İSTANBUL TECHNICAL UNIVERSITY ★ INSTITUTE OF SCIENCE AND TECHNOLOGY

RESEARCH ON BUILDING INTEGRATED PHOTOVOLTAIC SYSTEMS AND THEIR PERFORMANCE EVALUATION

M.Sc. Thesis by
Deniz ERDOĞAN

Department : **Architecture**
Programme : **Environmental Control and Building Technology**

JANUARY 2009

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(POLITECNICO DI TORINO)

JANUARY 2009

İSTANBUL TEKNİK ÜNİVERSİTESİ ★ FEN BİLİMLERİ ENSTİTÜSÜ

BİNALARA FOTOVOLTAİK ENTEGRASYONU VE PERFORMANS DEĞERLENDİRMESİNİN İRDELENMESİ

YÜKSEK LİSANS TEZİ

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FOREWORD

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January 2009 Deniz ERDOĞAN

Architect

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SUMMARY

This thesis aims both at studying the photovoltaic technology and its integration into buildings and at simulating and examining building integrated photovoltaics with a case-study building. In order to achieve this aim, firstly passive and active solar energy systems and their importance in building design for architects are explained, and photovoltaic modules are described from their history to new technologies as an active solar energy system with technical details of composition, connection and related equipments. Then the application of photovoltaics in buildings as roofing, façade, atrium and shading devices is clarified with significant photovoltaic integration samples throughout the world.

Afterwards, a case-study, which is a commercial building located in Turin, Italy is described with schedules and photovoltaic system's properties. This building is a part of a sustainable renovation project focused on decreasing energy demands; thereby the installation of photovoltaic panels. The case study is simulated by using PVSYST, DesignBuilder and EnergyPlus simulation tools. Besides, the actual utility ratio of photovoltaic system, which is the ratio of electricity produced by the photovoltaic system to the building total electricity consumption, is calculated according to simulation results. Finally, same case study is simulated for Istanbul, Turkey weather conditions in order to compare the electrical output and the utility ratio in the two different climates. The comparison of photovoltaic panels' utility ratio for the two cities is located at the end of the thesis.

BİNALARA FOTOVOLTAİK ENTEGRASYONU VE PERFORMANS DEĞERLENDİRMESİNİN İRDELENMESİ

ÖZET

Bu tez, hem fotovoltaik teknolojisini ve binalara entegrasyonunu hem de binalara fotovoltaik uygulamasının örnek çalışma binası ile simülasyonunun yapılmasını ve incelenmesini hedeflemektedir. Bu hedefi gerçekleştirmek için, öncelikle pasif ve aktif güneş enerjisi sistemleri ve bu sistemlerin mimarlar için bina tasarımındaki önemi açıklanmış ve fotovoltaik modüller aktif bir güneş enerjisi sistemi olarak tarihçesinden yeni teknolojilere kadar bileşim, bağlantı ve ilgili ekipmanların teknik detayları ile tanıtılmıştır. Ardından fotovoltaiklerin binalarda çatı, cephe, atriyum ve gölgeleme elemanı olarak kullanılması dünyadan göze çarpan örneklerle açıklanmıştır.

Daha sonra, ticari bir bina olan ve İtalya’nın Torino kentinde yer alan örnek çalışma binası çizelgeleri ve fotovoltaik sistemin özellikleri ile tarif edilmiştir. Bu bina, fotovoltaik panellerin de uygulandığı enerji yüklerini düşürmeye odaklanan sürdürülebilir bir yenileme projesinin bir parçasıdır. Örnek çalışma binası PVSYST, DesignBuilder ve EnergyPlus programları kullanılarak simule edilmiştir. Ayrıca, fotovoltaik sisteminin ürettiği elektrik miktarının binanın toplam elektrik tüketimine oranını tarif eden “fotovoltaik sistemin yararlılık oranı” simülasyon sonuçlarına göre hesaplanmıştır. Son olarak, aynı örnek çalışma binası, elektrik üretimini ve yararlılık oranını iki farklı iklimde karşılaştırabilmek için Türkiye’nin İstanbul ili koşulları için de simüle edilmiştir. Tezin sonunda bu iki şehir koşullarında fotovoltaik panellerin yararlılık oranının kıyaslaması yer almaktadır.

1. INTRODUCTION

1.1 Description of Problem

Energy efficient architectural design that cares about environment, sustainability and energy production from renewable energy resources has become a more important issue in recent years, particularly after the energy crisis in 1973, because of energy shortage and global warming in the world.

Energy efficient buildings have a large spectrum of different classifications, which starts from ecological building integrated into the topography and nature, to modern intelligent buildings that use passive and active solar systems and goes to zero energy buildings that do not have any energy need from exterior.

Approximately 50% of the primary energy demand in almost every country throughout the world is consumed by buildings. In other words, to solve the energy problems of the buildings means to solve 50% of the world's energy problems. The adoption of systems that use renewable energy in the buildings has both energy and environmental implications.

One of the most important renewable energy resources is solar energy. It can be used in buildings by passive or active systems. Photovoltaic systems are important devices to benefit from the solar energy because they are able to convert sunshine directly into electricity on site. However, it is more functional and reasonable to use photovoltaic in combination with passive solar concepts and active solar energy systems in the building design.

The photovoltaic systems can be installed on different parts of the building envelope, such as roof, façades, and can also be used as shading devices. At the same time, building integrated photovoltaic systems (BiPV) are a suitable solution not only for new projects but also for renovation projects.

Afterwards, the photovoltaic application helps to the architects to create energy-efficient and environment-friendly buildings that produce their own electricity and do not emit any harmful gas. To use solar energy in their design is a way for the architects to show their responsibility for a sustainable world. As Sir Norman Foster said “Solar architecture is not about fashion, it is about survival.”

1.2 Aim of Thesis

This thesis has two objectives: first of all it aims at introducing basic information on the photovoltaic technology and at analysing the integration of photovoltaic systems into the building (BiPV), with details and applications throughout the world. Moreover, the performance of a PV system installed in an office building as shading device is simulated for two different climate conditions: Turin (Italy) and Istanbul (Turkey).

The simulations are carried out by using three commercial software: PVSYST, DesignBuilder and EnergyPlus.

The electrical output of the PV system and how the shading affects the heating, cooling and lighting loads of the building, obtained with the simulations, are compared for the two different locations and relevant conclusions are found.

The comparison of the PV performance in Turin and Istanbul shows the benefits of installing PV systems in Turkey, and aims at being a contribution for the development of PV installations in Turkey.

1.3 Method of Thesis

The thesis analyzes a case study, which consists of a PV system installed on an office building located in Turin, Italy. The PV system is part of a renovation project of the building that aims at improving its energy performance with a sustainable approach. The photovoltaic panels in the case-study building are also used as shading devices

This case-study is simulated with PVSYST, DesignBuilder and EnergyPlus simulation tools, and the utility ratio of the photovoltaic system is numerically determined.

The simulations consist of 3 parts: the first part evaluates the electricity production of the photovoltaic system, the second one calculates the annual electricity consumption of the case-study building and the change ratios of the cooling and heating demands of the building due to the shading effect of the PV modules, and the last part focuses on the shading effect of the PV modules to the lighting loads.

Afterwards, the same case study building with the same control strategy and occupancy schedule is simulated in the Istanbul conditions, in order to compare its performance for two locations with different climates.

The thesis consists of different chapters that focus on specific topics.

Chapter 2 explains the fundamental parameters of solar energy systems, as passive and active systems and the solar energy projects in the future.

Chapter 3 introduces the photovoltaic technology, from the PV cell to the PV systems, their history, types and costs.

Chapter 4 focuses on the photovoltaic integration into buildings (BiPV), their advantages, design principles, components and usage types with remarkable applications all around the world.

Chapter 5 describes the case-study building, its working schedules and the photovoltaic system installed on it.

Chapter 6 contains the simulations results of the case-study PV system and building in Turin by using PVSYST, DesignBuilder and EnergyPlus, with input and output data of the tools.

Chapter 7 collects the simulation results of the same case-study building for Istanbul weather and site conditions, by using the same strategy of Chapter 6.

Chapter 8 includes the conclusions and recommendations for future works.

2. SOLAR ENERGY

2.1 Description of Solar Energy

Solar energy is the light and radiant heat from the Sun that influences Earth's climate and weather and sustains life. Sun, wind, wave power, hydro and biomass account for most of the available flow of renewable energy on Earth.[2]

The Earth receives 174 peta watts (PW) of incoming solar radiation at the upper atmosphere. Approximately 30% is reflected back to Space while the rest is absorbed by clouds, oceans and land. The spectrum of solar light at the Earth's surface is mostly spread across the visible and near-infrared ranges with a small part in the near-ultraviolet. [2]

Solar energy refers primarily to the use of solar radiation for practical ends. All other renewable energies other than geothermal derive their energy from energy received from the sun. Therefore, it is possible to say that the sun is the most important renewable energy resource in the world. The average irradiation for different countries and regions is given in Figure 2.1.

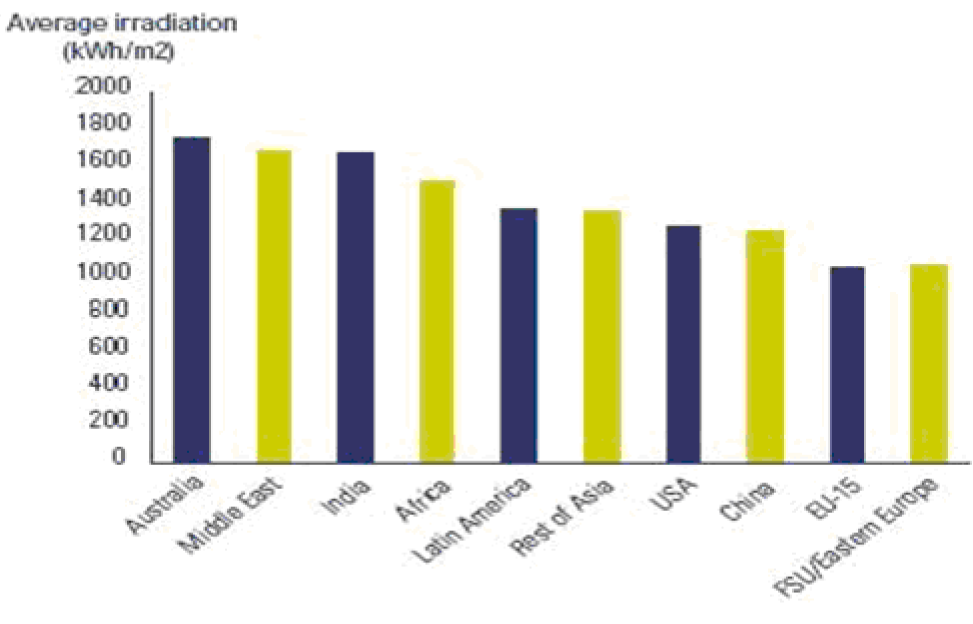


Figure 2.1 : Average Irradiation Values of Countries [63]

2.2 Importance of Solar Energy

According to the combination of global warming, reduction of fossil fuels and change of the ecological balance, the energy issue has become more and more important in these last decades, particularly after the energy crisis in 1973. Renewable energy resources (sun, wind, biomass, geothermal and hydro) can play an important role to a sustainable development.

