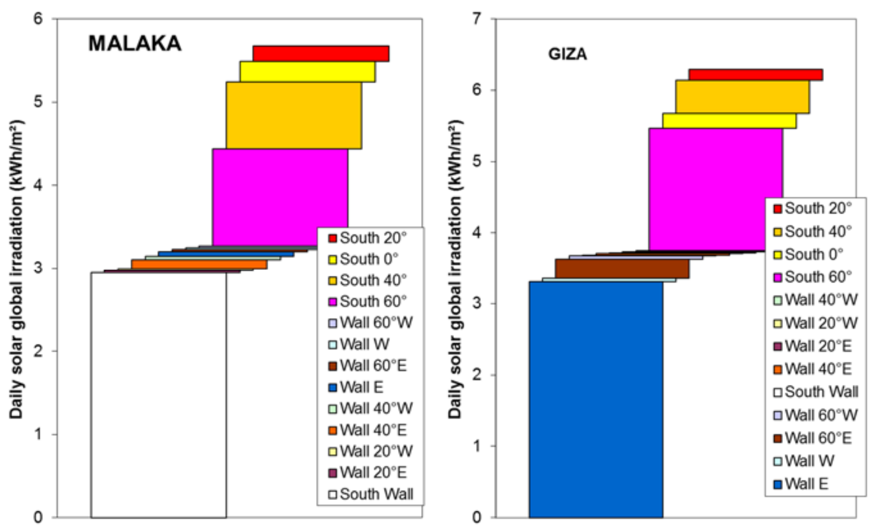
Table 3

Meteorological startions

Country	Location	Latitude	Longitude	Altitude
South Sudan	Malakal	N 09°33’	E 31°39’	390 m
Egypt	Giza	N 30°03’	E 31°13’	21 m
France	Paris	N 48°49’	E 2°20’	75 m
Finland	Utstsjoki	N 69°45’	44°02’	101 m

The annual mean of the daily solar irradiation for various cases (inclination and orientation) are shown in Fig. 10.

The best annual solar irradiations are always obtained for inclinations other than 90° (wall). The gap in energy between the best and the worst position is around 100% (the solar energy received by the solar collector varies almost by a factor of two); the best position depends on the latitude.



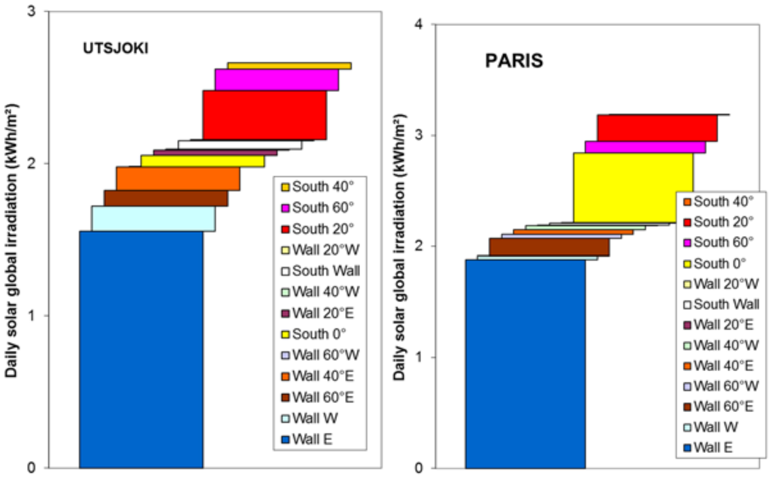


Fig. 10. Annual mean of daily solar irradiation.

The monthly repartition of the solar irradiation is interesting because the heat utilization varies greatly from one month to another. Fig. 11 shows this reparation for the chosen meteorological stations.

The influence of the inclination differs according to the latitude. The day length influences the available energy: two limit cases, the first for equator (Entebbe) with a theoretical sunshine duration constant over the year and the second for a site near the North Pole (Utsjoki) with a permanent night during some months (for Utsjoky 3 months).

