SECTION 1

INTRODUCTION

CONTENTS

1.1 DESCRIPTION OF THE ACTION TU1205: BUILDING INTEGRATED SOLAR THERMAL SYSTEMS (BISTS)

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Action chairman

The Renewable Energy Framework Directive 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 the generated greenhouse gas emissions. Therefore, developing effective energy alternatives for buildings is imperative. This energy is used primarily for heating and cooling of buildings and for the provision of hot water for domestic use. One way to reduce this dependence on fossil fuels is through the use of renewable energy sources and systems which are generally environmentally benign. In some countries, such as Cyprus, renewable energy systems (RES) and in particular solar water heating are used extensively, with 93% of all domestic dwellings currently equipped with such a system. The benefits of such systems are well known but one area of concern has been their integration. Most solar collector components are mounted on building roofs with no attempt to incorporate them into the building envelope. In many instances they are actually seen as a foreign element of the building roof. 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.

The Energy Performance of Buildings Directive (EPBD) requires that RES are actively promoted in offsetting conventional fossil fuel use in buildings. A better appreciation of solar thermal system (STS) integration will directly support this objective, leading to an increased uptake in the application of renewables in buildings. This uptake of RES in buildings is expected to rise dramatically in the next few years. This is further augmented by the recast of the Directive which specifies that the buildings in the EU should be nearly zero energy consumption (residential and commercial buildings by the year 2020 and public buildings by 2018, respectively). Meeting building thermal loads will be primarily achieved through an extensive use of renewables, following standard building energy saving measures, such as good insulation or advanced glazing systems. Solar thermal systems are expected to take a leading role in providing the thermal energy needs, as they can contribute directly to the building heating, cooling and domestic hot water requirements.

The main objective of the Action was to develop new novel solar thermal systems solutions suitable for building integration, definition of key parameters for their characterisation, modelling, simulation, demonstration and dissemination activities.

The Action consortium presents a critical mass of European knowledge, expertise, resources, skills and R&D in the area of solar thermal. Through collated consultation and enquiry, experimental investigation and development of modelling and simulation techniques, real and significant advances in Building Integrated Solar Thermal Systems (BISTS) can be achieved. This network provided the sharing of nationally based research and enabled the establishment of common platforms to accelerate transnational research projects in the area of building integrated solar thermal energy systems. A total of 24 countries participated in the Action, 22 EU member and 2 non-EU members. The EU member countries include: Austria, Belgium, Bulgaria, Cyprus, Denmark, France, Germany Greece, Hungary, Ireland, Israel, Italy, Lithuania, Malta, Netherlands, Poland, Portugal, Romania, Serbia, Spain, Turkey and United Kingdom. The Non-EU countries include Canada and the USA. The Action consortium presents a critical mass of European knowledge, expertise, resources, skills and R&D in the area of STS, which supported the creation of innovative ideas and concepts.

This Action achieved to collect and synthesise the research effort carried out in various countries in an attempt to join forces and focus resources to develop aesthetic and financially acceptable solutions that are appropriate to STS integration in the modern built environment. Such an effort cannot be fully explored in other research framework programs as networking is secondary to their stated targets.

The main advantage of carrying out this project within the COST framework was the creation of a platform from which scientists and engineers with many years' experience in the area of STS design and operation worked together in a concerted Action to generate viable solar solutions directed at the future integration of STS into buildings. This was achieved mainly through the networking offered by the Action and knowledge transfer. As part of the Action, three Training Schools were organised to train your engineers and architects on the concepts of BISTS. As part of the activities of this Action a Symposium and a Conference on Building Integrated Renewable Energy Systems (BIRES) were organised to increase awareness of the progress made by the network and inform the relevant industry with respect to the suggested solutions.

The scientific innovation concerned the development of novel BISTS solutions through modelling, simulation and experimental investigation. This network provided the immediate sharing of nationally based research and enable the establishment of common platforms to accelerate transnational research projects in the area of BISTS.

The main motivation for the Action was the collective concentration of resources and the targeted focusing of scientists who are involved in the design, development and evaluation of solar thermal systems. We believe that the Action managed to accelerate long-term technological improvement in STS mainly through critical review, experimentation, simulation and demonstration of viable systems for full incorporation and integration into the traditional building envelope. Additionally, factors like structural integrity, weather impact protection, fire and noise protection were considered. The most important benefit of this Action is the increased adoption of RES in buildings. Three generic European regions are considered; Southern Mediterranean, Central Continental and Northern Maritime Europe, to fully explore the Pan-European nature of STS integration.

All forms of solar collecting methodologies with a particular focus on thermosiphonic units, integrated collector storage units, forced circulation systems, evacuated tube collector systems and various low concentration compound parabolic units were considered. The ultimate objective was to produce a suite of market ready solutions/products and tools facilitating an easier route to market and their wider application. The Action also considered the needs of the industry (manufacturers, consultants, installers) and tried to suggest suitable solutions with the ultimate objective of increasing the penetration of STS to buildings. For this purpose, representatives of the relevant industry were invited in the various activities of the Action.

1.1.1 Aims of the Action

The main aim of the Action was to foster and accelerate long-term progress in the integration of renewable energy systems in buildings in Europe through market evaluation and expectation, design, development, characterisation and simulation of building integrated STS solutions and by addressing concerns that this system integration generate. Coupled with aesthetic and architectural challenges, many practical issues need to be resolved; for example, rain-water sealing, protection from overheating (thus avoiding increased cooling loads during the summer) and fire safety. These are some of the pressing concerns that need to be addressed for any design and require a cross disciplinary involvement of experts in the fields of renewable energy systems, architecture and materials. As STSs are latitude dependant with respect to facade application, three generic European regions were considered; Southern Mediterranean, Central Continental and Northern Maritime Europe, to fully explore the Pan-European nature of STS integration. Under the Action a full understanding of the economic factors and commercial environment that will direct full implementation of BISTS was carried out. This requires that developed BISTSs are near-to-market ready products (based upon the ongoing individual partner research projects), as both factory mass manufactured form or as a bespoke system, specifically tailored to a unique situation. Through on-going direct consultation with all relevant industry stakeholders, directed experimental investigation, problem identification and modelling/simulation resolution through to demonstration, the present consortium of European partners, with extensive expertise in STSs has collectively pooled resources to fundamentally change the accepted solar installation methodologies that affects residential, commercial (offices) and industrial buildings throughout Europe. The deliverables of the Action include the publication of a book describing the various systems installed in many parts of the word and this Handbook. The Handbook consists of five main sections after this introduction; the design process of BISTS, new options, analysis of new project concepts/ideas, conclusions and outlook and supporting material.

1.1.2 Impact of the Action

The single most important benefit that is derived through this Action is the increased adoption of renewables in buildings by facilitating greater market penetration of building integration of solar thermal systems. The individual benefits can be expressed through:

- Increased range of potential STS options, greater choice and wider application contributing to the achievement of targets outlined above by EU and by individual nations.
- National partnerships fostering a greater level of co-operation and access to specialism related to the Action, providing a platform that allowed the cross fertilisation of new ideas and concepts to meet the specific challenges that face the solar industry. This is expected to continue after the Action ends.
- Better aesthetic integration, architectural rhythms and themes.
- Structural/material developments relating to the thermal resistance of the building element, integrity of the element to the weather impact and fire and noise protection.

The impact resulted in increased knowledge of BISTS application by improving cost-efficiencies and aesthetic integration into the buildings. New software models for integrated simulation of BISTS were also developed as part of this Action. The activities will result in the enhancement and expansion of the scope of the EPBD. Additionally, the introduction of new technologies and materials into the building sector and the relevant impact on the standards in the field are expected to continue in the future. There will also be an impact on manufacturers, designers, architects, installers and the wider building construction industry.

1.1.3 Scientific program

This COST Action included four Working Groups:

(1) Development of new innovative methods for building integration of STS.

(2) Modelling and simulation of new BISTS and their behaviour as a renewable energy system (RES).

(3) Investigation of new applications for innovative integration of STS in various application areas like domestic, commercial and industrial buildings, and

(4) Dissemination. Dissemination of the research outcomes of the Action was undertaken through the STSMs and Training Schools and to end users through the Symposium, International Conference and website.

The scientific innovation relates to the development of novel building integrated STS. Through collated consultation and enquiry, experimental investigation and development of modelling and simulation techniques, real and significant advances in building integrated solar thermal energy systems were achieved. This network provided the immediate sharing of nationally based research and enabled the establishment of common platforms to accelerate trans-national research projects in the area of building integrated solar thermal systems.

The potential impact is an increasing knowledge base, with an emphasis on viable building integrated STS solutions through an improved practical understanding and cost-efficiency awareness and reduction in building energy and effective heating and cooling load management. The activities brings a broadening impact upon the scope of the Energy Performance of Buildings Directive and its recast, whilst facilitating the introduction of new technologies into building sector, and knock-on effects on building related regulations, systems standards such as the on-site performance testing of solar collectors and installation practices as well as off-site constructed building elements with the STS directly integrated which could improve cost and reduce unwanted site waste. All these issues and many others are presented in this handbook, which is the ultimate output of TU1205 Action.

1.1.4 Closing

Building integration of solar thermal systems creates a new way of applying these systems to buildings. We hope that the outcomes of the Action will help the industry to expand and produce more options in the near future. As a closing, as Action Chair, I would like to thank all active partners who contributed not only to this handbook but also to the other deliverables of the Action and above all the COST Office in Brussels for the financial support which enabled us to carry out this Action.

1.2 BISTS CLASSIFICATION AND CHARACTERISATION

Mervyn Smyth, Laura Aelenei

1.2.1 Classification

Building Integrated Solar Thermal Systems (BISTS) have been classified across a range of operating characteristics and system features and mounting configurations. The main classification criteria of all solar thermal systems (STS) are based on the method of transferring collected solar energy to the application (active or passive), the energy carrier (air, water, water-glycol, oil, electricity etc.) and the final application for the energy collected (hot water and/or space heating, cooling, process heat or mixed applications). Additionally, for BISTS the architectural integration quality based on structural, functional and aesthetical variations have to be classified. The collector as a central element of integration has to fulfil in some cases many more specifications than ordinary, add-on collectors. Figure 1.2.1 illustrates a simple BISTS classification.

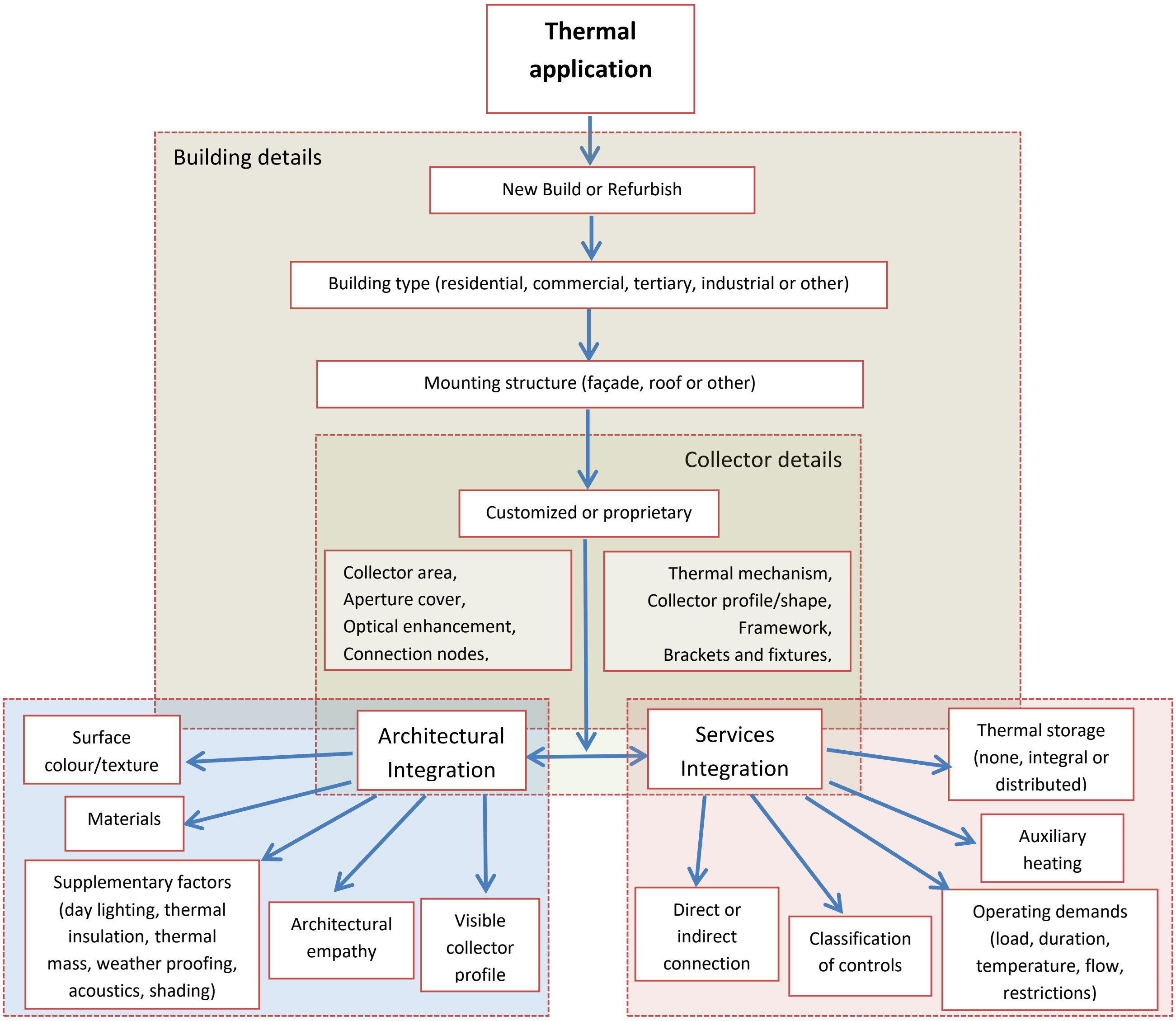

Figure 1.2.1. BISTS classification (COST TU1205, 2016).

The majority of BISTS can be classified as being either passive or active, e.g. in the first case using thermal buoyancy for fluid transport (natural convection or circulation) or no transport at all, and in the second case utilizing pumps or fans to circulate the thermal transfer fluid to a point of demand or storage (forced convection or circulation). A number of systems are however hybrids, operating in part through a combination of natural and forced transport methods. Many façade solar air heaters use thermal buoyancy to induce an air flow through the vertical cavities that can be further augmented with in-line fans (and heating) if necessary.

1.2.2 BISTS applications

BISTS deliver thermal energy to the building but additionally other forms of energy may contribute to the buildings energy balance. For instance, daylight comes through a transparent window or façade collector, or PVT systems will also deliver electrical power which may be used directly by any auxiliary electrical services. Heated air or water can be stored or delivered directly to the point of use. Although the range of applications for thermal energy is extensive, all of the evaluated studies demonstrate that the energy is used to provide one or a combination of the following;

- **Space heating**

Thermal energy produced by a BISTS may reduce the space heating load of a building by adding solar gains directly (e.g. by a passive window) or indirectly (e.g. by transferring heat from the collector via a storage to a heating element) into the building. An example is shown in Figure 1.2.2.

Figure 1.2.2. An indirect solar-comb construction BISTS (IEA n.d.).

- **Air heating and ventilation**

Thermal heat may be used also to preheat fresh air needed in the building. Air is heated directly or indirectly (in a secondary circuit) and using forced flow or thermosiphonic action is used to provide space air heating and/or ventilation to the building as shown in Figure 1.2.3 In some instances, an auxiliary heating system is used to augment the heat input because of comfort reasons.

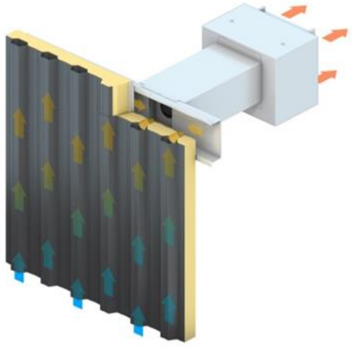

Figure 1.2.3. Solar air heating façade BISTS with auxiliary heating system (Kingspan n.d.).