The sun can be contributed as big amount of power to renewable energy requirement in the world; because the sun is one of the most important renewable energy resources in the world.

It is estimated that just one hour of solar energy received by the earth is equal to the total amount of energy consumed by mankind in one year. [1]

In addition; yearly energy resources and annual energy consumption are showed in Table 2.1. [2] As seen in the table; while the annual primary energy requirement is 369,7TWh and the electricity consumption is 45,2 TWh, renewable energy potential as solar and wind energies is 1.8 million of times bigger than the annual energy requirement.

Table 2.1: Yearly Energy Resources & Annual Energy Consumption [2]

Yearly energy resources & Annual energy consumption (TWh)	
Solar energy absorbed by atmosphere, oceans and Earth	751,296,000.0
Wind energy (technical potential)	221,000.0
Electricity (2005)	-45.2
Primary energy use (2005)	-369.7

Moreover; natural gas and nuclear power are expected to grow slowly over the next 40 year, at which point natural gas will start its decline. It is also expected that a new clean energy source of fusion energy will be demonstrated at increasing scales from 2030 – 2070, which will become commercially competitive and will begin to pick up increasing percentages of the global energy demand into the next century and future global energy consumption has given in Figure 2.2 . [3]

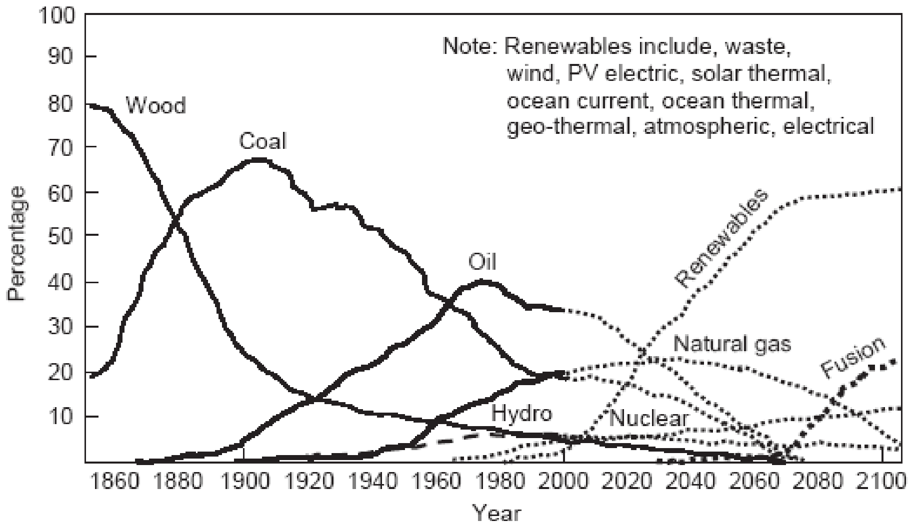


Figure 2.2 : Future Global Energy Consumption [3]

As seen in the figure, renewable energies, particularly the sun, are the biggest candidate as the energy source of the future.

On the other hand; renewable energy is, in most cases, an expensive form of energy compared with fossil-fuel alternatives. A quantitative assessment of current costs and the likely average reductions by 2020 has been presented in Table 2.2. However; it must not be forgotten that estimates can vary significantly depending on the site condition. [4] As seen in the Table 2.2, the costs for solar thermal and photovoltaic are estimated to decrease between 30 – 50%.

Table 2.2: Renewable Energy Cost Assessment [4]

	Current Cost	Cost Reductions by 2020
Bioenergy	High. Cost-effective in CHP applications with low fuel cost. Co-firing is a relatively low-cost retrofit option.	10-15%
Wind onshore	Relatively low; lowest compared to other renewables.	Up to 15-25%
Wind offshore	High.	20-30%
Solar Photovoltaic	Very high. Cost-effective only in niche markets.	30-50%
Solar Thermal	Very high.	30% +
Geothermal	High.	10%
Hydro	Relatively low for large hydro.	10%

Research on solar technology continues very intensively in order to increase the energy efficiency produced by solar energy systems, to decrease the costs and to produce new systems with easier use. In spite of high costs, many countries have noteworthy projects and plans to constitute solar power stations and solar fields that have an example in Figure 2.3.

Figure 2.3 : A Solar Field in Ontario, Canada [29]

Germany, which is produced the half amount of photovoltaic panels in the world, is the leader for the electricity production from photovoltaic, with 750MWp power capacity in 2007. Even though only 3% of total energy production comes from renewable energy resources in Germany, it is planned that this fraction will increase to 27% by 2020. Spain is the second one with 60MWp power capacity and it has two times more solar irradiation capacity than Germany. In USA, it is predicted that the energy production from the sun will reach 35% of the total energy production by 2050. Lastly; Japan has planned to build a solar power station in Space by 2030. [5]

2.3 An Approach to Solar Systems

Up to 50% of the primary energy demand of the world is consumed by the buildings. As seen in Figure 2.4 that refers to USA, buildings are responsible for 12% of the total water consumption, 68% of the total electricity consumption, 38% of the carbon dioxide emissions and 39% of the total energy use.

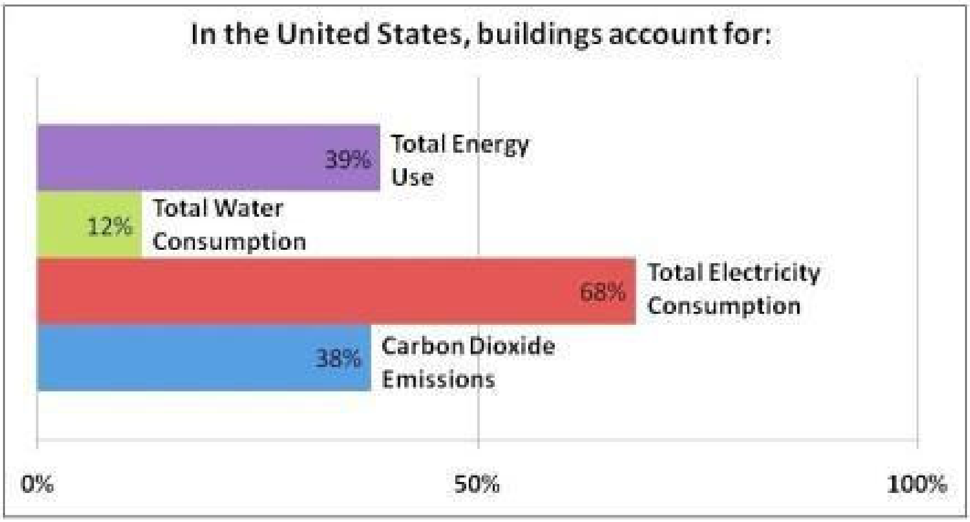


Figure 2.4 : Building Energy Consumption in USA [30]

A considerable value of the energy problems and gas emissions of the world could be solved by solving the energy problems of the buildings which have a consumption percentage about 50%. This duty is in the responsibility area of the architects who design buildings with energy conscious and efficient. In order to design an energy efficient building, the architects have to apply firstly to passive solar energy design parameters which will be described in this chapter. Solar system is going to be examined from the side of using of solar radiation in two broad categories:

- Passive solar systems
- Active solar systems

2.3.1 Passive solar systems

Passive solar design involves utilising natural forces such as the sun and wind for the heating, cooling and lighting of living spaces. Well-designed buildings take advantage of the natural energy characteristics in materials and air created by exposure to the sun that reduce the need to purchase utility energy source to control, for example, the temperature and lighting of a building. [1]

Passive solar systems collect solar heat, store and deliver it passively, without the need of any equipment fed by external energy. [6]

As mentioned before, passive solar systems use the solar energy to heat, cool and illuminate buildings. The basics of passive solar building design are that for cold weather, to maximize the heat gains and reduce the heat losses while allowing for sufficient ventilation and illumination; for warm weather, minimize heat gains, avoid overheating and optimize ventilation and illumination with sufficient way.

Main parameters of passive solar building design:

- Site of building,

- Location of building in the site,

- Orientation of building,

- Form of building,

- Building envelope,

- Sun control and natural ventilation system (passive control systems) [7]

These parameters are very important for the energy efficiency. Nevertheless, for an intelligent building design, passive concepts and active solar systems must be used together and supported each other. It must not be forgotten that the use of only active system is not enough to design an intelligent building.

2.3.1.1 Site of building

The location of the building defines the climatic properties, which effect energy consumption, such as solar radiation, wind exposure, air temperature and humidity.

Information on the climate may be considered on three levels:

- Macroclimate; macroclimatic data are gathered at meteorological stations and describe the general climate of region, giving details of sunshine, wind, humidity, precipitation and temperature.

- Mesoclimate; mesoclimatic data although sometimes more difficult to obtain, relate to the modification of macroclimate or general climate by established topographical characteristics of the locality such as valleys, mountains or large bodies of water and the nature of large-scale vegetation, other ground cover, or by the occurrence of seasonal cold or warm winds.