The influence of orientation is more important for locations at low latitude. The fact that the sun, during summer, sunsets and sunrises behind a south wall, explains that a wall oriented toward west or east receives more energy because it sees the sun rising earlier for east wall (it sees the sun setting later for west wall).

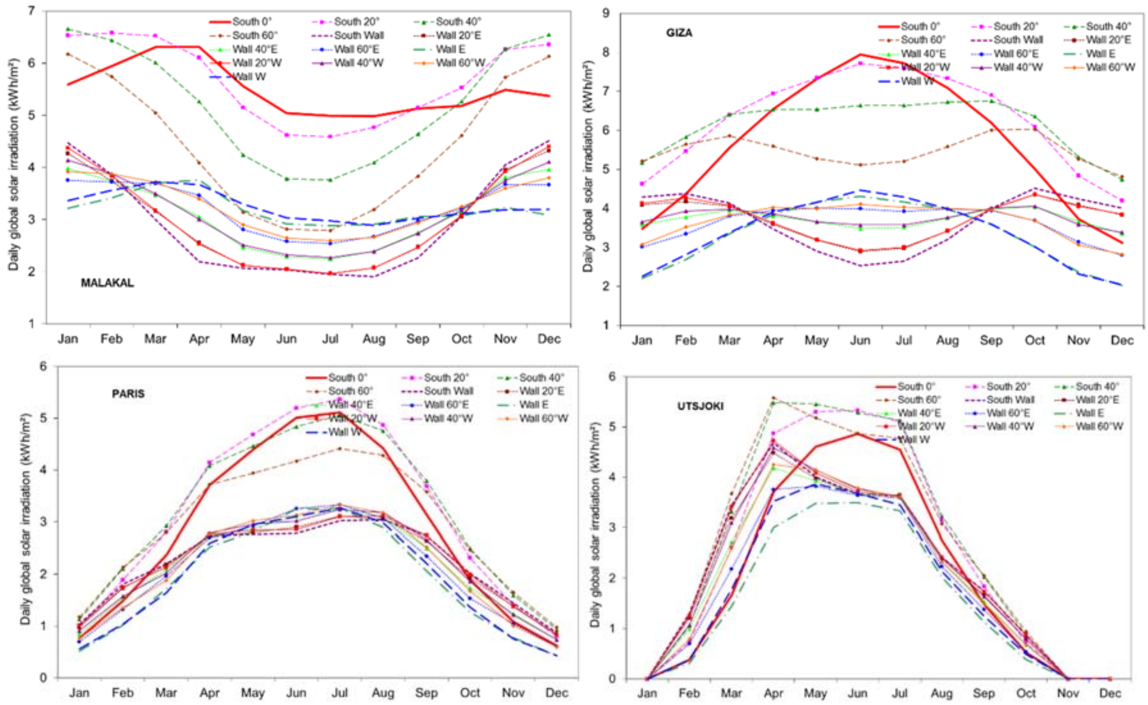


Fig. 11. Monthly mean of daily solar irradiation.

6. Conclusion

The main conclusions are:

- No general conclusion because depending on the latitude
- South is not always the best orientation: an office building needs heat when the employees are working (more energy the morning than the evening), then the orientation of the solar collector slightly toward South-east is beneficial.
- In summer, a wall receives less solar energy than a tilted plane but in winter, at high latitudes the solar energy is higher; then, when the building needs heat during winter, the vertical position is a correct position and in summer, when the heat need is small or null, the available solar energy is strongly reduced what can be an advantage.
- For low latitudes, the solar energy on a wall of all orientations is much lower than the energy received by a BISTS into a tilted plane.
- Using a BISTS can have positive or negative impacts on the availability of the solar energy according to the latitude of the application and the inclination of surface integrating the solar collector.
- Specific attention should be paid by architects to this point before deciding to integrate a solar collector into a building; a good compromise must be found between an aesthetic integration and an optimal inclination and orientation. They must take into account the utilization of the heat and the daily profile of utilization which can justify a special orientation.

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