- **Water heating**

Hot water demand in the building is the most popular application. In the majority of water heating BISTS, a customized heat exchanger or integrated proprietary solar water is used to transfer collected heat to a (forced) heat transfer fluid circuit and on to an intermediate thermal store and/or directly to a domestic hot water (DHW) application. In most instances, an auxiliary heating system is used to augment the heat input. An example is shown in Figure 1.2.4.

Figure 1.2.4. Roof integrated flat plate BISTS (NSAI Agreement, 2010).

- **Cooling and ventilation**

In cooling dominated climates buildings most of the time have an excess of thermal energy, and therefore BISTS can also be a technology to extract heat from a building. There are a number of methods described in providing a cooling (and/or ventilation) effect to a building; shading vital building elements, desiccant linings, supplying heat directly to 'sorption' equipment, induced ventilation through a stack effect and reverse operation of solar collecting elements for night-time radiation cooling as illustrated in Figure 1.2.5.

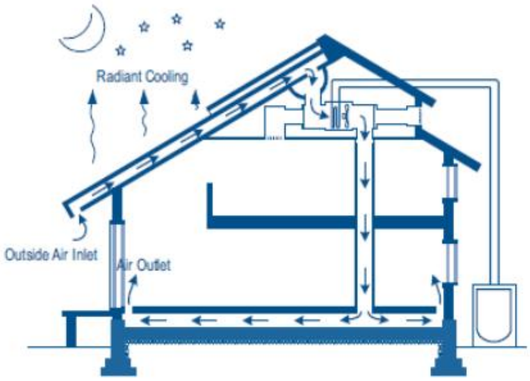

Figure 1.2.5. Radiant cooling via a reversed BISTS (OM Solar Association, n.d.).

1.2.3 BISTS case study classification

COST TU1205 (COST TU1205, 2016) has evaluated BISTS technologies based on a detailed review of applied case study examples from around the world. A total of 94 case studies were collated representing a diverse range of systems, installation and integration modes. The review was not conducted to produce a definitive, quantitative analysis of BISTS typology and characteristics but rather to provide an indicative understanding of the factors that form BISTS uptake and application. Figure 1.2.6 presents a taxonomy of the BISTS reviewed by the study.

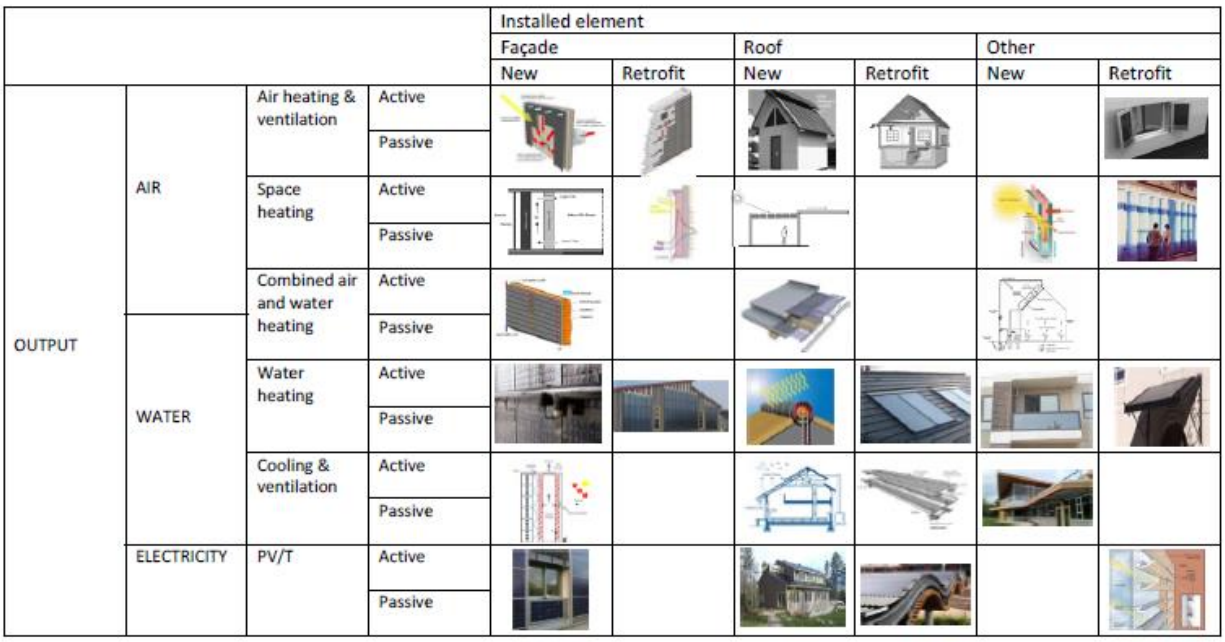

Figure 1.2.6. Taxonomy of BISTS case study evaluation (COST TU1205, 2016).

From the study conducted it is apparent that there are many BISTS configurations available, primarily in a commercial or demonstrational role, although there are many concept designs/configurations under development. Most of the reviewed systems, whilst taken from a small sample, indicate that water and air heating systems are the most common form of BISTS application, representing over 50% of the systems reviewed (Figure 1.2.7). Other applications involved some form of linked operation with other building related services or energy supply. This demonstrates the importance of multi-functionality in many BISTS, not only in providing a thermal gain and building structural element, but the perhaps the addition one or two other functions. This was evident in many of the conceptual systems reviewed were daylight control, power production and air movement were crucial factors in the system's design and operation.

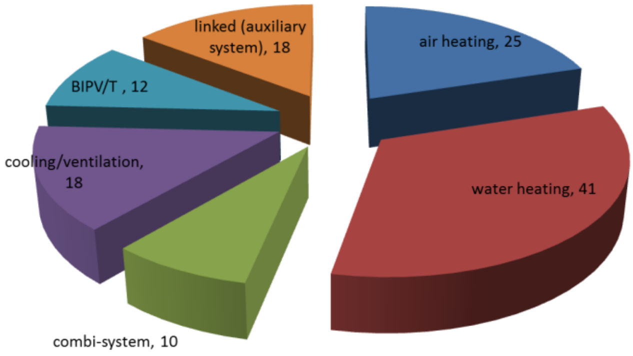

Figure 1.2.7. Breakdown of BISTS by application as reviewed by the case study evaluation.

The majority of BISTS documented are 'mounted' into the façade or roofing structures, as shown in Figure 1.2.8, with a significant number classified as being 'other'. This 'other' term embraces a multitude of integration options, from shading devices to balcony balustrades such as that shown in Figure 1.2.9. Many of the façade or roof integrated systems are modified generic solar thermal collectors adapted to a building integrated role.

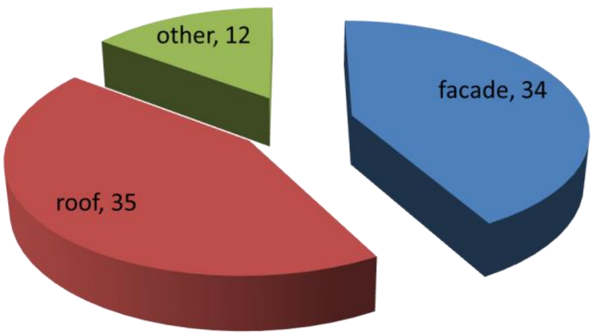

Figure 1.2.8. Breakdown of BISTS by building element integration as reviewed by the case study evaluation.

Figure 1.2.9. BISTS balustrade/railing feature (Glesolar, 2016).

Perhaps it is unsurprising that the vast majority of the case studies accumulated and reviewed are published by or represent systems tailored to a European context, both in location and climate. Whilst the action is a European led exercise, the collection of case study material was conducted from a global perspective and if the location bias of action can be temporally ignored, it does tend to indicate that the current work being conducted on BISTS is very much European. This is not unpredictable as Europe has been very active in driving through a raft of measures, legislatively, economically or other to support the uptake in renewables within a building context. The increased percentage of European BISTS as observed in this simplistic review is just mirroring the supported activity in this area.

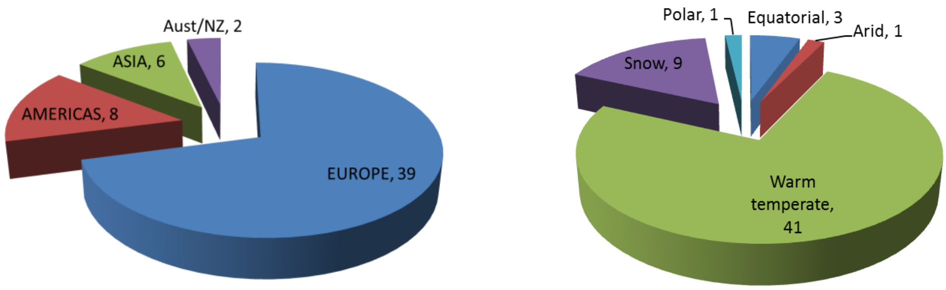

Figure 1.2.10. BISTS location by continent and climate as reviewed by the case study evaluation.

1.2.4 BISTS Characterization

The Energy Performance of Buildings Directive (EPBD) requires that Renewable Energy Systems (RES) are actively promoted in offsetting conventional fossil fuel use in buildings. A better appreciation of solar thermal system (STS) integration in buildings will directly support this objective, leading to an increased uptake in the application of renewables. This uptake of RES in buildings is expected to rise dramatically in the next few years. A solar thermal system is considered to be building integrated, if a component (in most cases the collector) is a prerequisite for the integrity of the building's functionality. If the building integrated STS is dismounted, dismounting includes or affects the adjacent building component which will have to be replaced partly or totally by a conventional/appropriate building component. The members of the Cost Action TU1205 produced a systematic characterization of BISTS (Figure 1.2.11): technological/performance characterization of BISTS, architectural integration characterization of BISTS, aesthetic characterization of BISTS, functional characterization of BISTS and environmental characterization of BISTS.

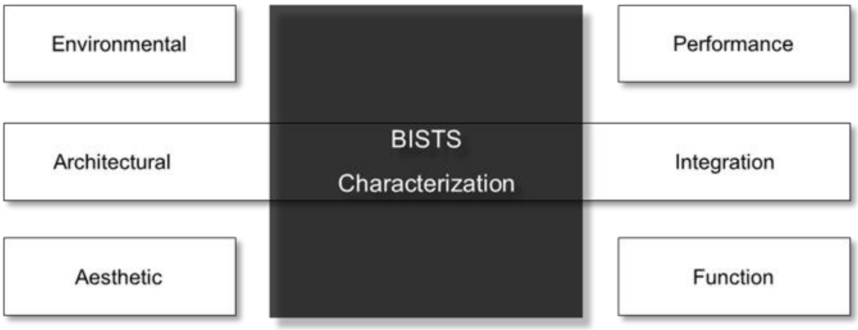

Figure 1.2.11. Main considerations for the systematic characterization of BISTS (Aelenei et al., 2016).

Characterisation is defined as the act of describing distinctive characteristics or essential features. In most solar thermal collecting systems the performance characterisation is commonly used as the most important criteria by which the system (or component) is represented. Building Integrated Solar Thermal Systems (BISTS) however are typically classified across a range of operating parameters and system features and mounting configurations and in many cases the performance could be a secondary consideration in their application. Therefore, BISTS characterisation most also account for the architectural integration based on structural, functional and aesthetical features. A comprehensive characterisation of BISTS is necessary to give designers, installers and end users confidence that the final solution selected is appropriate to the specific building requirements. In simplistic terms BISTS characterisation can be expressed as:

- Technological aspects (system and components, performance, services connection, etc.)
- Architectural aspects as constructive element (aesthetics, functionality, weather proofing and durability, noise attenuation, health and fire safety, etc.)
- Environmental aspects (embodied energy, LCA, toxicity, etc.)

1.2.4.1 Technological/Performance Characterization of BISTS

The accurate energy (performance) characterization of BISTS presents a potential problem. Considering the widely presented definition of a BISTS – ‘A solar thermal system is considered to be building integrated, if for a building component this is a prerequisite for the integrity of the building’s functionality’ makes one realize that the current methods for solar thermal characterization are based on independent, non-integrated components, and thus are inadequate in covering the extensive range of BISTS deployed. Only when the BIST components or systems are independent of the building elements (i.e., factory made and integrated later on-site), then the methodologies previously stated can be employed as the components/systems can be characterized without the need for the building. However, a collector integrated in a wall has different heat loss than the same collector just attached to the wall. Wherever the components/systems are embedded in the building, it is difficult to accurately determine the BISTS without considering the wider influence of the building. One example for BISTS performance characterization is illustrated in Figure 1.2.12.

Several authors have attempted to address the issue of an integrated solar system's contribution to a building's thermal energy needs using a range of methodologies cited by (Aelenei et al., 2016). Oliveira Panão et al., cited by (Aelenei et al., 2016) presented a study that reviewed and analyzed a simplified empirical method based on the Solar Load Ratio (SLR) and ISO 13790 methodologies.

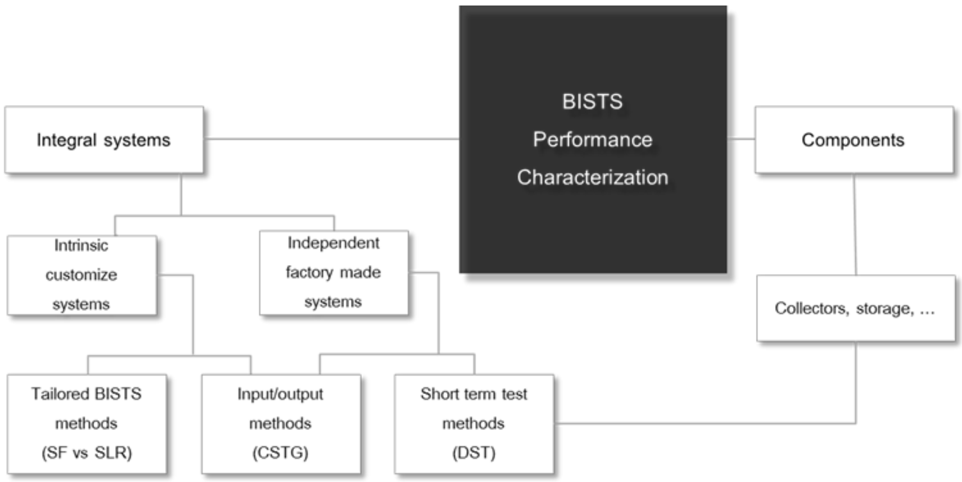

Figure 1.2.12. Classification of BISTS Performance Characterization methods.

1.2.4.2 Architectural Integration Characterization of BISTS

The usual practice of the implementation of SES has been the installation of PV and STC panels on flat and tilted roofs in buildings. The architectural integration of active solar systems is one of the main parameter examined for example by the International Energy Agency (IEA) programs. The factors of solar suitability are the relative amount of irradiation for the surfaces depending on their orientation, the inclination and location, as well as the potential performance of the photovoltaic system integrated in the building. Many authors (Aelenei et al., 2016) have tried to find a proper balance between technical and aesthetic requirements to formalize a set of criteria and recommendations which allow the defining of a suitable procedure when using solar technologies in the urban environment, especially on buildings whose architectural, historical or cultural features need to be considered most carefully. Fuentes cited by (Aelenei et al., 2016) proposed a classification integration method, where both PV and STC systems can be incorporated into buildings by either superimposition - where the system is attached over the existing building envelope, or integration - where the system forms a part of the building envelope. Superimposed – a simple method well suited in case of existing buildings. The solar modules are mounted on a structure; for e.g.: roof, on the building envelope and in parallel with them. There are no savings in substituting elements as the materials underneath the solar modules are not replaced. With superimposition, architectural integration can still be achieved as the buildings can be made elegant. If this is the case, it may also be called architectural integration but is certainly not building integration. Integrated – The PV and STC systems are used both as an architectural element as well as a means of energy generation. This method is most likely to be suitable for new buildings. The traditional constructive elements are substituting for PV and STC materials. Savings are possible where the cost of the substituted elements is below that of the traditional elements.