- Microclimate; at the microclimate level, the human effect on the environment and how this modifies conditions close to the buildings can be considered. [8]

2.3.1.2 Location of building in the site

Careful orientation of buildings is vital for passive solar energy gains. The location and distance between other buildings and barriers such as trees affect both the amount of the solar radiation and the wind exposure.

Distance between buildings should be adjusted to obtain the optimum solution. As potential future obstacles to the solar exposure, it should be considered not only the effect of existing buildings but also of future buildings.

2.3.1.3 Orientation of building

The orientation of building affects the amount of direct solar radiation received by the building and defines heat losses and heat gains of building. At the same time, it affects directly the natural ventilation and the heat losses because of air infiltrations.

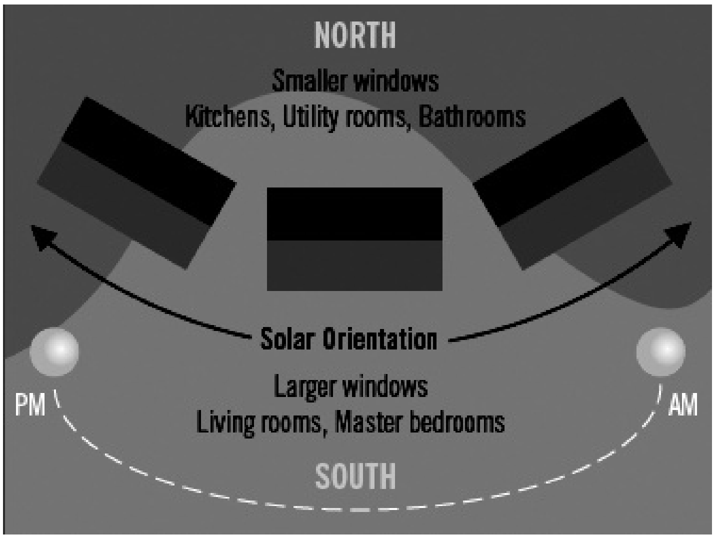


Figure 2.5 : Solar Orientation [31]

Depending on the altitude angles of the sun during winter and summer, south is the best orientation to have maximum direct solar radiation in winter and minimum solar radiation in summer on building surfaces in Northern Hemisphere. The north is the best orientation for the buildings in Southern Hemisphere. An example for solar orientation of building and rooms for Northern Hemisphere is given in Figure 2.5.

2.3.1.4 Form of building

The form of building plays a great role in the energy performance of a building. It must be designed according to the climate properties to get efficient and conscious results from passive solar components and the satisfaction of the users.

Compact forms are suitable for cold climate conditions to minimize the surface area that is responsible for heat loss. In hot – dry climate, compact forms and forms with courtyard are useful to minimize the heat gains and to get cool and shady areas. In hot – humid climate, narrow and long forms towards dominant wind direction to maximize natural ventilation must be designed. In warm climate, again compact form can be chosen but less strictly than cold climate. In the design of a energy efficient building, these parameters must be considered. [7]

2.3.1.5 Building envelope

A building envelope is the separation between the interior and the exterior of a building. It serves as the outer shell to protect the indoor environment as well as to facilitate its climate control. Building envelope design is a specialized area of architectural and engineering practice that includes all areas of building science and indoor climate control. [2]

Designers are not always able to choose and/or change previous parameters such as climate, site, location and sometimes even form, but they are more independent to define the envelope. Moreover, it provides a good opportunity to design passive solar buildings.

The building envelope consists of transparent and opaque components whose thermal properties are significantly different from each other.

The most important physical properties that effect thermal performance of building envelope are:

- Heat transfer coefficients of opaque and transparent components,

- Decrement factor of opaque component,

- Time lag of opaque component,

- Absorption, reflection and transmission coefficients of opaque and transparent components. [7]

2.3.1.6 Sun control and natural ventilation system

Passive control systems, such as sun control and natural ventilation, let the user to benefit of solar radiation and with only when they are necessary. [7]

Sun control is mainly realized by the use of shading devices, which block the direct solar radiation from entering a window during certain times of a day. Shading devices affect natural lighting, solar gains and the building performance.

Natural ventilation consists of the natural circulation of external air into the building, and it is realized by opening the windows.

2.3.2 Active solar systems

Unlike the passive solar design, active solar systems are independent elements that can be organized and operated either in the building or quite apart from the building.

For buildings, solar collectors and photovoltaic panels are the most suitable and common active systems.

2.3.2.1 Solar thermal collectors

Solar collectors are heat exchangers that use solar radiation to heat a working fluid, usually a liquid or air.

A solar collector is basically a flat box and is composed of three main parts, a transparent cover, tubes which carry a coolant and an insulated back plate. The solar collector works on the green house effect principle; solar radiation incident upon the transparent surface of the solar collector is transmitted through this surface. The inside of the solar collector is usually evacuated, the energy contained within the solar collect is basically trapped and thus heats the coolant contained within the tubes. The tubes are usually made from copper, and the back plate is painted black to help absorb solar radiation. The solar collector is usually insulated to avoid heat losses. [32]

The scheme of a solar collector is given in Figure 2.6. Arrows show the direction of the fluid flow through the copper pipes when the sun heats the collector panels.

Figure 2.6 : Scheme of Solar Collector [32]

2.3.2.2 Photovoltaics

Photovoltaics is the direct conversion of light into electricity at the atomic level. Some materials exhibit a property known as the photoelectric effect that causes them to absorb photons of light and release electrons. When these free electrons flow in a closed electric circuit, an electric current results and electrical power is generated. [33]

The photovoltaics system is an active solar system that can be integrated into buildings. It will be explained in detail in Chapter 3.

3. PHOTOVOLTAICS

Photovoltaic (abbreviated as PV) is a physical mechanism that directly converts solar radiation into electricity. It is based on the photovoltaic effect. Photovoltaics and PV technology will be explained in this chapter.

3.1 Definition of Photovoltaics

Photovoltaics (PV) or solar electric cells are solid state semiconductor devices that convert solar radiation directly into electricity with no moving parts, requiring no fuel, and creating virtually no pollutants over their life cycle. [12]

Photovoltaic technology generates direct current (DC) electric power measured in Watts (W) or kilowatts (kW) from semiconductors when they are illuminated by photons. As long as light is shining on the solar cell, it generates electrical power. When the light stops, the electricity stops. Solar cells never need recharging like a battery. Some PV modules have been in continuous outdoor operation on Earth or in Space for over 30 years. [13]

Photovoltaic cells are based on the photovoltaic effect that is shown in Figure 3.1.

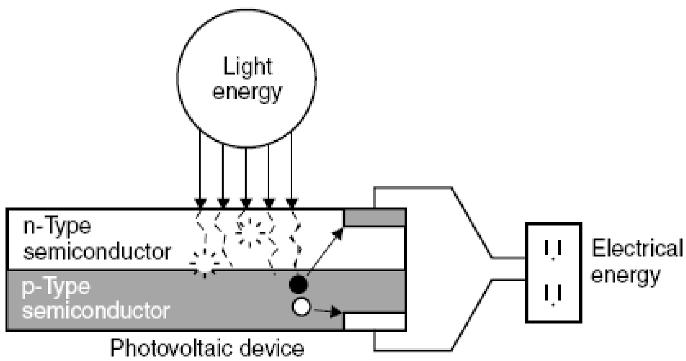


Figure 3.1 : The Photovoltaic Effect [14]

The photovoltaic effect may be very briefly explained in this way: sunlight is composed of photons, which are discrete units of light energy. When the photons strike a PV cell, some are absorbed by the semiconductor material and the energy is transferred to electrons. With their new found energy, the electrons can escape from their associated atoms and flow as current in an electrical circuit. [14]

3.1.1 A brief history of photovoltaics

The direct relation between light and electricity was demonstrated by Antoine Henri Becquerel in 1839. However, it was not until the development of diodes in 1938 and transistors in 1948 that the creation of a solar cell became possible.

The foundation for modern PV technology was laid in the early 1950s, when researchers at Bell Telephone Laboratories discovered and developed crystalline silicon (c-Si) solar cells, which they patented for the first time in 1955 and successfully used in Space applications in 1958. Despite early attempts to commercialise silicon solar cells on a larger scale, the technology was not developed enough to warrant large-scale production until the 1980s. Since then, laboratory and commercial development has progressed steadily, creating a portfolio of available PV technology options at different levels of maturity – and experience that can be expressed by a robust learning curve (price reduction vs.) cumulative production of commercial PV technology. [9]

3.1.2 Advantages and disadvantages of photovoltaics

Some of the advantages and disadvantages of photovoltaics are given in following lines. It is noted that they include both technical and nontechnical issues. Often, the advantages and disadvantages of photovoltaics are almost completely opposite of conventional fossil-fuel power plants. [13]

The advantages of photovoltaics are:

- The fuel source (the sun) is essentially infinite,
- No emissions, no combustion or radioactive fuel for disposal (does not contribute perceptibly to global climate change or pollution),
- Low operating costs (no fuel),
- No moving parts (no wear),
- Ambient temperature operation (no high temperature corrosion or safety issues),
- High reliability in modules (> 20 years),
- Modular (small or large increments),

- Quick installation,
- Can be integrated into new or existing building structures,
- Can be installed at nearly any point-of-use,
- Daily output peak may match local demand,
- High public acceptance,
- Excellent safety record. [13]

In spite of having lots of advantages, photovoltaics have a few disadvantages. However, it should be noticed that several of these disadvantages are nontechnical but relate to economics and infrastructure. Disadvantages of photovoltaics have been arranged below:

- Fuel source is diffuse (sunlight is a relatively low-density energy),
- The energy storage is necessary, for the loads that occur when there is not the sun,
- High installation costs,
- Poorer reliability of auxiliary (balance of system) elements including storage,
- Lack of widespread commercially available system integration and installation so far,
- Lack of economical efficient energy storage. [13]

3.2 Composition of Photovoltaics

The basic element in the photovoltaic module is the solar cell which absorbs sunlight and converts it directly into electricity. The basic structure of a photovoltaic cell is shown in Figure 3.2. It is made by: cover glass, transparent adhesive, antireflection coating, front contact, n-Type semiconductor, p-Type semiconductor and back contact.

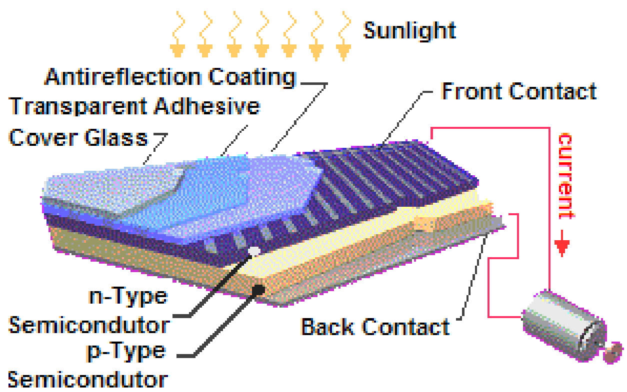


Figure 3.2 : Photovoltaic cell construction [34]

The solar cell consists of a thin piece of semiconductor material, which in most cases is silicon. [12]

Photovoltaic semiconductor materials also include gallium arsenide, copper indium diselenide, cadmium sulphide and cadmium telluride. [14]

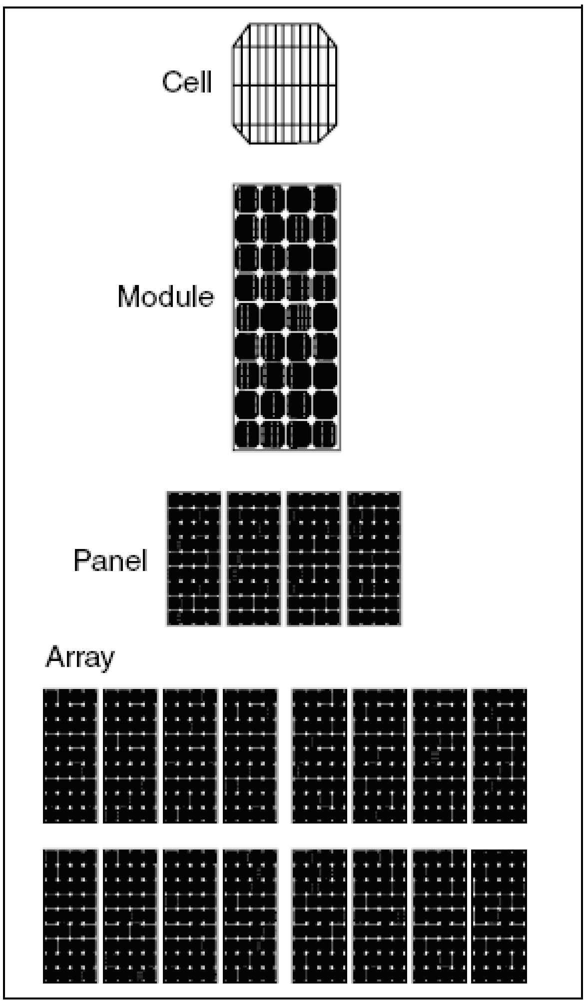


Figure 3.3 : Modularity of photovoltaics [14]

PV cells are the basic building blocks of PV modules. When modules are fixed together in a single mount they are called a panel and when two or more panels are used together, they make an array. The modular properties of the PV elements are given in Figure 3.3. [14]

3.3 Types of Photovoltaics

Mainly, solar cells can be subdivided in two different types:

- Crystalline solar cells

- Thin-film solar cells

3.3.1 Crystalline solar cells

The most commonly used PV cell material is silicon. PV cells made of single-crystal silicon (often called monocrystalline cells) are available on the market today with efficiencies close to 20%. Laboratory cells are close to theoretical efficiency limits of silicon that is 29%. [12] Figure 3.4 shows a monocrystalline silicon cell sample.

Figure 3.4 : Monocrystalline silicon cell [12]

Polycrystalline silicon is easier to produce and therefore cheaper. It is widely used, since its efficiency is only a little lower than the single-crystal cell efficiency. [12] A sample of polycrystalline silicon cell is given in Figure 3.5.

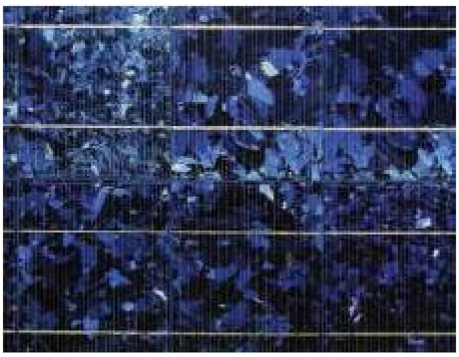


Figure 3.5 : Polycrystalline silicon cell [12]

Gallium arsenide (GaAs) is another single-crystal material suitable for high efficiency solar cells. The cost of this material is considerably higher than silicon which restricts the use of GaAs cells to concentrator and space applications. [12]

3.3.2 Thin-film solar cells

In order to lower the cost of PV manufacturing, thin-film solar cells are being developed by means of using less material and faster manufacturing processes. The major work on thin films during last 10 years has been focused on amorphous silicon (a-Si). The long-term advantage of amorphous silicon compared to crystalline silicon is due to its manufacturing process: it requires less energy and material, leading to a shorter energy payback time. Figure 3.6 shows two samples of amorphous silicon cell. [12]

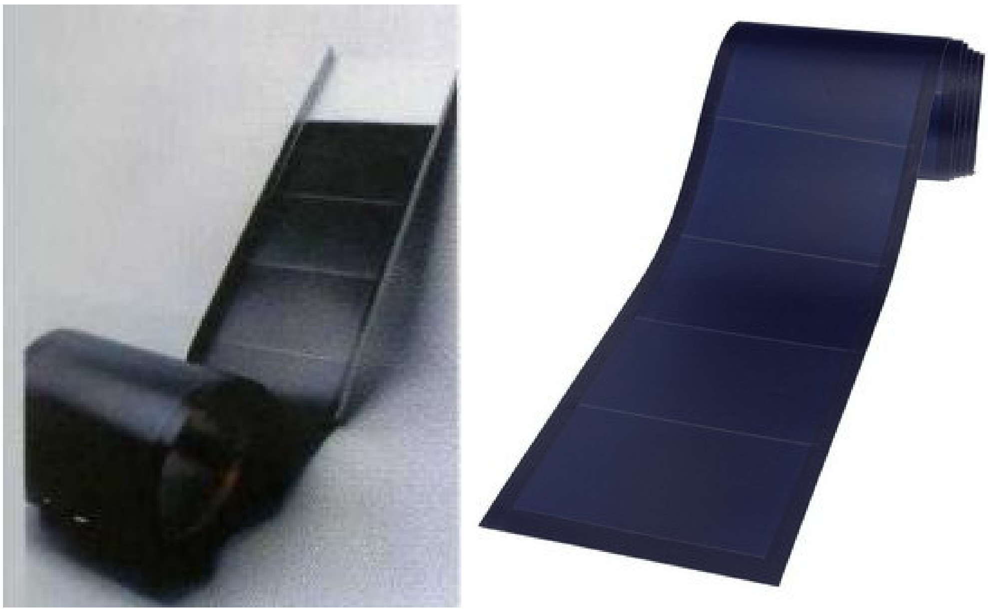


Figure 3.6 : Samples of amorphous silicon cell [12]

Other thin-film materials are Cadmium-Telluride (Cd-Te) and Copper-Indium-Diselenide (CIS). Nowadays, cells made of these materials are produced in laboratories with efficiencies of about 15%. [12]

The distribution by technology of the PV cell production is given in Figure 3.7. As seen in the figure, polycrystalline (multicrystalline) silicon cell production is the first one with 58%. Monocrystalline silicon cell follows it with 32%. Thin-film cell production is at 7%.

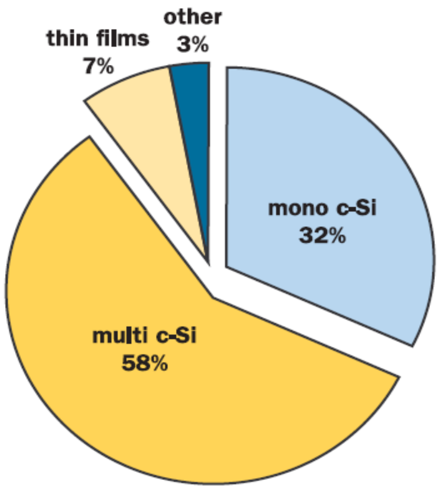


Figure 3.7 : Distribution of cell production [15]

Theoretical and practical efficiencies of crystalline silicon, gallium arsenide, amorphous silicon, Copper-Indium-Diselenide and Cadmium-Telluride solar cells are collected in Table 3.1. [12]

Table 3.1: Theoretical and practical efficiencies of different types of solar cells [12]

Material	Theoretical efficiency	Laboratory cell (1994)	Module (1994)
Crystalline Silicon	29%	23%	15%
GaAs	31%	25%	-
Amorphous Silicon	27%	12%	8%
CIS	27%	17%	11%
CdTe	31%	16%	10%

3.4 Connection Types of Photovoltaics

Photovoltaic (PV) systems are made of a modular components. Solar cells can be connected in series or parallel in virtually any number and combination. Therefore, PV systems may be realized in an extraordinarily broad range of power: from milliwatt systems in watches or calculators to megawatt systems for central power production. [12]

3.4.1 Series connection of photovoltaic modules

When voltage sources are connected in series, the voltage increases. Series wiring does not increase the amperage produced. Series wiring connections are made at the positive (+) end of one module to the negative (-) end of another module. Figure 3.8 shows two modules wired in series. [18]

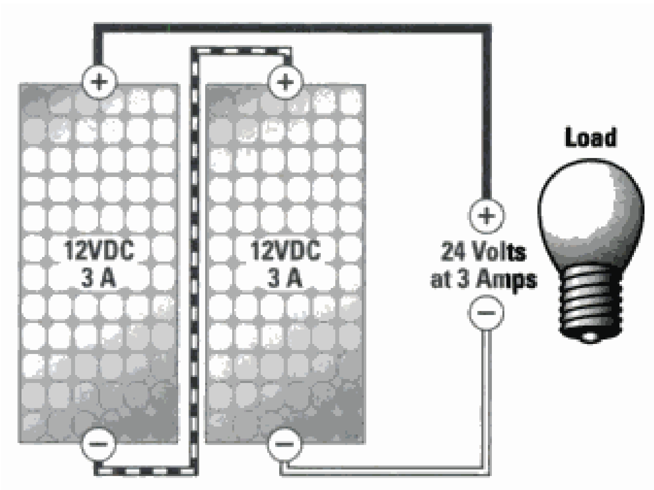


Figure 3.8 : PV modules in series [18]

Some rules concerning series circuits are given below:

- When loads or sources are wired in series, voltages are additive.