Golic et al. cited by (Aelenei et al., 2016) present a general model for SWHS integration in residential building refurbishment that considers several basic phases in order to facilitate problem-solving and to enable the individual optimization processes for various BISTS designs. Measurable criteria such as Building Potential and Degree of Feasibility are introduced in order to estimate the suitability of SWHS integration. The architectural integration of active solar systems was a main parameter examined by the IEA Photovoltaic Power Systems Programme (PVPS) in Task 7. According to the PVPS programme, the factors of solar suitability are “the relative amount of irradiation for the surfaces depending on their orientation, the inclination and location, as well as the potential performance of the photovoltaic system integrated in the building. The IEA PVPS Task 7 defined a kit of indicators to evaluate: natural integration, designs that are architecturally pleasing, good composition of colours and materials, dimensions that fit the gradual, harmony, composition, PV systems that match the context of the building, well-engineered design and use of innovative design. Jo and Otanicar cited by (Aelenei et al., 2016) developed a methodology for assessing the potential capacity and benefits of installing rooftop solar integrated systems in an urbanized area. Object oriented image analysis and geographical information systems were combined with remote sensing image data to quantify the rooftop area available for solar energy applications and therefore predict the potential benefits of urban scale photovoltaic system implementation.

Regarding aesthetic characterization, criteria for the aesthetic building integration were developed and published cited by (Aelenei et al., 2016). One study enables communities to define a required quality of building-integration for certain districts leading manufacturers to develop more successful BIST elements. Two other subjective methodologies employed to characterize the aesthetic integration of solar systems on buildings are based on subjective interpretation of the visual integration of the solar absorbing elements into the building elements/fabric. Although both methods do not directly refer to building integrated solar thermal systems, the wording can be interpreted to encompass features that are equally representative of BISTS. Reijenga and Kaan cited by (Aelenei et al., 2016) present a methodology to assess the aesthetic integration of building integrated PV. Rush cited by (Aelenei et al., 2016) also uses five categories to characterize the level of visual integration of building services systems in buildings. These services are interconnected, and the nature of the connection identifies the level of integration which permits the designer to investigate alternative levels of integration to conserve space, material, and time. Probst and Roeker proposed a new method cited by (Aelenei et al., 2016), to help authorities preserve the quality of pre-existing urban areas while promoting solar energy use. The method is based on the concept of architectural “criticity” of building surfaces, "criticity" level of a surface is defined by the sensitivity of the urban context and by the visibility of the integrated system from the public domain.

When solar thermal collectors are integrated into roofs or facades, whether transparent or non-transparent, they substantially change the physical functionality of the building. Light and direct solar transmittance, vapour diffusion, thermal bridges and insulation level as well as sound transmission may change dramatically. The solar thermal component might enhance the building performance as well as the building element might enhance the energy or functional performance (e.g. mechanical stability) of the solar component. Conversely misplaced and wrong installations might deteriorate the overall performance and user comfort. Therefore, these aspects have to be thoroughly planned in all detail and the installation work supervised. The main function of BISTS is to produce thermal energy. In the case of hybrid systems BIPV/T electricity will also be produced. A whole range of additional functions related to building physics and constructional requirements can be addressed by BISTS: thermal insulation, acoustic insulation, humidity regulation, rain and wind tightness, solar protection, daylighting, structural functions, fire resistance, security protection. There are different levels of building integration depending on the number of functions being delivered by BISTS. While partially integrated solar thermal systems have a poor scope of functionality, fully integrated systems are characterized by functional complexity. Moreover, external layers of the building envelope STC can influence the aesthetic potential and design options. STC systems can be used to replace normal building components with their multifunctional potential as an external skin similar to that exhibited by integrated PV systems. Clearly the multi-functionality of the collector makes it applicable to integration and can provide the advantage for the designer to use fewer building elements, as the collector fulfils several functions. Achieving functional requirements must be accompanied by fulfilling aesthetic requirements. This requires that the functional and aesthetic aspects are considered simultaneously, taking into account the various building aesthetics, building physics and STC mounting criteria categories. Moreover, there are many contextual aspects that must be considered that have location specific characteristics. The following Figure 1.2.13 illustrates the many of the external/internal relationships that influence the final characteristics adopted by any BIST system.

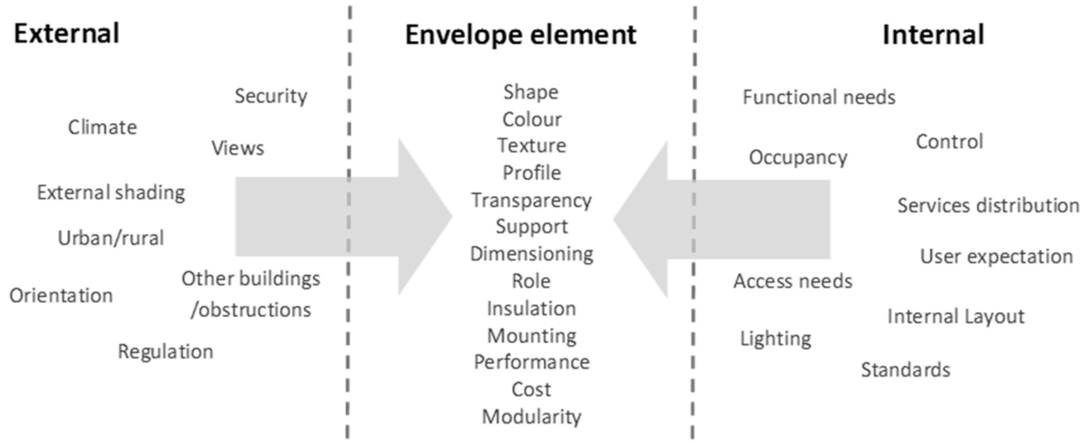

Figure 1.2.13. External / internal relationships that influence the final characteristics.

1.2.4.3 Environmental Characterisation of BISTS

A critical review on Life Cycle Analysis (LCA) about solar systems with emphasis on BIST installations has been presented (Lamnatou et al., 2015a). Several issues such as BISTS influence on building ecological profile, ongoing standardization and environmental indicators were discussed. It was demonstrated that in the literature there are few studies about real BIST (and solar thermal/electrical) installations and there is a need for more LCA investigations which evaluate the BISTS itself and/or in conjunction with the building. Active systems that can provide energy for the building would be interesting to be evaluated from ecological point of view. Studies about BISTS influence on building life-cycle performance could also offer useful information in the frame of sustainable built environment.

In the same way as LCA implementation on multiple systems and products, LCA implementation on BIST installations should also follow ISO 14040:2006 and ISO 14044:2006. More specifically, the phases of goal and scope definition, life-cycle inventory, life-cycle impact assessment and interpretation should be adopted. Modelling BISTS life-cycle can be conducted e.g. by focusing on the system itself (Lamnatou et al., 2014; Lamnatou et al., 2015b) or by integrating the system in the whole life-cycle assessment of the building (Lamnatou et al., 2015a).

In order to assess the whole life-cycle footprint and BISTS contribution to the environmental impacts and benefits, the following processes/factors are crucial for the life-cycle calculations:

- Materials used for BISTS components (the materials utilized for construction elements could be also taken into account): phases of manufacturing, maintenance, etc.
- Materials added (or replaced) over lifespan
- Energy consumed by the BISTS
- Energy delivered inside and outside of the building system and produced by the BISTS

There is a need for more LCA studies within the field of BIST systems, especially based on multiple life-cycle impact assessment methodologies and environmental indicators in order to provide a complete picture of the ecological profile of the proposed systems. Moving in this direction, LCA models which are based on a newly-developed method (for example ReCiPe) along with other methodologies such as IPCC 2013 GWP (for different time horizons), ecological footprint and USEtox, can offer useful information about the environmental performance of a solar system.

1.2.5 Case study characterisation

There are numerous methods available to characterise BISTS, as detailed in the previous sections. However, very few, if any, of the case studies reviewed have applied any of the presented characterisation methodologies. Those that have are exclusively focused on performance characterisation and tend to default to thermal performance characterisation of factory made systems (EN 12976-2, ASHRAE 93, EN ISO 9806, etc.). The lack of other characterisation methods being utilised would seem to indicate that the approaches are too onerous or difficult to apply.

The roof integrated solar micro-concentrating collector (Sultana, 2011) is a typical example (Figure 1.2.14). A novel modular concept designed primarily for commercial high temperature applications is characterised and presented as a stand-alone system. Many of the other case studies reviewed use the same or similar methods, with most examples presenting the energy delivery to the building load, resulting in energy savings, solar fraction or CO_2 emission values.

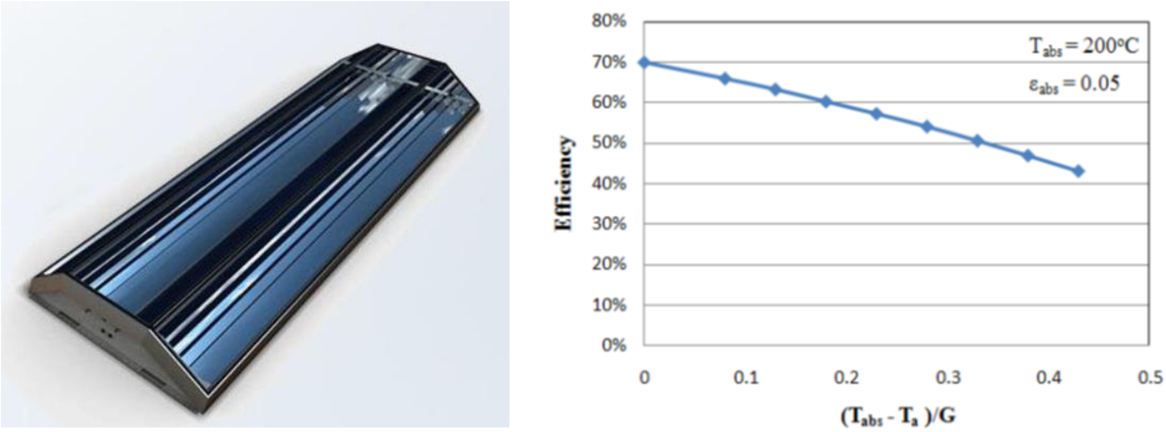

Figure 1.2.14. The roof integrated solar micro-concentrating collector with standard (default) thermal performance characterisation for BISTS (Sultana, 2011).

A number of the case studies reviewed do consider the wider thermal influence of the BISTS on the building envelope and internal volume. But again the performance characterisation methods applied are limited. The OM solar integrated dwelling is typical (Figure 1.2.15). A simple evaluation of the BISTS impact on the building's internal environment is presented, resulting in measured annual performance. In most cases this includes energy delivery or envelope U values but generally this approach results in overall benchmarking indices which can be used to compare and contrast.

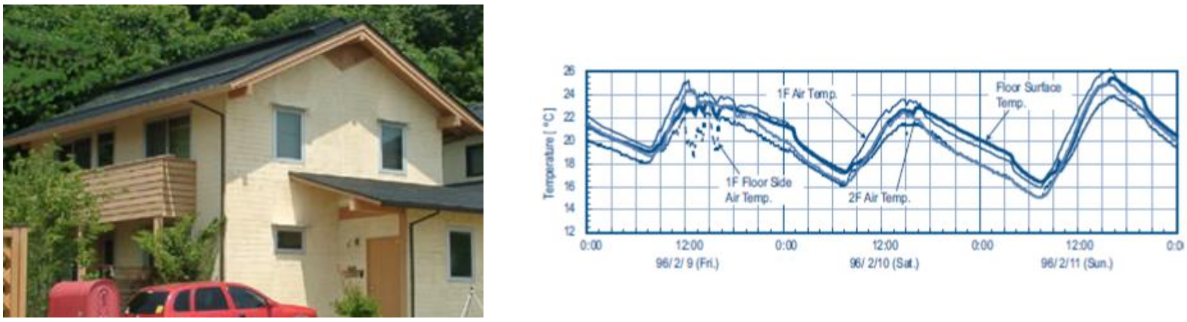

Figure 1.2.15. The OM solar integrated dwelling with simple indoor temperature profile produced by air heating BISTS (OM Solar Association, n.d.).

Given the importance of solar thermal building integration and the scarcity of applied characterisation (performance, technical, architectural, environmental or otherwise) it is apparent that much work is still needed in this area.

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OM Solar Association, (n.d.) 4601 Murakushi-cho, Hamamatsu, Shizuoka Prefecture, 431-1207 JAPAN. http://www.omsolar.net/

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1.3 SOLAR RADIATION APPLIED TO BISTS

Gilles Notton, Christian Cristofari

1.3.1 Introduction

The objectives of this chapter are to give some information on solar radiation: movement, position, intensity and to show how the solar irradiance varies versus the position and the inclination of a solar collector.

The fact to be integrated into the building 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? These are some of the questions that this analysis will attempt to answer.

This section will be divided in 3 sub-sections:

- position of the sun
- solar radiation components
- influence of position and orientation on available solar energy: case study of roof and walls

1.3.2 Geometrical Aspect

This are some geometrical aspects of solar radiation received by the earth required to calculate the solar irradiance received by a plane at the earth's surface.

1.3.2.1 Earth motion around the sun

The earth revolves around the sun in an elliptic orbit with the sun at one of the foci. The plane of earth revolution around the sun is called the ecliptic plane. (Figure 1.3.1).

The amount of solar radiation reaching the earth is inversely proportional to the square of its distance from the sun. The mean sun-earth distance is called one astronomical unit: r_0 = 1 AU = 1.496 x 10^8 km.

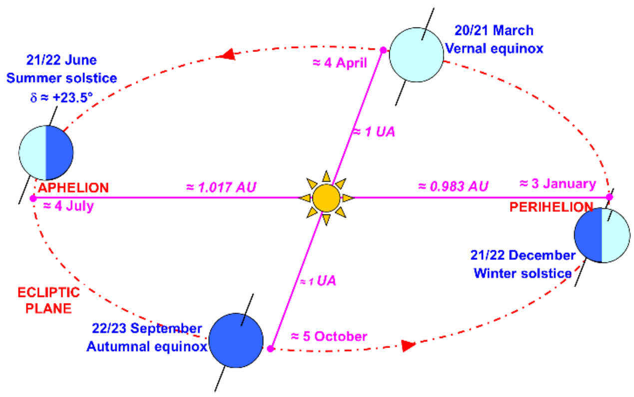


Figure 1.3.1. Motion of the earth around the sun.

The earth is at its closest point to the sun (perihelion) on approximately the 3rd of January and at its farthest point (aphelion) on approximately the 4th of July. The eccentricity correction factor of the earth's orbit can be calculated by this simple expression (more complicated ones are available in the literature) (Iqbal, 1983):

$$E_0 = (r/r_0) = 1 + 0.033\cos(2\pi d_n/365) \tag{1.3.1}$$

where d_n is the day number of the year, ranging from 1 on 1 January to 365 on 31 December (Figure 1.3.2).

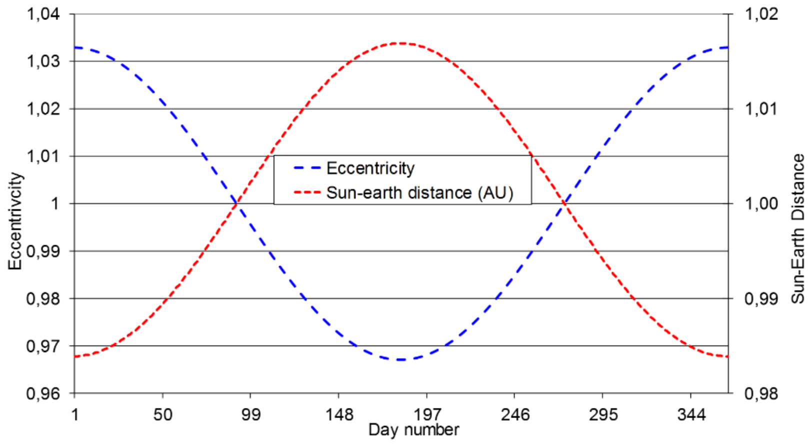


Figure 1.3.2. Eccentricity correction factor and sun-earth distance versus the day.

The earth itself rotates around an axis called polar axis which is inclined at around 23.5° from the normal to the ecliptic plane. The earth's rotation around this axis causes the diurnal change in radiation income and the position of this axis relative to the sun causes seasonal changes. If the angle between the polar axis and the normal to the ecliptic plane remains constant, the angle between a line joining the centers of the sun and the earth to the equatorial plane changes every instant and is called solar declination δ (Figure 1.3.3). Its value is zero at the spring and fall equinox (literally the day is equal to night). In 24 hours, the maximum change in declination is less than 0.5° and we can consider the declination as constant during the day. δ can be calculated by this simplified equation (Figure 1.3.4):

$$\delta = \sin^{-1}\left\{0.4\sin\left[\frac{360}{365}(d_n - 82)\right]\right\} \text{ in degrees} \tag{1.3.2}$$

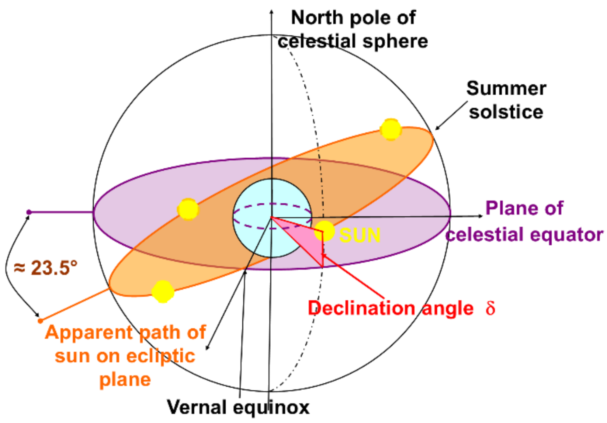


Figure 1.3.3. Celestial sphere showing apparent path of sun and sun's declination angle.

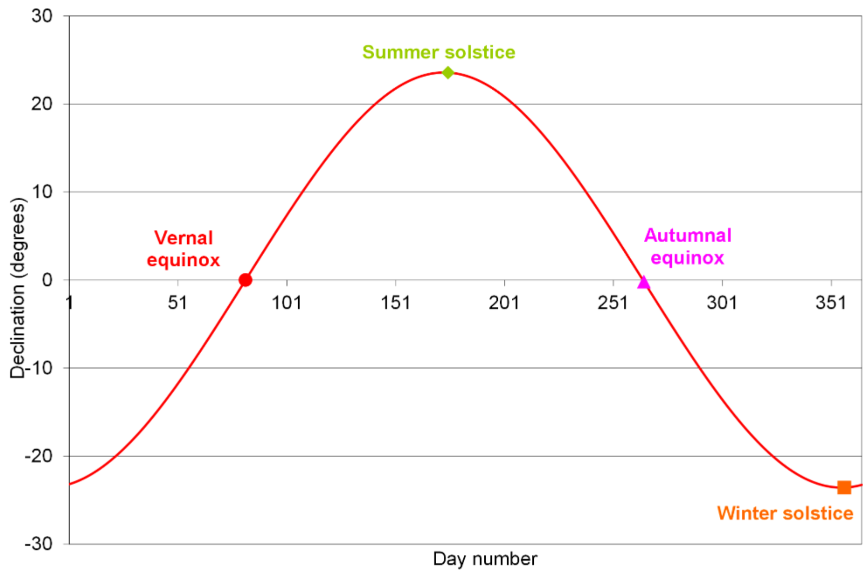


Figure 1.3.4. Variation the sun's declination versus the day number.

1.3.2.2 Apparent motion of the sun

The apparent motion of the sun seen by a fixed observer situated at the latitude ϕ in the north hemisphere is shown in Figure 1.3.5 (Iqbal, 1983).

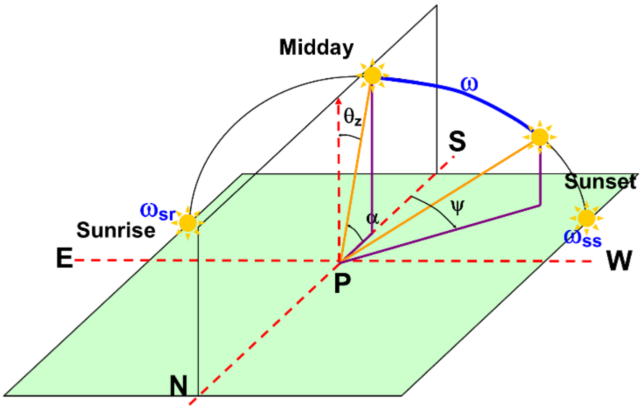


Figure 1.3.5. Definition of sun's altitude α, zenith angle θ_z, azimuth Ψ and hour angle ω.

The solar altitude α (also called solar elevation) is the sun's angular height above the observer's celestial horizon. The solar azimuth Ψ is the angle at the local zenith between the plane of the observer meridian and the plane of a great circle passing through zenith and the sun (it varies between 0° and ±180° - positive = east). The hour angle □ is the angle measured at the celestial pole between the observer's meridian and the solar meridian (counting from midday, it changes 15° per hour = 360°/24h). ω is calculated by:

$$\omega = 15(12 - h_{TST}) \text{ in degree} \qquad (1.3.3)$$

where h_{TST} is the local apparent time also called true solar time (in hours).

For the following calculations, the latitude and the longitude of the considered site must be known. To situate a point on the earth, the latitude ϕ (North-South) and the longitude λ (East-West) are needed, they are based respectively on the position of parallel lines that are parallel to the equator, and meridians that circle the globe via both poles and which refer to the Prime meridian (Greenwich.) (Figure 1.3.6).

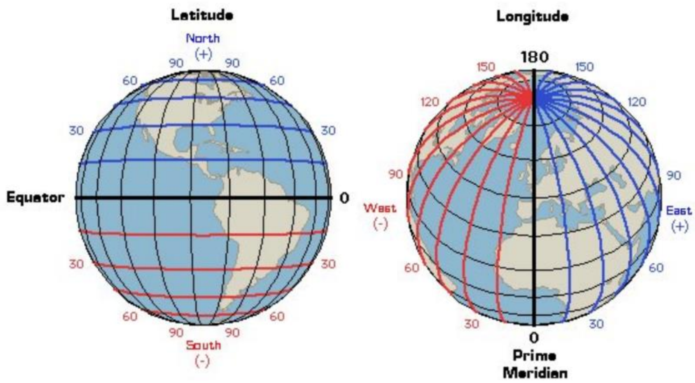


Figure 1.3.6. Latitude and longitude presentation.

For a given geographical position, (defined by the latitude Φ), the solar altitude α and the zenith angle θ_z ($\theta_z = \frac{\pi}{2} - \alpha$) are given by:

$$sin(\alpha) = cos(\theta_z) = sin(\delta)sin(\Phi) + cos(\delta)cos(\Phi)cos(\omega) \qquad (1.3.4)$$

And the azimuth angle is given by:

$$cos(\Psi) = [sin(\alpha)sin(\Phi) - sin(\delta)]/[cos(\alpha)cos(\Phi)] \qquad (1.3.5)$$

1.3.2.3 Day lengths

From equation (1.3.4), the sunrise hour angle for a horizontal surface can be deduced. At sunrise, the solar altitude α = 0 then:

$$0 = sin(\delta)sin(\Phi) + cos(\delta)cos(\Phi)cos(\omega) \Rightarrow \omega_{sr} = cos^{-1}[-tan(\Phi)tan(\delta)] \qquad (1.3.6)$$

The sunrise angle is equal to the sunset angle except for the sign difference (symmetry with respect to midday). The day length is $2\omega_{sr}$ and can be written in hours:

$$DL = \tfrac{2}{15} cos^{-1}[-tan(\Phi)tan(\delta)] \qquad (1.3.7)$$

We note that:

- in the polar region, during the winter, the sun does not rise, thus $cos(\omega_s) > +1$ and during the summer, there is a continuous day of about 6 months
- at the equator, Φ=0, therefore ωσ=π/2 and the day length is independent of the day and equal to 12h;
- at the equinoxes, δ=0 therefore ωσ=π/2 and the day length is the same whatever the latitude is and equal to 12h

In Figure 1.3.7, an illustration of the sun path in equinoxes and solstices is shown. A tilted surface, sometimes, does not “see” the sun (in summer) because the sun is behind the plane and consequently, the sunrise and sunset hours are not always identical for horizontal and inclined surface. This issue is discussed further below.

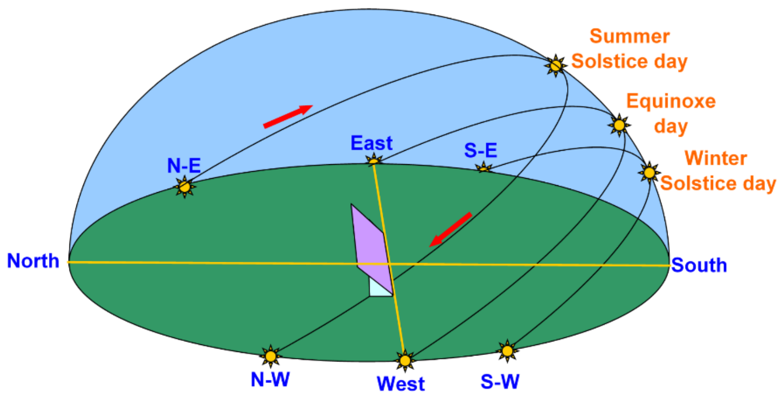


Figure 1.3.7. Illustration of the sun path according to the period of the year.

In Figure 1.3.8 the day length for a horizontal plane according to the site latitude versus the day number is shown.

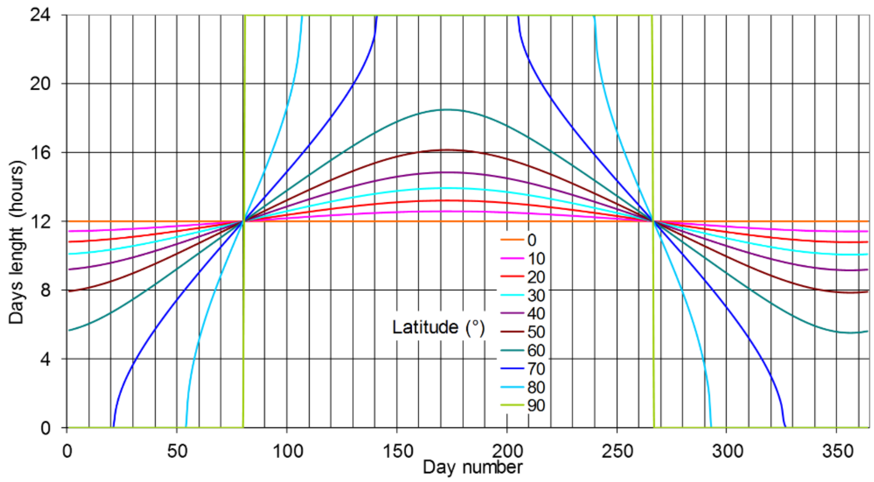


Figure 1.3.8. Day length versus the day number for various latitudes (for horizontal plane).

The theoretical sunshine duration is the same whatever the latitude is for the two equinox days. Two specific remarks: for equator; the day length is the same during all the year and for latitude 90°, the day length is 24 hours during 6 months (continuous day), then zero during 6 months (continuous night).

1.3.2.4 Position of the sun relative to inclined and arbitrarily oriented surface

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.

In order to determine the incidence angle θ with respect to a surface sloped at β from horizontal and oriented at γ from the local meridian (Figure 1.3.9), Eq. (1.3.8) is used.

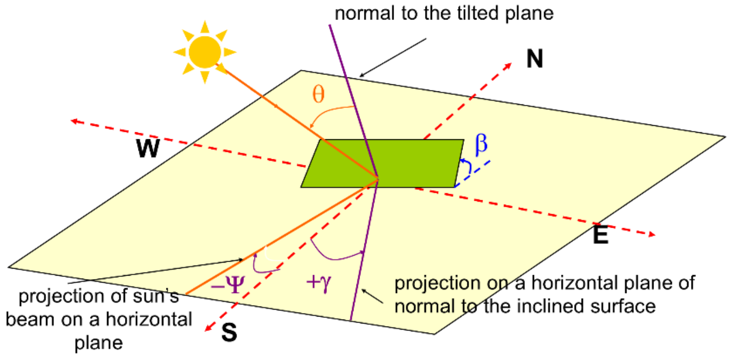


Figure 1.3.9. Position of sun relative to an inclined plane.

$$\cos\theta = (\sin\phi\cos\beta - \cos\phi\sin\beta\cos\gamma)\sin\delta + \\ + (\cos\phi\cos\beta + \sin\phi\sin\beta\cos\gamma)\cos\delta\cos\omega + \\ + \cos\delta\sin\beta\sin\gamma\sin\omega \tag{1.3.8}$$

As said before, 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). For an arbitrarily oriented and tilted surface, the sunset hour and sunrise hour are not symmetrical about midday (as for a horizontal surface). It is necessary to watch for the two possible situations when the sunrise hour might be lower than the sunrise hour for a horizontal surface or when the sunset hour is lower than the corresponding one for horizontal plane. The sunrise hour is obtained numerically through iteration by setting $\theta = 90°$ in Eq. (1.3.8) (explicit expression exists too (Iqbal, 1983)) and introducing this result in Eq. (1.3.3) for determining sunrise and sunset hour $h_{sr,TST}$ and $h_{ss,TST}$. The sunrise hour cannot be lower than the sunrise hour for horizontal plane (and sunset hour cannot be greater than for horizontal plane), thus:

$$h_{sr,TST} = max[h_{sr,TST}(\beta = 0, \forall\gamma); h_{sr,TST}(\beta,\gamma)] \tag{1.3.9}$$

$$h_{ss,TST} = min[h_{ss,TST}(\beta = 0, \forall\gamma); h_{ss,TST}(\beta,\gamma)] \tag{1.3.10}$$

1.3.2.5 Extraterrestrial solar irradiation on inclined and arbitrarily oriented surface

The extraterrestrial irradiance (solar irradiance before entering into the atmosphere and before being scattered and attenuated by the atmosphere) is computed. Calculating the extraterrestrial radiation is required only to observe the influence of inclination and azimuth angles on the beam radiation (mainly present by clear sky days); in this case, the optic length (more important at sunset and sunrise) is not taken into account; subsequently, the same impact on global solar irradiance at ground level will be shown after introducing the diffuse radiation and keeping in mind that the sky diffuse radiation generally decreases when the inclination angle increases.