- Current is equal through all parts of the circuit.

- In a series circuit, batteries are connected end-to-end or positive (+) to negative (-). Batteries placed in series will provide a total voltage equal to the sum of each individual battery voltage.

3.4.2 Parallel connection of photovoltaic modules

When loads or sources are wired in parallel, currents are additive and voltage is equal through all parts of the circuit. To increase the amperage of a system, the voltage sources must be wired in parallel. This wiring increases the current produced and does not increase voltage. Figure 3.9 shows PV modules wired in parallel. [18]

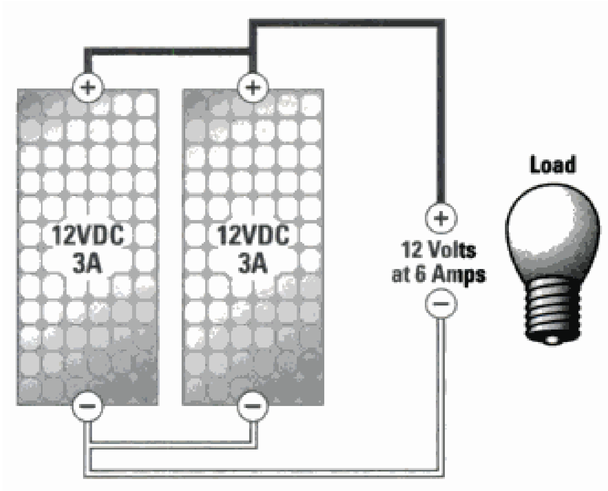


Figure 3.9 : PV modules in parallel [18]

Parallel wiring is from positive (+) to positive (+) and negative (-) to negative (-). Batteries are also often connected in parallel to increase the total amps, which increases the storage capacity and prolongs the operating time. [18]

Systems may use a mix of series and parallel wiring to obtain required voltages and amperages. In figure 3.10, parallel and series wiring are used together. [18]

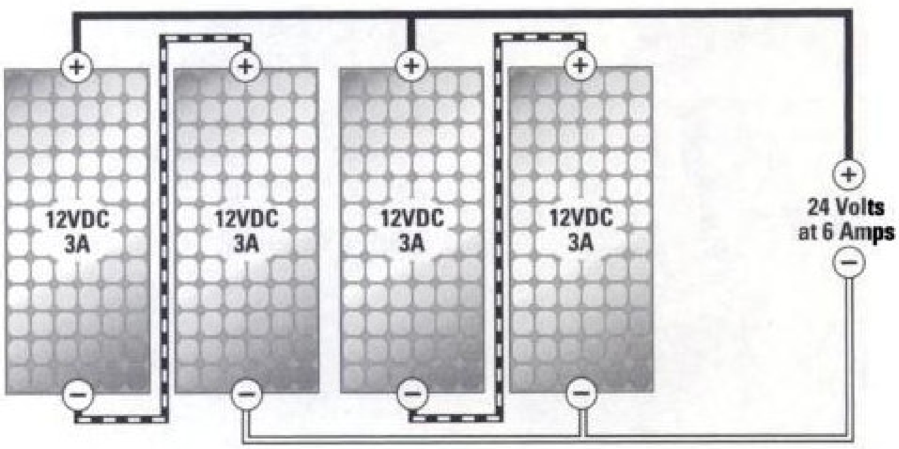


Figure 3.10 : PV modules in series and parallel [18]

3.5 Usage Types of Photovoltaic Systems

The photovoltaic cells produce direct current (DC) electricity and can either be:

- used directly as DC power,

- converted to alternating current (AC) power, or

- stored for later use. [16]

There are basically two different PV systems: those with a connection to an (available) electricity grid and remote or "stand-alone" systems. While in the first case the grid serves as an ideal storage component and ensures system reliability, the stand-alone systems require a storage battery. This battery serves as a buffer between the fluctuating power generated by the PV cells and the load. [12]

3.5.1 Grid-connected systems

PV systems may be connected to the public grid. This requires an inverter for the transformation of the PV-generated DC electricity to the grid AC electricity at the level of the grid voltage and frequency. [12]

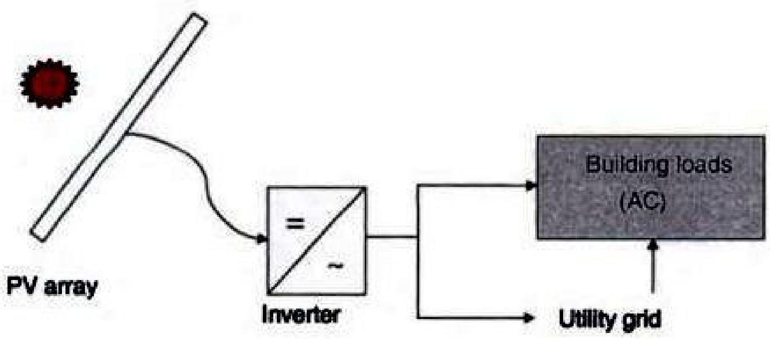


Figure 3.11 : Schematic diagram of grid-connected photovoltaic system [17]

Figure 3.11 shows a block diagram of a grid-connected PV system suitable for building integration.

3.5.2 Stand-alone systems

PV systems are most effective at remote sites off electrical grid, especially in locations where the access is possible by air only, e.g. in alpine regions.

A storage battery is needed. Excess energy produced during times with no or low loads charges the battery, while at times with no or low solar radiation the loads are met by discharging it. A charge controller supervises the charge/discharge process in order to ensure a long battery lifetime. As in the grid-connected systems, an inverter, when required, transforms DC to AC electricity. Schematic diagram of stand-alone system is shown in Figure 3.12. [12]

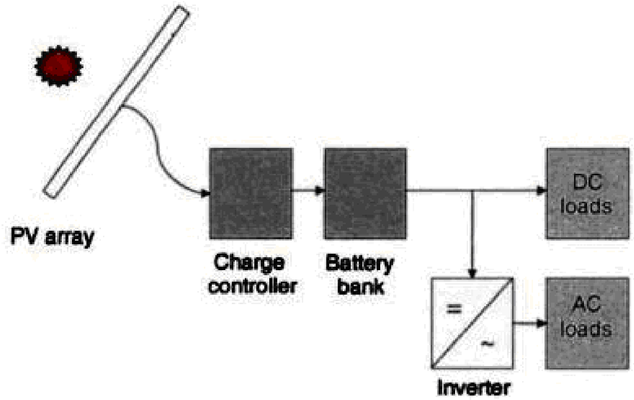


Figure 3.12 : Schematic diagram of stand-alone photovoltaic system [17]

Hybrid systems may contain more than one renewable power source. Adding a wind turbine to a PV system is a common combination in areas with high wind energy potential like coastal or hilly regions. Principle schematic of a hybrid PV power system is given in Figure 3.13. [12]

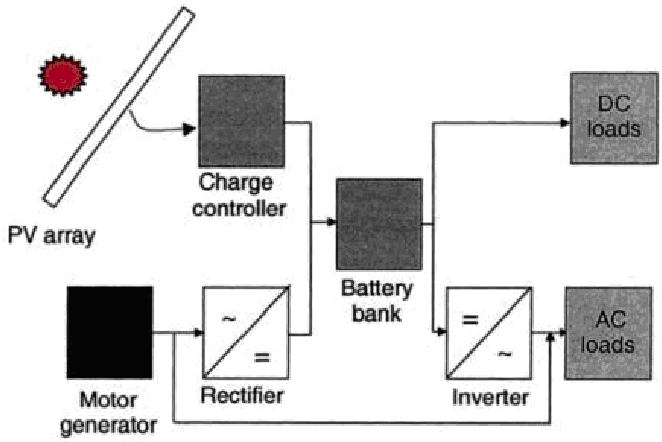


Figure 3.13 : Schematic diagram of hybrid system incorporating a photovoltaic array and a motor generator [17]

3.5.3 Direct use systems

There are applications where the load matches the available radiation exactly. This eliminates the need for any electricity storage and backup. A typical example is the electricity supply for a circulation pump in a thermal collector system. [12]

3.6 Related Equipment to Photovoltaic Systems

There are many other components associated with the establishment of a photovoltaic power supply, other than those directly attributed to the solar modules. Batteries, regulators, inverters and other system components are collectively referred to as the "balance of system" or "BOS". [19]

Variety of components of a PV system includes fixing material, mounting structure, bypass diodes, blocking diodes, fuses, cables, terminals, overvoltage/lightning protection devices, circuit breakers and junction boxes. [12]

3.6.1 Batteries

Batteries are required in many PV systems to supply power at night or when the PV system can not meet the demand. The selection of battery type and size depends primarily on load and availability requirements. In all cases, batteries must be located in an area without extreme temperatures and with some ventilation.

For a PV system, the main requirement is that the batteries be capable of repeated deep discharges without damage. Deep-cycle lead-acid batteries are commonly used. For more capacity, batteries can be arranged in parallel. [20]

3.6.2 Battery charge controllers

Controllers regulate power from the PV modules to prevent the batteries from overcharging. The controller can be a shunt or series type and can also function as a low-battery-voltage disconnect to prevent battery overdischarge.

Some controllers can optimize the operating voltage of the PV modules independently of battery voltage so that the PV operates at its maximum power point. [20]

3.6.3 Inverters

An inverter is used to convert direct current (DC) into alternating current (AC) electricity. The inverter's output can be single-phase or multiphase, with a voltage 120 or 220 V and a frequency of 50 or 60 Hz. Inverters are rated by total power capacity, which ranges from hundreds of watts to megawatts. Some inverters have good surge capacity for starting motors; others have limited surge capacity. The designer should specify both the type and the size of the load the inverters is intended to service.