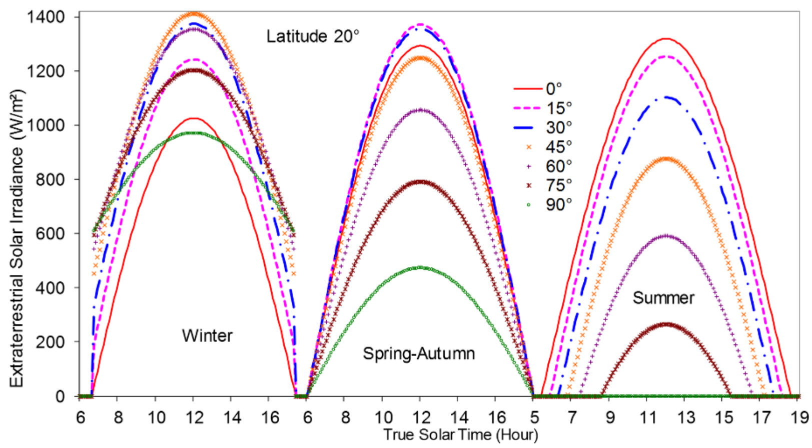
The extraterrestrial irradiance on a normal plane $I_{0,n}$ is given by Iqbal (1983)

$$I_{0,n} = E_0 I_{sc} \tag{1.3.11}$$

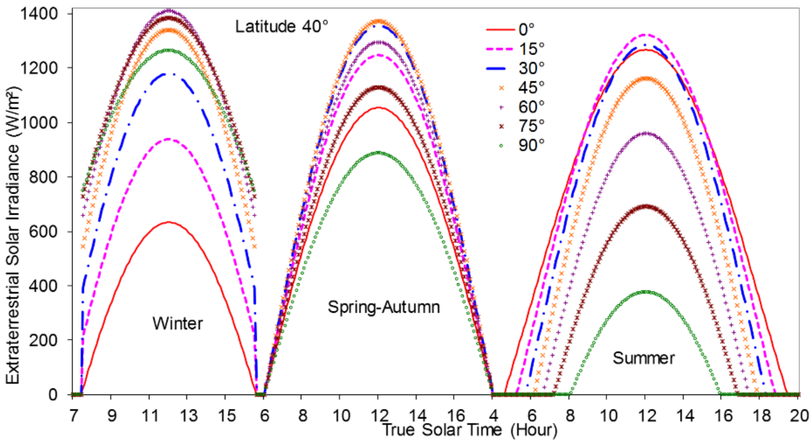
where E_0 is the eccentricity correction factor of the earth's orbit (Eq. 1.3.1) and I_{sc} the solar constant taken equal to 1367 W.m^{-2} according to the World Meteorological Organization (Iqbal, 1983). The extraterrestrial irradiance on a tilted plane is calculated from Eqs. (1.3.8) and (1.3.9):

$$I_{0,\beta,\gamma} = E_0 I_{sc} \cos\theta \tag{1.3.12}$$

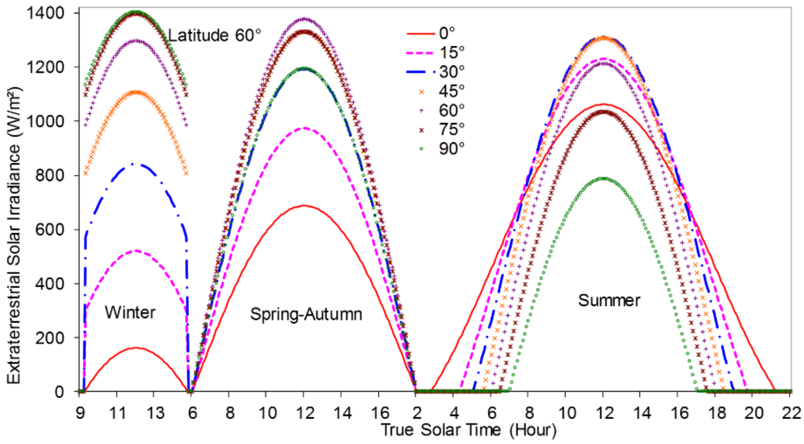
Figure 1.3.10 shows the influence of the inclination for a south plane situated respectively at 20°, 40° and 60° latitude for solstice and equinox days.



a)



b)



c)

Figure 1.3.10. Influence of inclination for a plane at three latitudes a: 20°, b: 40° and c: 60° for the four seasons.

Figure 1.3.10 is interesting for the form of curves, not for their amplitude. At ground level, the solar irradiance is reduced (see paragraph 1.3.3.1) and the gap between the curves for each inclination is reduced due to influence of diffuse radiation (Notton and Diaf, 2014). The sunshine duration is reduced with the inclination during summer but even if the sun is behind the plane, at the ground level, the plane receives diffuse component from sky dome or reflected by the ground. In summer, for a south wall, the sun is always behind the wall and the corresponding curve does not appear in Figure 1.3.10.a.

It has been shown, from extraterrestrial solar irradiation calculations, that the optimal inclination for maximum annual solar irradiation is equal to the location latitude ϕ, for maximum summer and winter production respectively to $\phi - 10°$ and $\phi + 10°$.

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.

As a case study, Figure 1.3.11 illustrates the influence on inclination for a south surface in the City of Ajaccio (Lat 41°55’) on the monthly average of daily extraterrestrial irradiation.

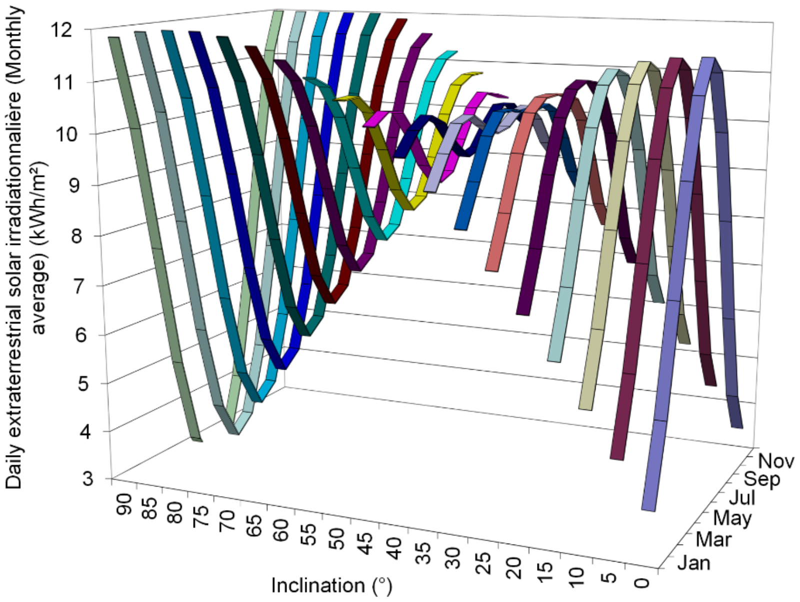
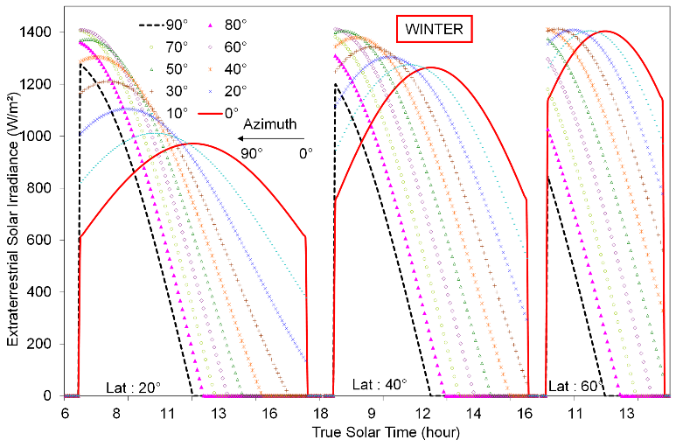


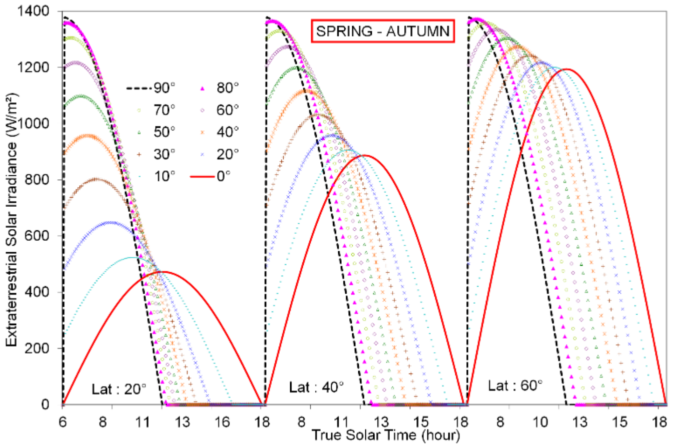
Figure 1.3.11. Daily extraterrestrial solar irradiation versus the month and collector inclination for Ajaccio.

The orientation of the solar collector is also an important factor influencing the available solar energy. A BIST is often integrated into a wall and according to the orientation of this wall, the amount of incident solar radiation varies. Figure 1.3.12 shows the orientation influence on the extraterrestrial solar radiation received by a wall (inclination 90°) for three latitudes. As a symmetry exists around midday, only wall oriented toward East are presented (similar curves are obtained for West façades). The sunshine duration, as expected, is very much influenced by the orientation. The latitude plays an important role. The more the collector is oriented east, the more the solar irradiance is high during morning, the sunrise hour is earlier and the solar day length reduced. Even if the daily solar irradiation is lower than for South orientation, there may be advantages:

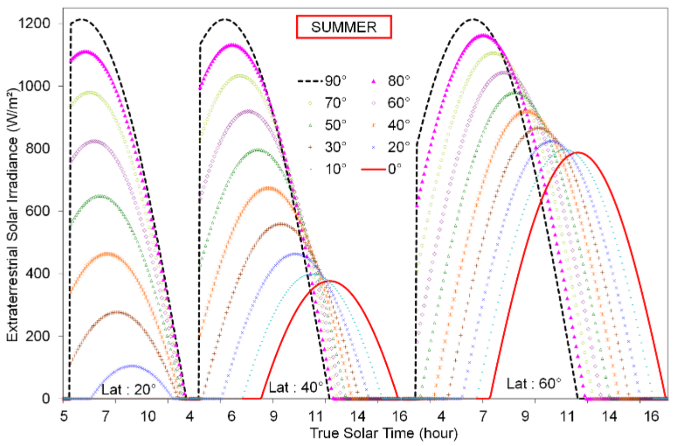
- For an office building, it is more interesting to heat in the morning when the workers arrive and early afternoon than in evening when the desk rooms are empty; then, a partial east orientation is preferred.
- For a hotel where the hot water requirements occur the morning, an east orientation is a good solution, another solar collector can be integrated into a south wall for morning needs;



a)



b)



c)

Figure 1.3.12. Influence of a wall orientation on the extraterrestrial solar radiation a) in winter b) in spring and autumn c) for summer.

The daily extraterrestrial irradiation is shown in Figure 1.3.13, for south planes and walls with various orientations.

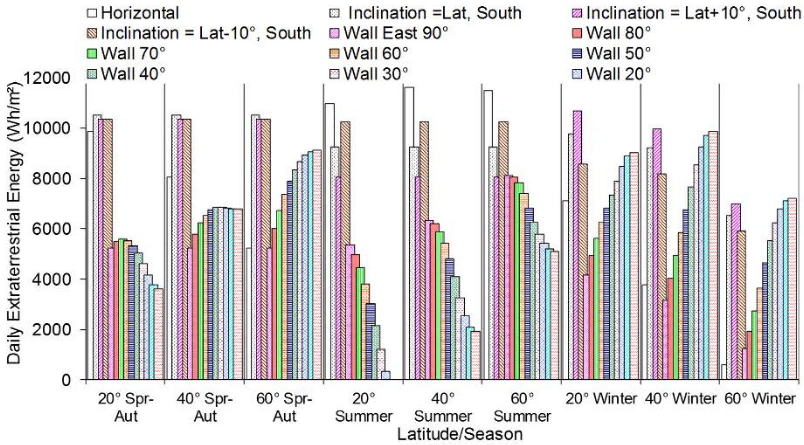
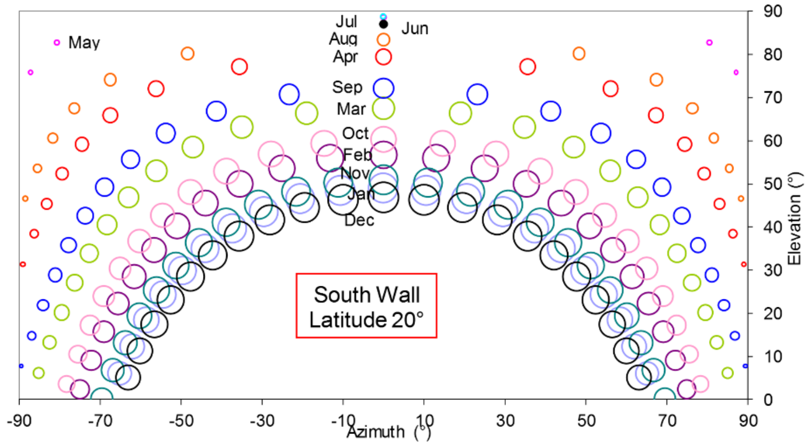
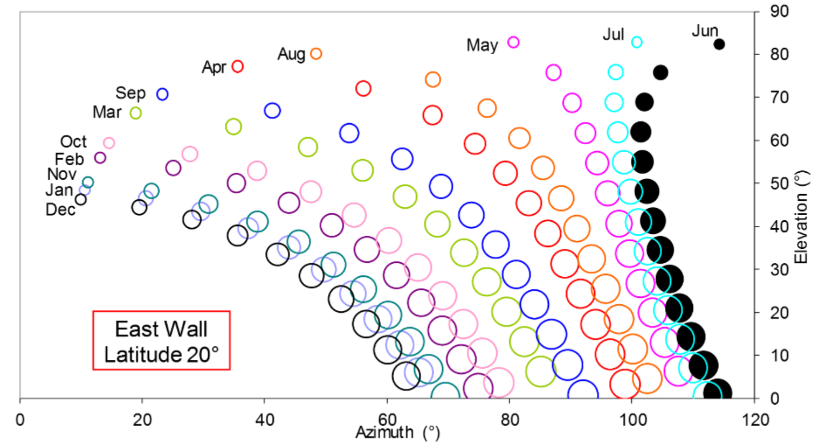
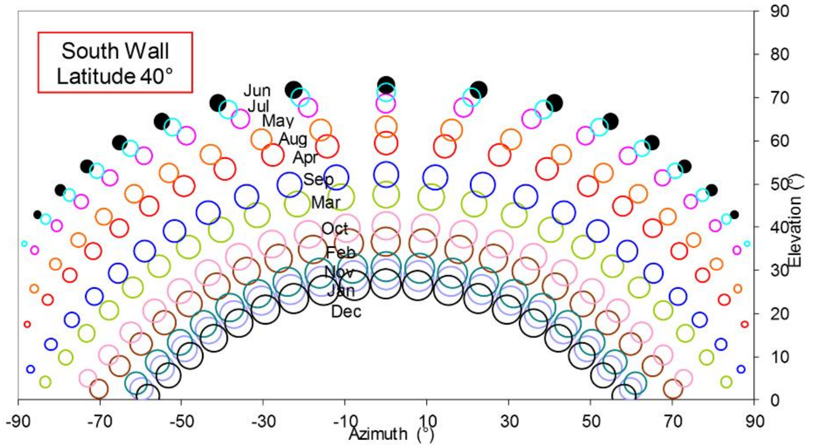


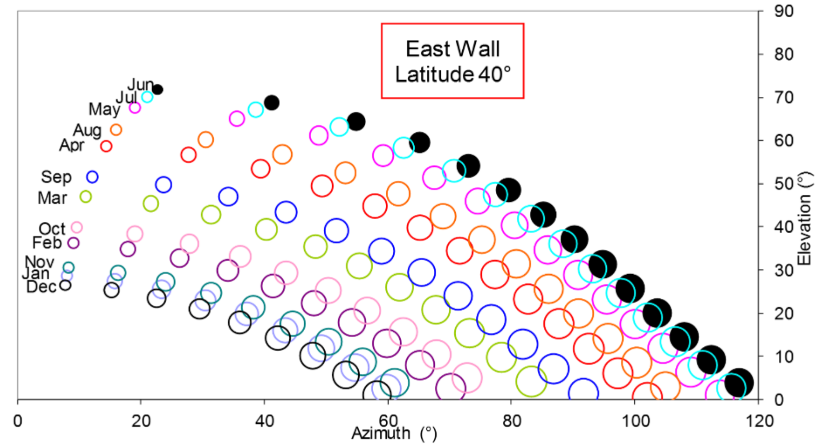
Figure 1.3.13. Comparison of daily extraterrestrial irradiations versus orientation and inclination.

In Figure 1.3.14, the sun position appears, with sun height and azimuth, and the bubble size is proportional to the cosines of the incident angle, i.e., the larger is the bubble, and the bigger is the solar energy because the extraterrestrial irradiance is proportional to the cosines angle (Eq. (1.3.12). East and South walls are compared for three latitudes for each season. The latitude influence appears clearly on Figure 1.3.14 and consequently, the conclusions on the reduction of the available solar energy for BIST compared with for non-integrated STS will depend on building situation.


South Wall
Latitude 20°
May
Jul
Aug
Apr
Jun
Sep
Mar
Oct
Feb
Nov
Jan
Dec
Azimuth (°)
Elevation (°)


East Wall
Latitude 20°
Apr
Aug
May
Jul
Jun
Sep
Mar
Oct
Feb
Nov
Jan
Dec
Azimuth (°)
Elevation (°)


South Wall
Latitude 40°
Jun
Jul
May
Aug
Apr
Sep
Mar
Oct
Feb
Nov
Jan
Dec
Azimuth (°)
Elevation (°)


East Wall
Latitude 40°
Jun
Jul
May
Aug
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Sep
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Oct
Feb
Nov
Jan
Dec
Azimuth (°)
Elevation (°)

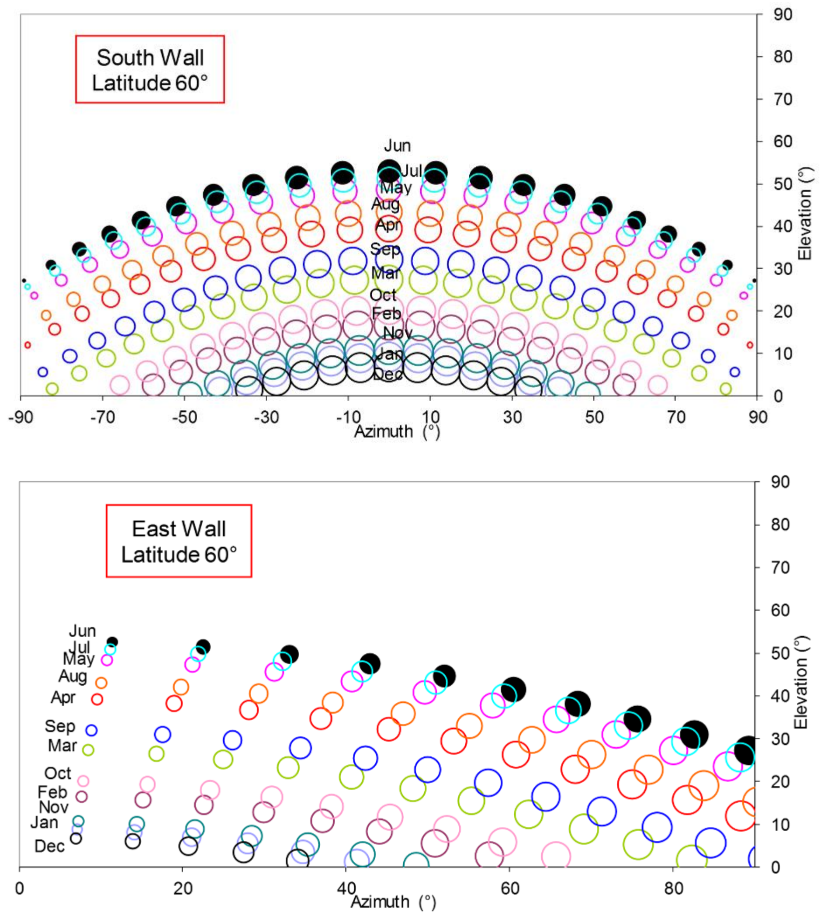


Figure 1.3.14. Sun position and importance of the incident radiation for South and East walls and latitudes of 20°, 40° and 60°.

An overview of the inclination and orientation influences on the available solar energy is presented in this section; but considering extraterrestrial irradiation is not a realistic approach because diffusion, absorption and scattering effects when solar radiation passes through the atmosphere are not taken into account. Therefore:

- The solar radiation on the ground is much lower than extraterrestrial one,
- The trajectory length of the solar ray through the earth's atmosphere depends on the sun position via the optical air mass and its absorption is higher for high zenith angle (attenuation intensity varies versus the time);
- Sky diffuse radiation plays an important role and the amount of diffuse radiation is maximum for a horizontal plane, offsetting the positive impact of inclination on beam radiations.

1.3.3 Solar Radiation Components

1.3.3.1 General overview

The spectral distribution of radiation arriving on the surface of the earth is important for energy application such as photovoltaic ones, much less for thermal ones. It is a function of its extraterrestrial distribution and the atmospheric constituents. The rate of total solar energy at all wavelengths incident on a unit area exposed normally to sun's rays at one astronomical unity is considered as slightly fluctuating around a value equal to 1367 W.m^{-2}. When solar radiation enters the earth's atmosphere, a part of the incident energy is removed by scattering and a part by absorption. Thus, the extraterrestrial spectrum is modified. 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 (Figure 1.3.15)

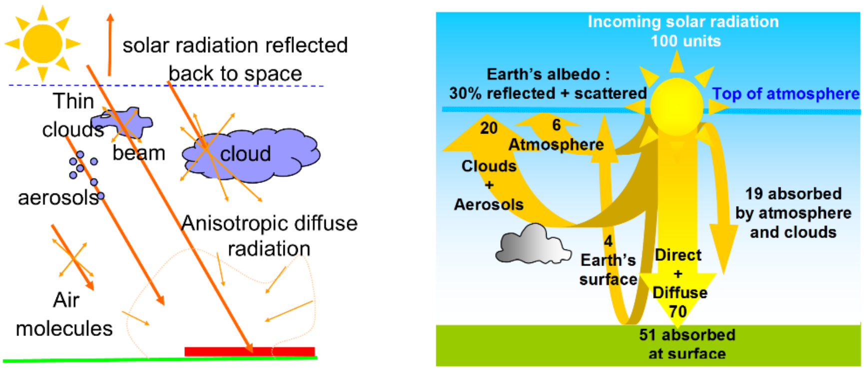


Figure 1.3.15. Radiations arriving on the ground.

The solar radiation arriving on a solar collector has a beam component (sometimes is zero due to cloudy sky), a diffuse component coming from the sky and when the solar collector is not horizontal, a third component (diffuse) arriving from the ground (Figure 1.3.16).

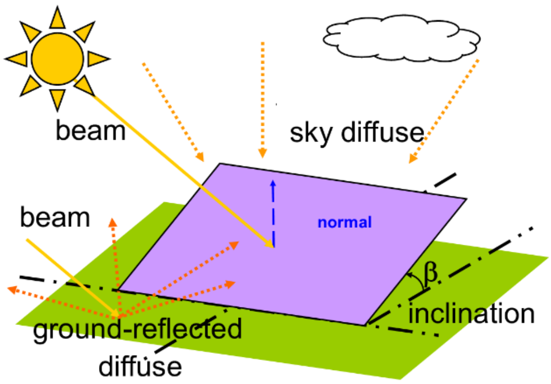


Figure 1.3.16. Component of the solar radiation onto a tiled surface.

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

$$I_{\beta} = I_{b,\beta} + I_{r,\beta} + I_{d,\beta} \qquad (1.3.13)$$

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. For a tilted plane, the diffuse radiation coming from the sky part behind the plane is not incident on the plane (Figure 1.3.17). As said in section 1.3.2.5, the diffuse component offsets the positive impact of inclination on the beam component.

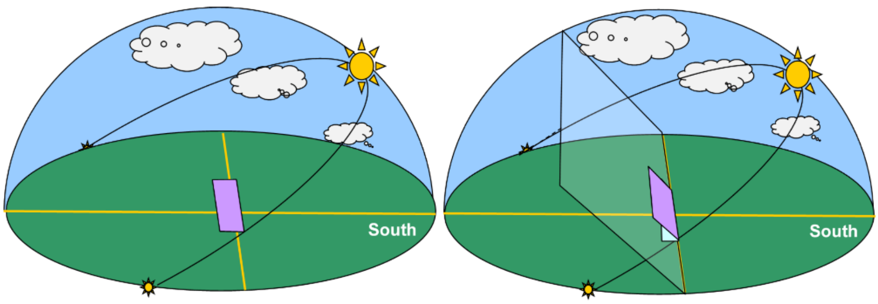


Figure 1.3.17. Sky diffuse radiation on horizontal and tilted planes.

For illustrating purposes, the three components of solar irradiance were plotted for Ajaccio in Figure 1.3.18 for a clear sky day and a 45° tilted plane and for a cloudy sky day on a 30° tilted plane.

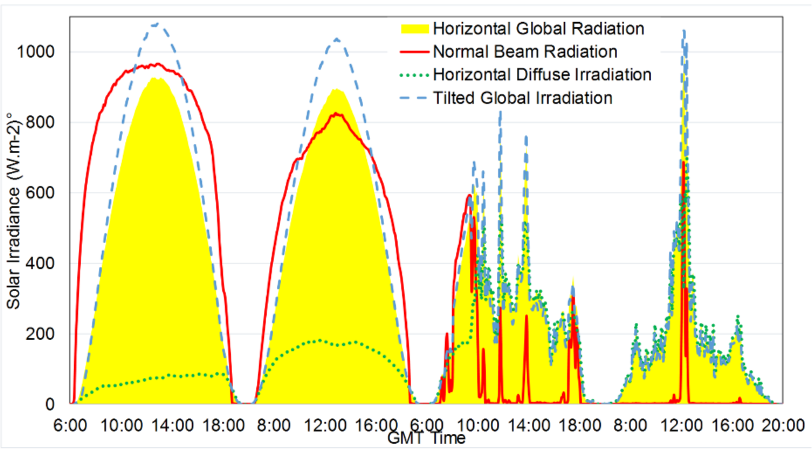


Figure 1.3.18. Two examples of tilted solar irradiance.

Horizontal solar global radiation is the form most commonly measured. Depending on the objective (whether for sizing, simulation, etc.) the time-step of useful meteorological data is different: monthly average daily data may be used for solar potential overview but short-time data (from minute to hourly) are required for an efficient simulation. Solar irradiation on non-horizontal surfaces is much less available, and is difficult to model due to the effect of diffuse radiation anisotropy over the sky's dome. Converting solar irradiation from horizontal to inclined plane is obtained by using accurate models for monthly average values while less reliable methods are used for data measured on an hourly basis and more again for shorter time steps.

At present, a multiplicity of solar irradiation sensors of different types and price levels are available on the market. The measuring instrument for global radiation is a pyranometer based on a thermopile principle, but the price of these instruments is such that calibrated photovoltaic cells are increasingly used throughout the world (Figure 1.3.19). The sensitivity of these solar cells sensors is different and numerous studies are carried out to determine their accuracy.

Figure 1.3.19. The solar sensors installed at the Fraunhofer IWES Kassel (some solar cell sensors and one pyranometer) (Zehner et al., 2009).

The beam radiation is more complicated to measure; the normal beam radiation is measured by a pyrheliometer, a telescopic type of instrument with a narrow aperture. This instrument faces the sun and follows its motion, thus it must be mounted on a solar tracker (Figure 1.3.20).

Figure 1.3.20. Pyrheliometer (beam radiation), pyranometer (global radiation) and pyranometer with shading black ball (for sky diffuse radiation).

The sky diffuse component is measured by a pyranometer equipped with a shading disk (the black ball in Figure 1.3.20) or a shadow band (in this case the system does not follow the sun but sky diffuse irradiation is underestimated because a part of the sky is also hidden; it is necessary to correct the measure). The horizontal diffuse component I_d can be also calculated in subtracting the normal beam radiation $I_{b,n}$ to the horizontal global one I by:

$$I_d = I - I_{b,n} cos(\theta_z) \qquad (1.3.14)$$

1.3.3.2 Calculation of solar components

The behaviour of the solar radiation according to the type differs: a same quantity of diffuse or beam radiation arriving on a solar collector will not have the same "effect" for the thermal (or photovoltaic) conversion; therefore, it would be good to have the measure of all the components in the frame of a precise study of the thermal behaviour of a solar collector.

Unfortunately, the three components are rarely measured all over the world; numerous correlations were developed to estimate these components from the most available solar radiation: the horizontal global solar irradiation. Numerous models are 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. Arslan et al. (2014) showed the difficulties for estimating the diffuse solar component. Khatib et al. (2011) used artificial neural networks (ANN) for estimating the diffuse solar irradiation because this method showed a good adequacy. Pop et al., (2014) estimated the beam radiation using a parametric modelling. Olmo et al., (1999) developed a model of tilted global solar irradiation only requiring the global radiation, the sun' azimuth and elevation. Notton et al., (2013) used ANN for the calculation 10-min tilted solar irradiation from horizontal ones. ANNs were often used for estimation of solar energy (Kalogirou and Şencan, 2010). Another method consists in coupling two types of models as illustrated on Figure 1.3.21: 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.

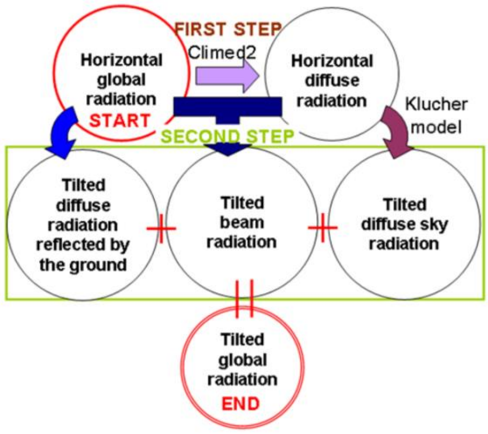


Figure 1.3.21. Chosen method for determining the tilted solar irradiation from horizontal one.

94 combinations were tested from experimental hourly global irradiations in Ajaccio by Notton et al., (2006b) using 7 horizontal diffuse solar irradiation models (Notton et al., 2004) and 15 tilted diffuse solar irradiation models (Notton et al., 2006a). The nRMSE (normalized root mean square error) obtained with these combinations are around 10% and the best combination conduces to a nRMSE of 8.11% for 45° and 10.71% for 60° (De Miguel et al., 2001). With the Olmo method (Olmo et al., 1999), nRMSE was 12.14% for 45° and 17.01% for 60°. Thus, to observe the influence of inclination and orientation on the solar irradiation received by BIST systems, the combination of two models is used:

- The Climed2 model developed by De Miguel et al., (2001) calculates the horizontal diffuse irradiance I_d from the horizontal global irradiance:

$$\begin{cases} f = 0.995 - 0.081 M_T & if \quad M_T \leq 0.21 \\ f = 0.724 + 2.738 M_T - 8.32 M_T^2 + 4.967 M_T^3 & if \quad 0.21 < M_T \leq 0.76 \\ f = 0.180 & if \quad M_T > 0.76 \end{cases} \tag{1.3.15}$$

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

- The second step consists in computing the tilted global irradiance from the horizontal global and diffuse ones (Eq. 1.3.13).
  $I_{b,\beta}$ is the beam solar radiation on the inclined plane and is calculated by (Iqbal, 1983):

$$I_{b,\beta} = (I - I_d)\left(\frac{\cos\theta}{\cos\theta_z}\right) \tag{1.3.16}$$

$I_{r,\beta}$ is the diffuse solar radiation reflected by the ground (Iqbal, 1983):

$$I_{r,\beta} = \frac{1}{2}\rho I\left(1 - cos\,\beta\right) \quad (1.3.17)$$

where ρ is the ground albedo often taken equal to 0.2 and depends of the ground type).

$I_{d,,\beta}$ is the diffuse solar radiation coming from the sky and is the more complicated component to estimate. We chose to use the Klucher's model (Notton et al., 2004; 2006b; Klucher, 1979)

$$I_{d,\beta} = I_d\left[0.5\left(1 + cos\left(\frac{\beta}{2}\right)\right)\right]\left[1 + F\,sin^3\left(\frac{\beta}{2}\right)\right]\left[1 + F\,cos^2(\theta)sin^3(\theta_z)\right] \quad (1.3.18)$$

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

The sky diffuse component is maximum when $\beta = 0$ because when the plane is horizontal, it sees all the sky dome. Thus, the more the plane is inclined, the less this component is.

These two models were chosen for their good accuracy and for the simplicity of utilization. ANN models are more efficient but their implementation is more complex and the generalization of an ANN model developed for one meteorological site to sites at various latitudes is not proven.

1.3.4 Influence of BIST Inclination and Orientation on Available Solar Irradiation

In section 1.3.3.5, such study was realized using extraterrestrial solar radiation; only the influence of inclination and orientation on beam radiation before entering in atmosphere was shown. The results are not representative of what is happening at the ground level because only beam radiation is considered. In this section, the cloudy, partially cloudy and clear day and the impact of inclination and orientation are presented. Then, by using data from the meteorological stations situated at various latitudes the differences due to latitudes will be observed.