Inverters can supply AC power independently or can synchronize the waveform frequency to another AC power supply such as the electric utility or a portable electrical generator. [20]

3.6.4 Bypass diodes

Partial shading of modules may cause "hot spot" effects and can damage PV modules. To avoid this, bypass diodes should be used according to the module manufacturer's specification. [12]

3.6.5 Various components

Blocking diodes prevent current flow backwards into a string.

Fuses protect cables from overcurrent. Fuses would be required only in case of more than four strings in parallel assuming standard modules.

Cables are usually double-insulated and UV-resistant.

Overvoltage/lightning protection devices will keep voltage transient out of the systems.

Circuit breakers between the PV generator and the inverter or charge controller are needed to remove the PV generator's voltage from the main DC line.

The mounting structure holds the modules in place. It must take all mechanical loads, potential wind loads, snow cover and thermal expansion/contraction with an expected lifetime of at least 20 years. [12]

3.7 Photovoltaic Market

According to development and requirements in photovoltaic technology PV module production and module production capacity is enlarged dramatically. In Figure 3.14, these values can be seen for reporting countries (MW) between 1992 and 2006.

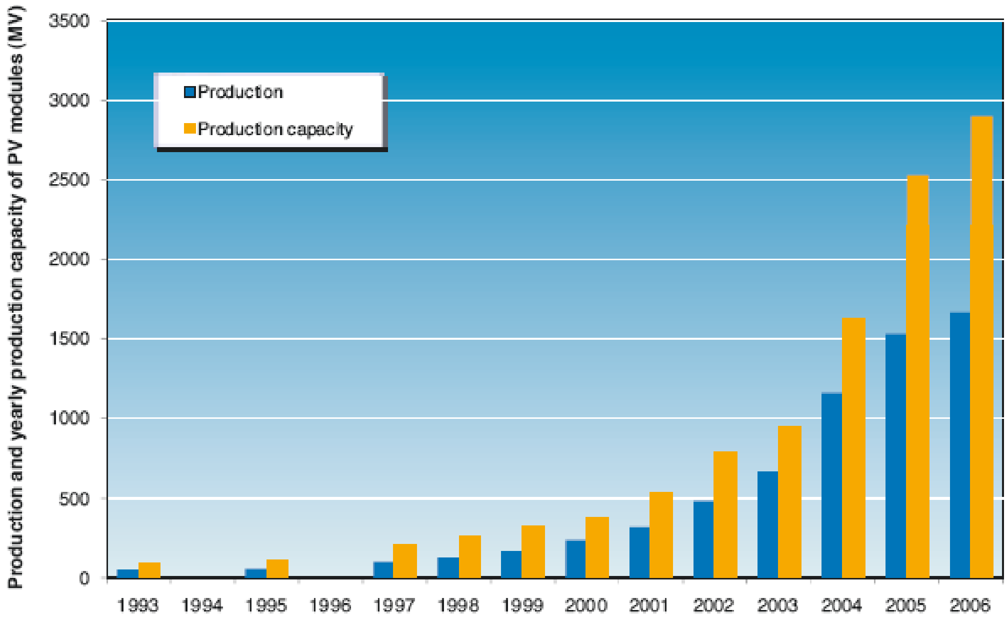


Figure 3.14 : PV module production and yearly module production capacity [10]

PV production capacity is always growing to answer the requirement of PV installation. PV production is divided by countries in Figure 3.15. As seen in the figure Japan has almost 50% of total production and Germany and USA follows it.

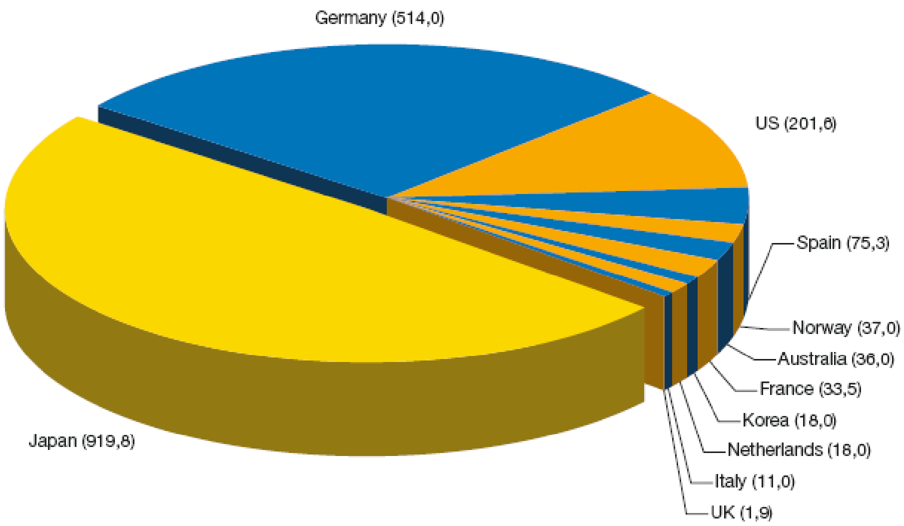


Figure 3.15 : PV cell production (MW) by country in 2006 [10]

About 1,5 GWp of PV capacity were installed during 2006 (an increase of 15% over the previous year) which brought the total installed to 5,7 GW. As in recent years, by far the greatest proportion (82%) was installed in Germany and Japan alone. [10] Cumulative installed grid-connected and off-grid PV power in reporting countries is shown in Figure 3.16.

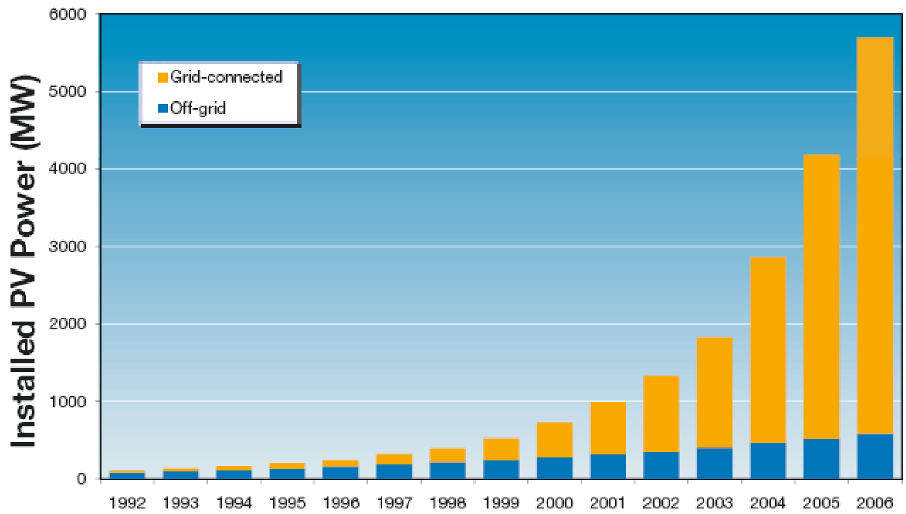


Figure 3.16 : Cumulative installed PV power in the reporting countries [10]

The public budgets for market stimulation, research and development, and demonstration and field trials in 2006 in the IEA PVPS countries varies from country to country as seen in Table 3.2 for 2006 budgets.

Table 3.2: Public budgets in 2006 [10]

Country	R&D		Demonstration/ field trials		Market stimulation		Total	
	EUR	USD	EUR	USD	EUR	USD	EUR	USD
AUS	4,2 M	5,2 M	0,4 M	0,5 M	14,2 M	17,8 M	18,8 M	23,5 M
AUT	1,3 M	1,6 M	included in R&D ammount		see notes below		–	–
CAN	3,2 M	4,0 M	2,5 M	3,2 M	0,1 M	0,1 M	5,8 M	7,3 M
CHE	9,5 M	11,9 M	0,2 M	0,2 M	1,8 M	2,3 M	11,5 M	14,4 M
DNK	6,7 M	8,4 M	0,7 M	0,8 M	–	–	7,4 M	9,2 M
DEU	66,0 M	82,5 M	–	–	see notes below		–	–
FRA	26,2 M	32,8 M	–	–	20,0 M	25,0 M	46,2 M	57,8 M
GBR	10,6 M	13,3 M	11,6 M	14,5 M	–	–	22,2 M	27,8 M
ISR	0,1 M	0,1 M	–	–	–	–	0,1 M	0,1 M
ITA	4,8 M	6,0 M	0,2 M	0,3 M	6,0 M	7,5 M	11,0 M	13,8 M
JPN (METI)	21,8 M	27,2 M	93,5 M	116,9 M	28,5 M	35,7 M	143,8 M	179,8 M
KOR	15,8 M	19,7 M	0,2 M	0,3 M	81,3 M	101,6 M	97,3 M	121,6 M
MEX	0,8 M	1,0 M	0,7 M	0,9 M	–	–	1,5 M	1,9 M
NLD	9,4 M	11,7 M	–	–	3,0 M	3,8 M	12,4 M	15,5 M
NOR	1,7 M	2,1 M	–	–	–	–	1,7 M	2,1 M
SWE	1,5 M	1,9 M	–	–	0,7 M	0,9 M	2,2 M	2,8 M
USA	97,4 M	121,8 M	2,4 M	3,0 M	352,0 M	440,0 M	451,8 M	564,8 M

3.8 Cost of Photovoltaics

On average, system prices for the lowest price off-grid applications are double those for the lowest price grid-connected applications. In 2007:

- The lowest achievable installed price of grid-connected systems varied between countries, averaging 6,9 USD per watt. Typically prices were around 6,5 USD to 7,5 USD per watt.

- The average price of modules in the reporting countries marginally decreased (average around 4,4 USD per watt)compared with the corresponding figure for 2006.

Significant milestone will be the achievement of cost-competitiveness of PV with traditional energy sources and other emerging technologies in the various markets. The continuous development of PV technology is expected to help reduce the price for solar electricity to match the price for retail electricity by 2015 in a number of markets. [11]

Evolution of price of PV modules and systems accounting inflation effects between 1996 and 2006 is given in Figure 3.17.