1.3.4.1 Influence on daily solar irradiance profile

In Figures 1.3.22 and 1.3.23 the global solar irradiance for various inclination and orientation are plotted. Three days were chosen, the first one in August with a clear sky, mainly composed by beam radiation, a second one in January with a cloudy day (rainy day) with only diffuse solar radiation and a third day in December with a partially cloudy sky. These curves were plotted from experimental horizontal solar irradiance data measured in Ajaccio, and the model described in section 1.3.3.1 has been used for computing tilted solar irradiance.

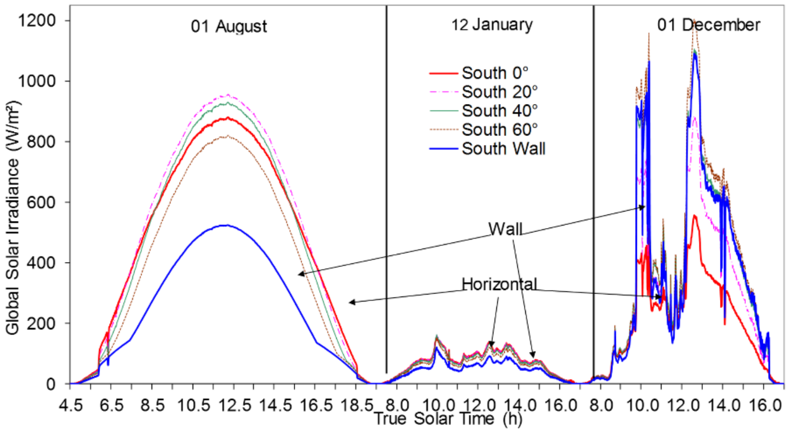


Figure 1.3.22. Influence of inclination for three particular days (South orientation).

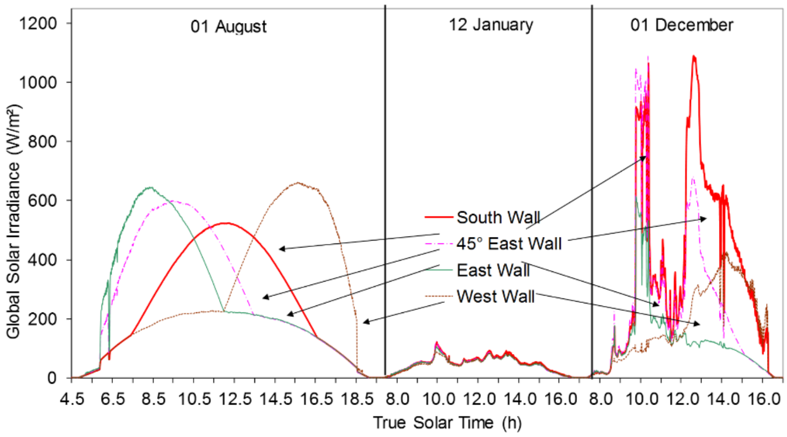


Figure 1.3.23. Influence of wall orientation for three particular days.

The daily solar irradiations were reported in the Table 1.3.1.

Table 1.3.1. Daily solar irradiation (kWh/m²)

	South 0°	**South 20°**	**South 40°**	**South 60**	**South Wall**	**45° East Wall**	**East Wall**	**West Wall**
01/08	7.17	7.61	7.15	6.12	3.83	4.18	4.05	4.44
12/01	0.68	0.69	0.66	0.59	0.45	0.44	0.42	0.42
01/12	2.02	2.93	3.53	3.78	3.38	2.27	1.15	1.63

Concerning the inclination influence:

- A similar behavior for clear sky day as for the extraterrestrial solar irradiance; the influence of inclination is important;
- For the cloudy day, there is a very small influence because the sky is totally cloudy and even if the part of the sky seen by the collector is reduced when the inclination increases, the diffuse radiation stays small, decreasing a little when the inclination increases.
- For the partially cloudy sky, the influence depends partly on beam and diffuse components.

Concerning the orientation influence:

- For the clear sky day, there is a difference with the observations realized during the extraterrestrial study, because an East wall receives again solar radiation in the afternoon due to sky diffuse and ground reflected solar radiation. In the extraterrestrial study, only the solar radiation coming directly from sun was taken into account. More energy is captured by an East wall during summer because the sun rises earlier than for a South wall (the sun rises behind the wall).
- For the cloudy day, there is no influence which is normal because in our model considers the sky diffuse radiation identical in all the direction and depends only on the inclination; this hypothesis is not really correct because as seen in Figure 1.3.17, according to the position of the sun and of the clouds, this component is more or less high;
- For the last day, the influence depends partly on the diffuse and beam component in the global radiation and on its repartition over the day.

As can be seen there are high differences about the solar energy received for a BIST versus the inclination and the orientation of the surface into which the BIST is integrated.

1.3.4.2 Influence on annual and monthly average values of solar irradiation

In Section 1.3.3.1 an example for a Mediterranean site situated at 41°55’ of latitude is given. The influence of inclination and orientation of the surface on the gain or deficit of solar power and on the daily solar irradiance profile according to the sky state (and on the season) has been studied.

Now the objective is to see the consequences on the energy received versus the location of the BIST (latitude).

Thus, eight sites were chosen over the World situated at various latitudes (from 0° to 70° by step of about 10°) and with available hourly global solar irradiations (one characteristic year). The characteristics and position of the stations are presented in Table 1.3.2 and Figure 1.3.24.

Table 1.3.2. Situation of meteorological stations.

	Countries	Station	Latitude	Longitude	Altitude
1	Uganda	Entebbe	N 0°03’	E 32°37’	1155 m
2	South Sudan	Malakal	N 9°33’	E 31°39’	390 m
3	Algeria	Tamanrasset	N 22°47’	E 5°31’	1377 m
4	Egypt	Giza	N 30°03’	E 31°13’	21 m
5	France	Ajaccio	N 41°55’	E 8°48’	4 m
6	France	Paris	N 48°49’	E 2°20’	75 m
7	Sweden	Borlänge	N 60°26’	E 15°30’	153 m
8	Finland	Utsjoki	N 69°45’	E 44°02’	101 m

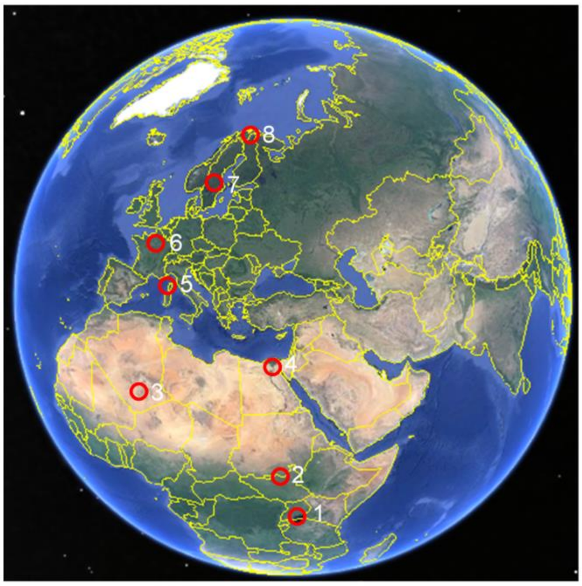


Figure 1.3.24. Position of the 8 meteorological stations (google map, 2015).

Using the model described in Section 1.3.3.2, the solar irradiation received by the solar collector with a given inclination and orientation was calculated hour per hour.

Figure 1.3.25 shows the annual average of daily solar irradiation on various surfaces; the solar energy gain versus the inclination and orientation of the solar collector can be observed clearly. 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%, i.e., the solar energy received by the solar collector varies almost by a factor of two; of course the ideal position depends on the latitude.

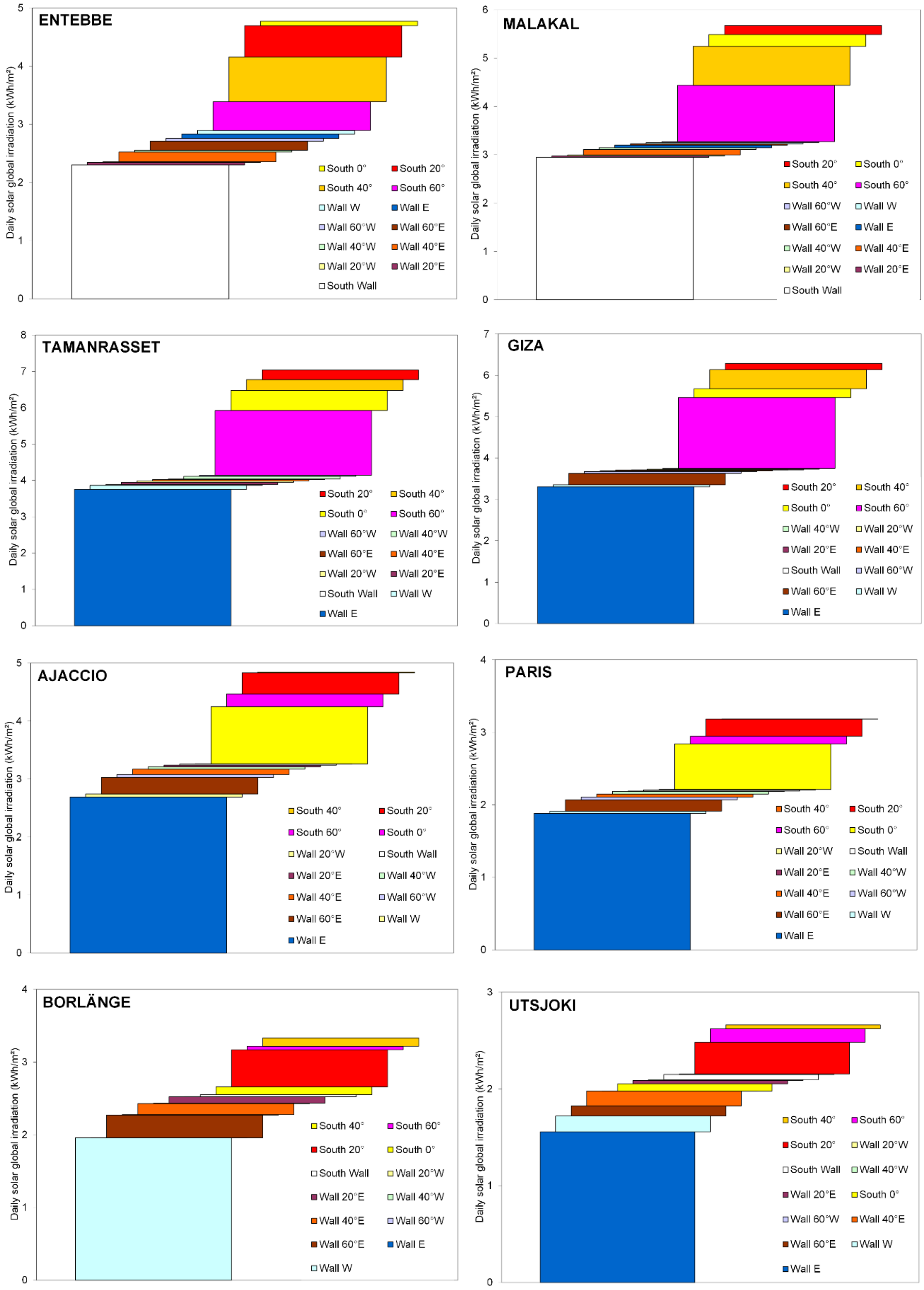
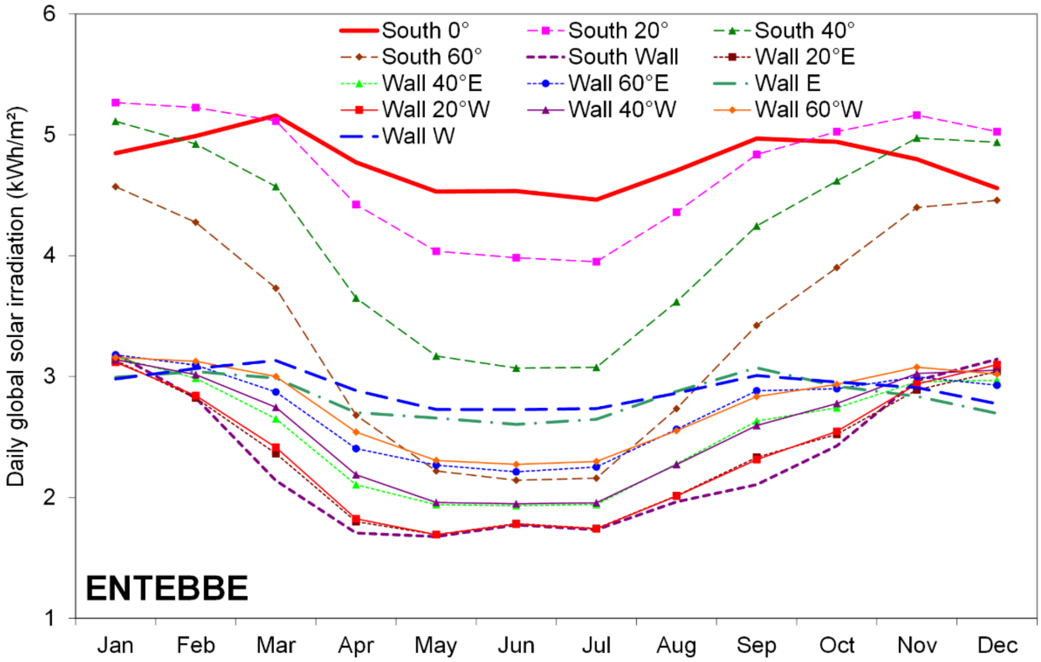
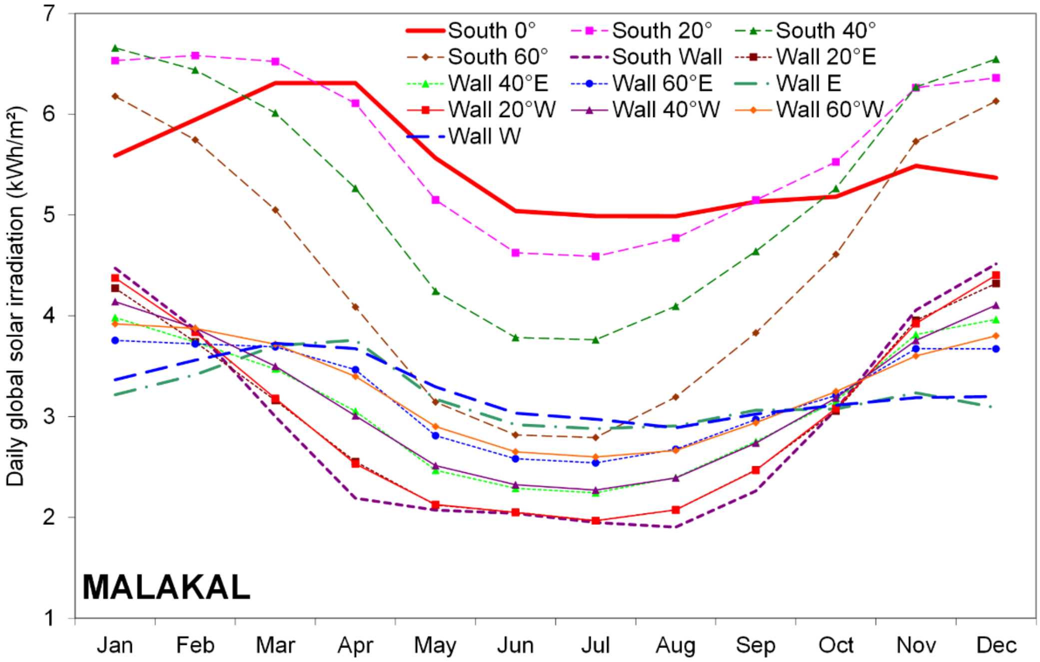


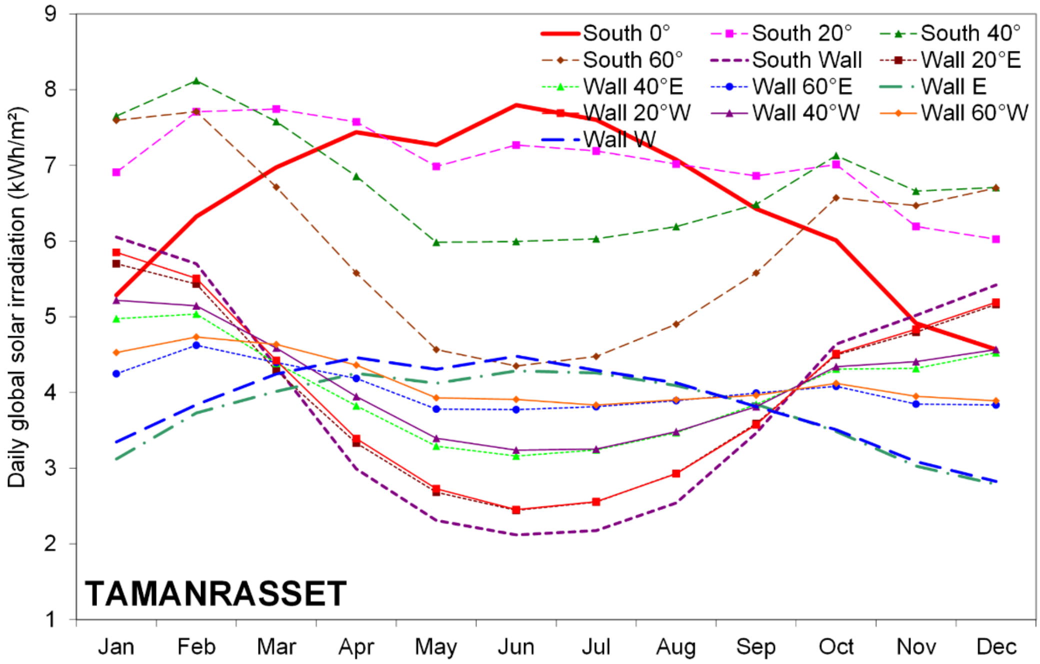
Figure 1.3.25. Annual average of daily solar irradiation for various inclinations and orientations.

The annual solar energy is not sufficient to have a good idea on the influence of inclination and orientation; it is useful to observe this influence at a shorter time step and particularly at a monthly scale. Monthly averages of global solar irradiation incident on the BIST are plotted in Figure 1.3.26. Several cases were reviewed:

- A solar collector oriented toward South at 4 inclinations (horizontal, 20°, 40°, 60°)
- A wall (inclination 90°) at various orientations toward East or West (East, 20° E, 40°E, 60°E, South, 20°W, 40°W, 60°W and West).






TAMANRASSET
Daily global solar irradiation (kWh/m²)
South 0°
South 20°
South 40°
South 60°
South Wall
Wall 20°E
Wall 40°E
Wall 60°E
Wall E
Wall 20°W
Wall 40°W
Wall 60°W
Wall W
1
2
3
4
5
6
7
8
9
Jan
Feb
Mar
Apr
May
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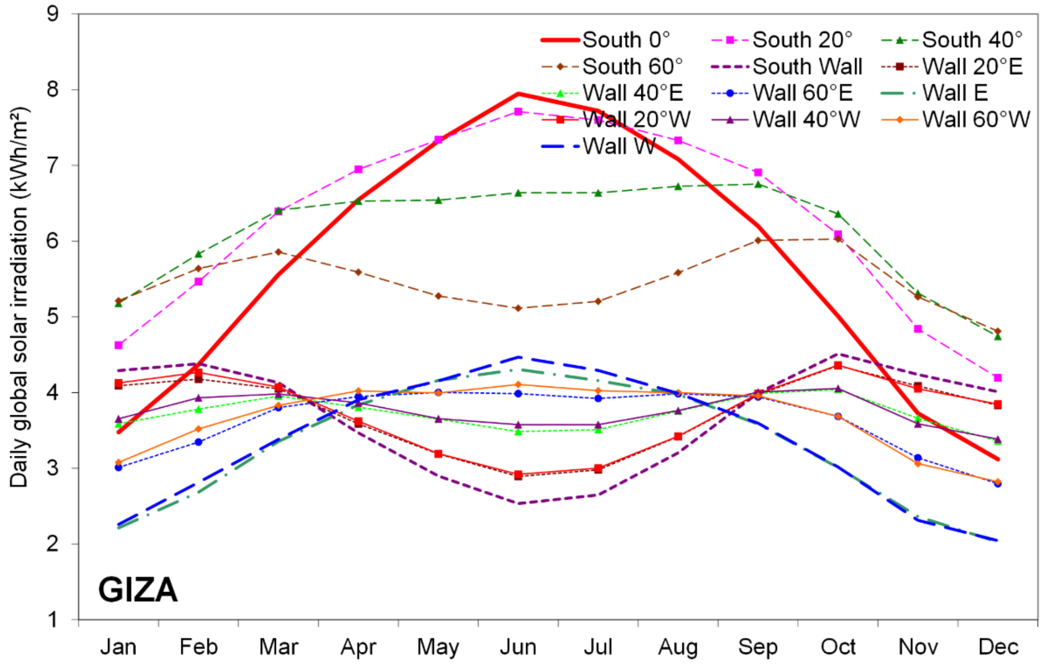
Aug
Sep
Oct
Nov
Dec


GIZA
Daily global solar irradiation (kWh/m²)
South 0°
South 20°
South 40°
South 60°
South Wall
Wall 20°E
Wall 40°E
Wall 60°E
Wall E
Wall 20°W
Wall 40°W
Wall 60°W
Wall W
1
2
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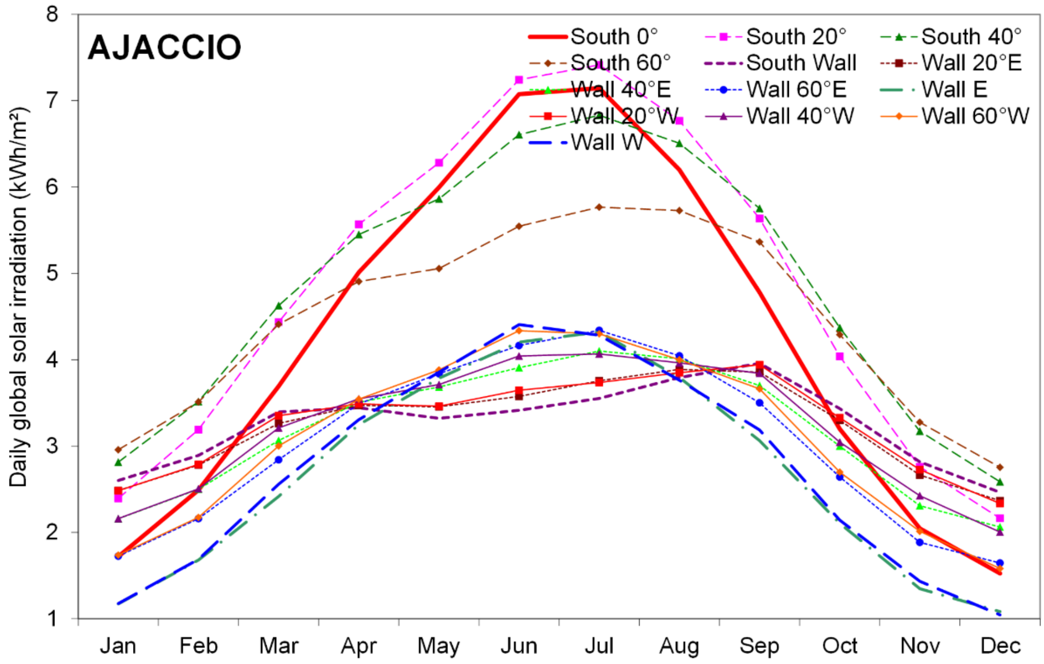
AJACCIO
Daily global solar irradiation (kWh/m²)
South 0°
South 20°
South 40°
South 60°
South Wall
Wall 20°E
Wall 40°E
Wall 60°E
Wall E
Wall 20°W
Wall 40°W
Wall 60°W
Wall W
8
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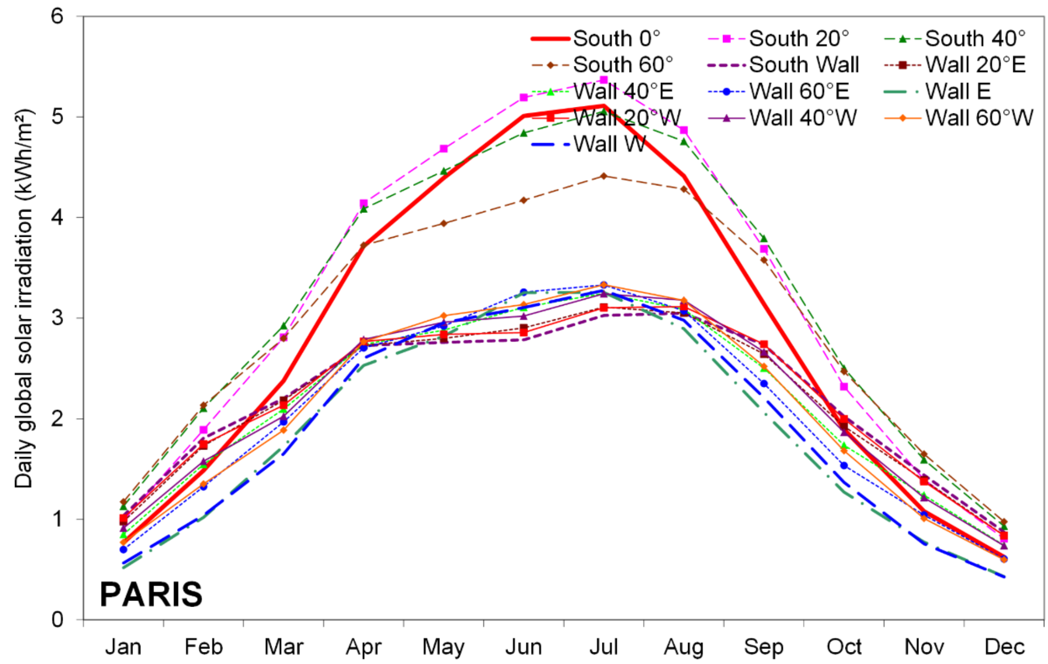
PARIS
Daily global solar irradiation (kWh/m²)
South 0°
South 20°
South 40°
South 60°
South Wall
Wall 20°E
Wall 40°E
Wall 60°E
Wall E
Wall 20°W
Wall 40°W
Wall 60°W
Wall W
6
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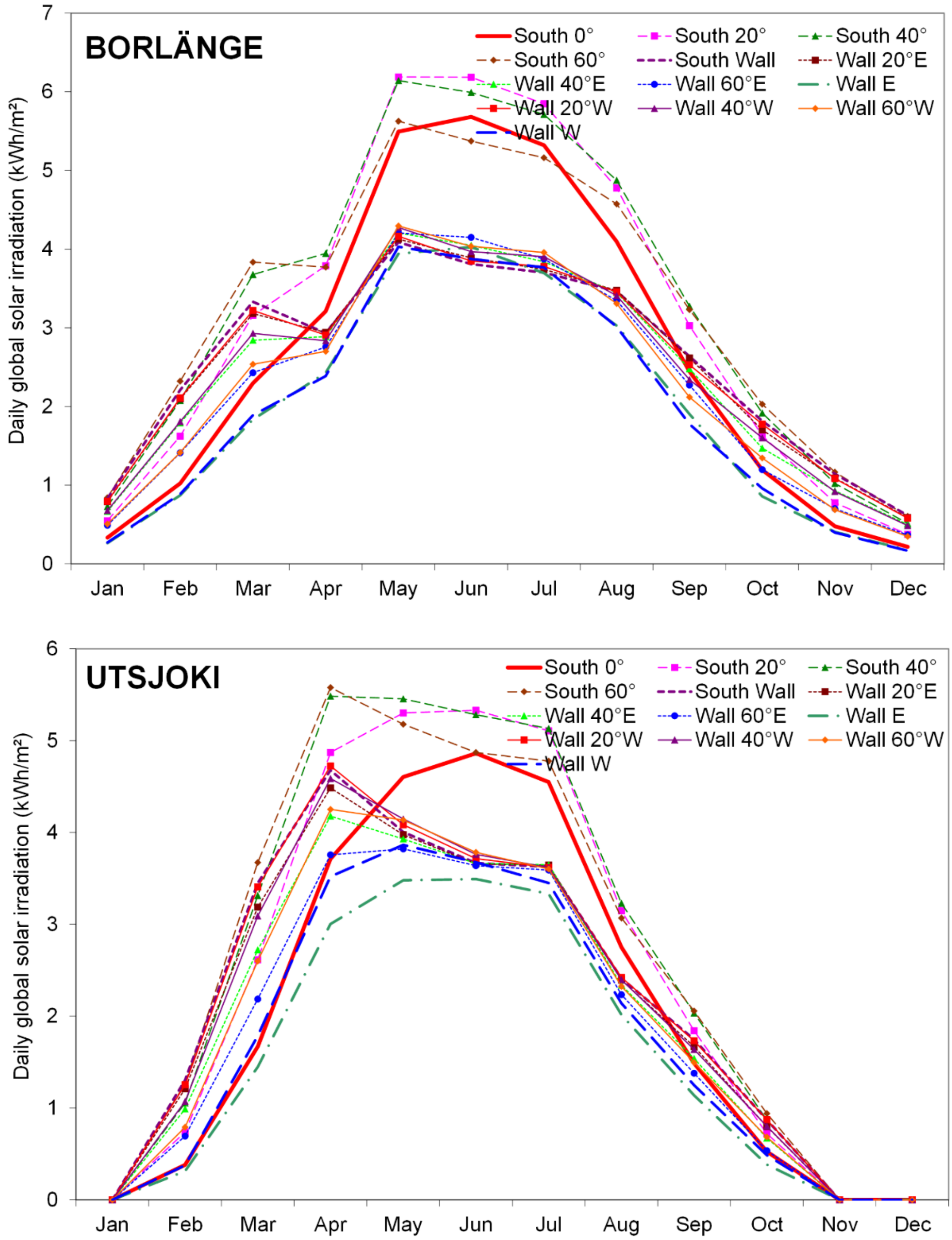

Figure 1.3.26. Monthly average of daily global solar irradiation for various inclinations and orientation.

The influence of the inclination differs according to the latitude of the meteorological station; of course the sun incidence angle depends of the latitude. The day length influences the available energy (Figure 1.3.8): two limit cases, the first for equator (Entebbe) where the theoretical sunshine duration is 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).

Concerning the influence of orientation, it 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).

In specific applications, it can be useful to choose any orientations other than toward South: as an example, an office building needs heat when the employees are working into the building, then it is interesting to collect more energy the morning than the evening and consequently to orientate the solar collector slightly toward South-east; in these conditions, the heat will be available in winter as soon as the employees arrive into the building.

During summer, a wall receives generally less solar energy than a horizontal or a tilted plane but in winter, at high latitudes the solar energy is higher or identical; 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 which can be an advantages compared with other inclinations.

Otherwise, for low latitudes, the solar energy received by a wall, whatever the orientation is, is much lower than the solar energy received by a solar collector integrated in a tilted plane.

Consequently, integrating a solar collector in a building 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.

1.3.5 Conclusions

The objectives of this chapter were to give some information on solar radiation: received by a solar collector according to its position, i.e., latitude, inclination and orientation.

The question we tried to answer was: does a solar collector integrated into a building reduces the solar energy available to be converted into thermal energy by the solar collector? The answer is not very clear and depends on various factors as latitude, inclination of the integrating surface.

Firstly, the influence of the solar incidence angle was analysed in studying the 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, the study was extended to the solar radiation received at the ground level.

The influence at different time scales have been observed:

- During a day for three sky conditions: clear, cloudy and partially cloudy sky; the sky state plays an important role because the various solar components differs (diffuse, reflected and beam) and the effects of inclination are opposite versus the solar radiation type.
- Over the year at a monthly scale: according to the month, a solar collector position can be optimal or not; we saw that in some cases, integrating a solar collector into a wall can be advantageous; the latitude of the site where the solar collector is installed influences the results on the impact of inclination and position and makes it impossible to generalize them.

- 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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