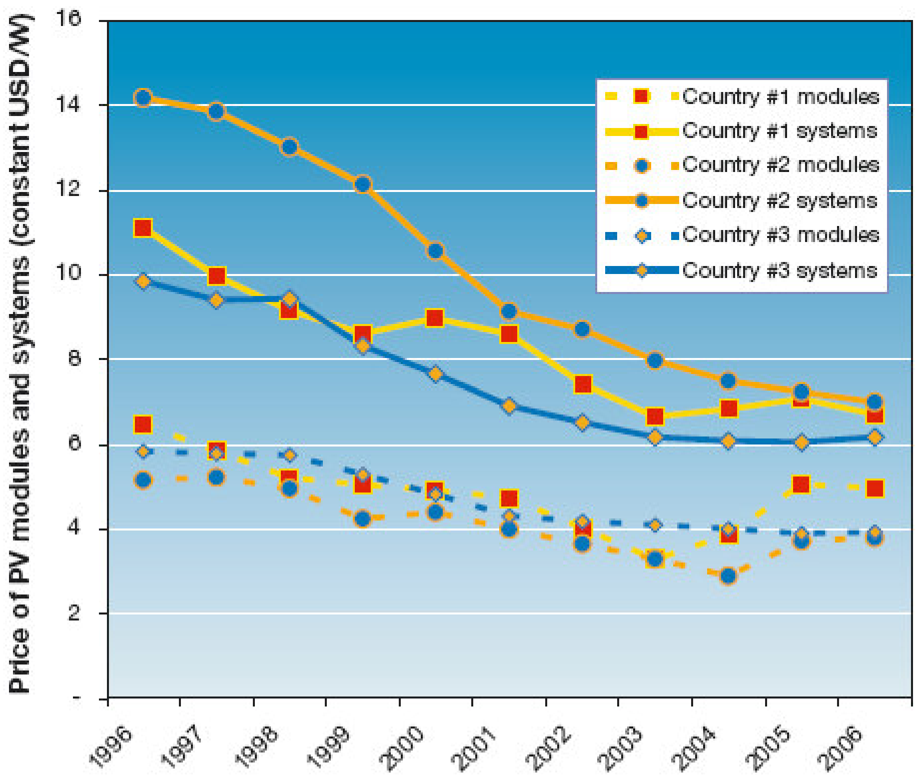


Figure 3.17 : Evolution of PV modules and systems accounting for inflation effects[10]

3.9 New Photovoltaic Technologies

Researches and developments in photovoltaic technologies continue dramatically. While the size of photovoltaics is becoming smaller, efficiency of PV cells increase. Nanotechnology PV cells, flexible organic based solar cells and holographic concentrator PV modules are a few of these new developments.

Nanotechnology is the engineering of functional systems at the molecular scale. New nanotechnologic cells are 100 times thinner than the previously used silicon wafers. The cells conducted energy with the help of vacuum pressure and were deposited onto glass as a substrate. This new technology developed by Nanosolar works by simply printing a conductor ink onto the glass to create a solar panel. Figure 3.18 shows a nanotechnology PV cell. [35]

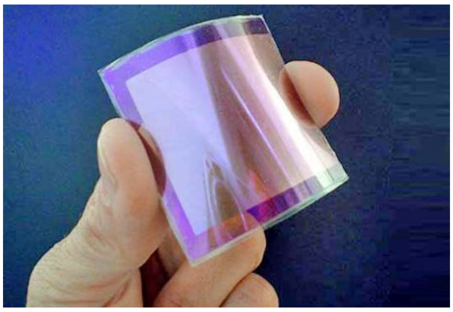


Figure 3.18 : Nanotechnology PV cell [35]

Traditionally, solar energy has been expensive, however, Massachusetts based Konarka has successfully developed a new process to manufacture solar cells with an inkjet printer. The solar cells are made without silicon and are manufactured into a thin, light film and do not require a clean room like traditional silicon cells. These organic (carbon/plastic/oil) cells aren't as efficient as their silicon counterparts, but their production cost is much less. Figure 3.19 shows organic PV cell. [36]

Figure 3.19 : Organic PV cell [36]

Prism Solar Technologies in New York has developed a proof-of-concept solar module that uses holograms to concentrate light, possibly cutting the cost of solar modules by as much as 75 percent, making them competitive with electricity generated from fossil fuels. Currently, the approach to overcoming this cost factor of silicon-based solar panels is to concentrate light from the sun using mirrors or lenses, thereby reducing the total area of silicon needed to produce a given amount of electricity. [37]

Figure 3.20 : Holographic Concentrator PV cell [37]

The last technology in this part is Spherical solar cell technology developed by a Kyoto-based company, Kyosemi. The innovative new Sphelar is a matrix of tiny, spherical-shaped solar cells. The spheres are designed to absorb sunlight at any angle, and therefore do not require motorization for tracking the sun. Based on their geometry, Sphelar cells even optimize the use of reflected and indirect light, and have been shown to convert energy with close to 20% efficiency. Figure 3.21 shows spherical PV cell and its schmatic work principle. [38]

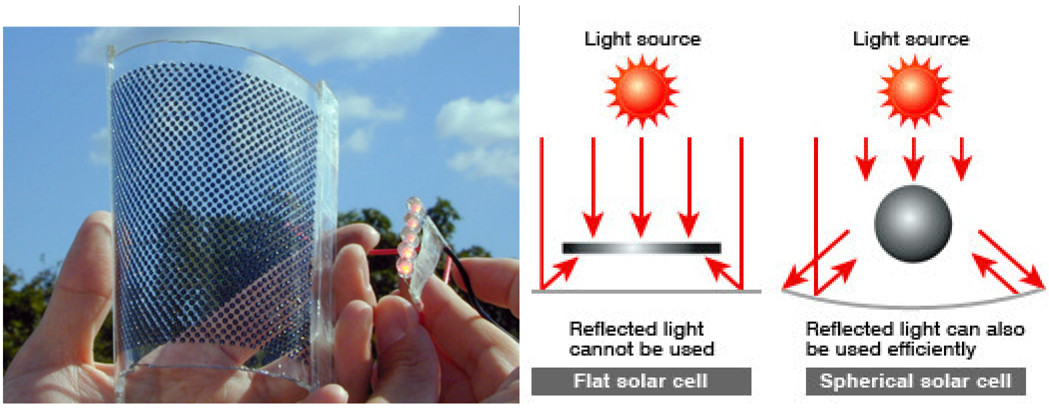


Figure 3.21 : Spherical PV cell and comparison with Flat solar cell [38]

4. BUILDING INTEGRATED PHOTOVOLTAICS

As mentioned in the previous chapter, one of the most promising renewable technologies is Photovoltaics which is a truly elegant means of producing electricity on site, directly from the sun, without concern for energy availability or environmental harm. These solid-state devices simply make electricity out of sunlight, silently, with marginal maintenance, no pollution and no depletion of materials. Photovoltaics are also exceedingly versatile; this technology can power water pumping, grain grinding, communications and village electrification in the developing Countries, and can produce electricity for the buildings and distribution grids of the industrialized countries. [12]

General information and technical features about photovoltaics have already been given in Chapter 3. Integration of photovoltaic technologies into buildings called "Building Integrated Photovoltaics" and abbreviated as "BiPV", and its details are explained with noticeable applications all around the world in this chapter.

4.1 Definition of Building Integrated Photovoltaics

The building envelope is composed out of the roof, the façade and the parts that have a contact to the ground. In other words, envelope is an interface between the indoor and the outdoor of the building. A PV module is designed and manufactured for outdoor use. All products available are suitable for exposure to sun, rain and other climatic influences. [12] Therefore, according to this feature, photovoltaics could be used on building envelope directly as a building element or with conventional envelope components.

A building is a combination of many complex systems such as structural, mechanical, electrical and others. Changes to the parameters of one system affect the others. An assessment of the performance of a building-integrated PV system as an element of building skin therefore requires a multidisciplinary approach. A building integrated PV system in fact adds another function: electrical power generation. [12]

Photovoltaics and architecture are a challenge for a new generation of buildings. PV systems will become a modern building unit, integrated into the design of the building envelope (roofs and facades). [12]

BiPV systems are multifunctional building materials, and they are therefore usually designed to serve more than one function. For example, a BiPV skylight is an integral component of the building envelope, a solar energy system that generates electricity for the building, and also a daylighting element. [14]

The architects, together with the engineers, are asked to integrate the PV at least on four levels during the planning and realization of the building:

- Design of a building (shape, size, orientation, colour)

- Mechanical and structural integration (multifunctionally of a PV element)

- Electrical integration (grid connection and/or direct use of the power)

- Maintenance and operation control of the PV system must be integrated into the usual building maintenance and control. [12]

4.1.1 History of building integrated photovoltaics

In the 1970s, PV applications for buildings began appearing in the United States. Aluminium-framed PV modules were connected to, or mounted on, buildings that were usually in remote areas without access to the electric power grid.

In the 1980s, PV module add-ons to roofs began being demonstrated. These PV systems were usually installed on utility-grid-connected buildings in areas with centralized power stations.

In the 1990s, BiPV construction products specially designed to be integrated into a building envelope became commercially available. [14]

4.2 Benefits of BiPV Systems

BiPV has many benefits to environment, grid, building and its owner. Some of them are summarized below:

- Provide grid support, particularly in areas of summer peak loads,
- Eliminate costs and losses in transmission and distribution of electricity,
- Create a diverse and resilient energy system,

- The small units typically require no special approvals or permits,
- Can be rapidly installed, [1]
- It does not require any extra land area; the building itself becomes the PV support structure,
- Contribute to decrease the external electrical demand of the building,
- It is a silent system,
- System electrical interface is easy,
- BiPV components displace conventional building materials and labour, reducing the net first cost of the PV system,
- On site generation of electricity offset imported and often carbon-intensive energy,
- Architecturally elegant; well-integrated systems increase market acceptance,
- Provide the building owners for a highly visible public expression of their environmental commitment,
- Provide significant sectoral greenhouse gas (GHG) offsets in line with GHG emission reduction targets, [1]
- It is multifunctional element,
- The energy contribution to the building does not limit to the production of electricity but also affects its thermal and lighting performance. Therefore, the BiPV system can be designed according to the building's heating, cooling and daylighting loads. For instance, the application of semi transparent PV modules in atria is an excellent application of PV that provides for shading, reduces the cooling load, admits daylight and generates electricity.
- The heat co-generation of a PV/T system provides another contribution to a building's thermal performance. For example, heat is produced when ambient air is vented behind the BiPV glass panels to cool the solar cells. (PV cells perform more efficiently at lower temperatures.) The captured warm air may then be used to preheat water or air for building services. [21]

4.3 Main principles of BiPV system design

BiPV systems are suitable not only for new projects, but also for renovation projects, even if the definiton of BiPV during the first stages of the design is a more efficient and aesthetical solution.

The parameters of increasing the efficiency of PV panels in the building are similar to solar energy system's parameters, and they should be optimized to obtain the best results from BiPV system.

Unlike any other building installations, BiPV can affect every aspect of the design process:

- Layout and orientation.
- Form and massing.
- Layout and height of surrounding buildings and plantings.
- Energy strategy.
- Building structure and modularity.
- Selection and assembly of other building materials, components and systems.
- Capital and running costs.
- Construction integrity and detail.
- Appearance and architectural expression.
- Manner in which building owner and its occupants are perceived. [1]

4.4 Components and Working Principle of BiPV Systems

The standard element of a BiPV system is the PV module. Individual solar cells are interconnected, encapsulated, laminated on glass, and framed to form a module. Modules are connected in series and parallel with cables and wires to form a PV array.

BiPV systems are made up of BiPV construction materials that depend on where they are mounted in the building, and on balance-of-system (BOS) hardware. [14] The BOS hardware is explained in Chapter 3.

A grid connected photovoltaic system receives back-up power from a utility's grid when the PV system is not producing enough power. When the system produces excess power, the utility is required to purchase the power through a metering and rate arrangement. [39]

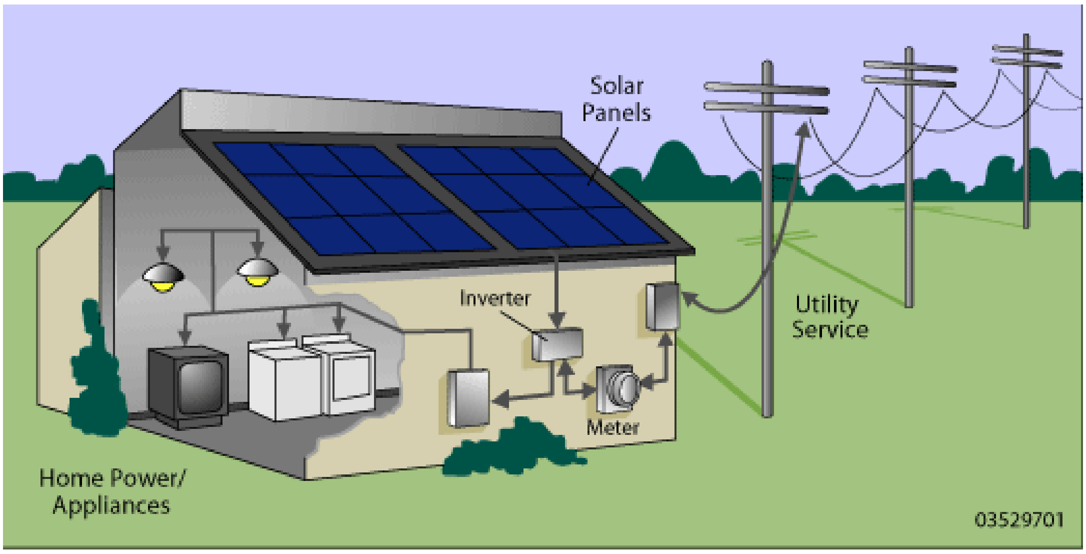


Figure 4.1 : Residential Grid connected PV system [40]

Figure 4.1 shows the main principles of a grid-connected PV system for a residential building, but the basic is same for all kind of buildings. As seen in the figure, when the sun shines on the solar panels, the DC electricity produced by solar panels is sent to the inverter that converts it into AC electricity. This electricity could be used in the building or if it exceeds its energy demand, it is sold to the grid by using the meter. A more detailed scheme of grid-connected PV system is shown in Figure 4.2.

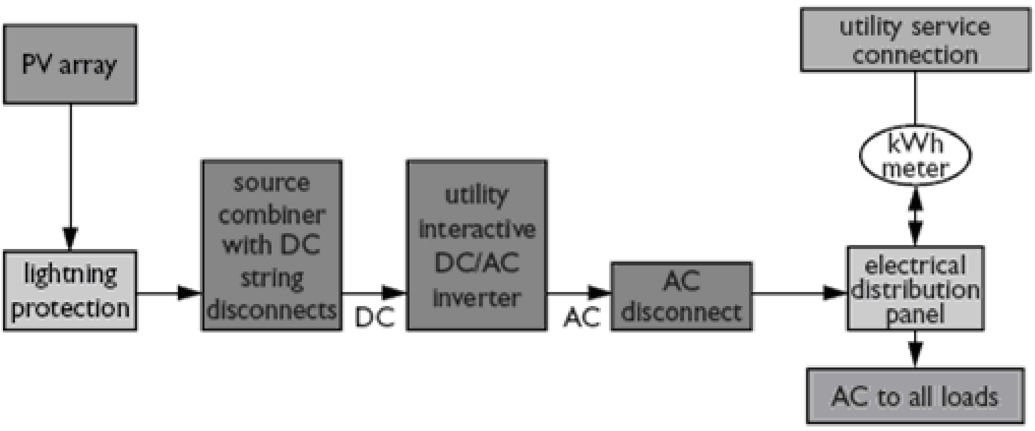


Figure 4.2 : Block diagram of a Utility-interactive PV system

4.5 Types of BiPV Systems

BiPV is an effective building energy-efficient component in residential, commercial, industrial and institutional buildings and structures for both new projects and renovation projects.

Any building surface that intercepts the sun is a candidate for PV integration. Many buildings incorporate semi-attached elements in addition to walls and roofs, such as awnings, light shelves, canopies and fences. All of these surfaces can deliver the multiple benefits of BiPV, producing energy while performing other architectural functions. [22]

Commercially available BiPV system types are:

- Façade systems
- Roofing systems
- Atrium systems
- Shading systems [14]

4.5.1 Façade systems

BiPV facade systems include laminated and patterned glass, spandrel glass panels, and curtain wall glazing systems. These BiPV products can displace traditional construction materials.

- Laminated glass is a standardized BiPV product. It is composed of two pieces of glass with PV solar cells sandwiched between them, and encapsulant of ethylene-vinyl acetate (EVA) or another encapsulant material, and a translucent or coloured tedlar-coated polyester backsheet. It can also be made with only one piece of glass and a tedlar backsheet. Architects can specify the colour of the tedlar backsheet. [14]

A laminated glass BiPV element and its application can be seen in Figure 4.3.

- Spandrel panels are the opaque glass used between floors in commercial glass building facades.

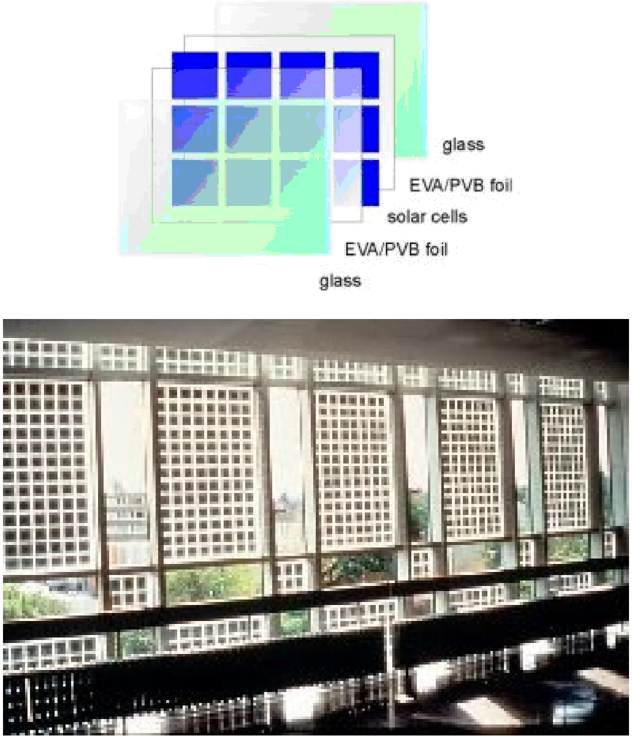


Figure 4.3 : PV laminated glass composition and application [41, 42]

- A glazed curtain wall is a non-load-bearing exterior wall suspended in front of the structural frame and wall elements. Patterned or fritted glass is semitransparent with distinctive geometric or linear designs. Some companies sell custom-made BiPV glazing products, available in any size or dimension and consisting of any PV technology. These products can be used in commercial glazing application. [14] Figure 4.4 shows a building with PV glazing curtain wall.

Figure 4.4 : PV Curtain wall [43]

4.5.2 Roofing systems

Roofing systems include BiPV shingles, metal roofing, and exterior insulation roof systems. These BiPV products can displace traditional construction materials.

- Flexible thin film amorphous silicon BiPV shingles can replace asphalt shingles. This BiPV product is nailed to the roof deck, similarly to the traditional connection of asphalt shingles to a roof. Figure 4.5 shows a roof application with photovoltaic shingles.[14]

Figure 4.5 : PV roof shingles application [44]

- BiPV metal roofing can replace an architectural standing seam. The thin film amorphous silicon PV material is laminated directly onto long metal roofing panels. The BiPV metal roofing panels, with edges turned up, are laid side by side and a cap is placed over the standing edges to form a seam. These metal panels can be installed by a traditional roofer followed by an electrician. [14] A metal roof application can be seen in Figure 4.6.

Figure 4.6 : PV metal roof application [45]

- As an exterior insulation BiPV roof system, PV laminates are attached to polystyrene insulation, which provides for thermal insulation. It rests on the waterproof membrane without penetrating or being mechanically fastened to the building. In an interlocking tongue-and-groove assembly, the panels are weight down by pavers that surround the system to provide access for maintenance and repairs. Channels or raceways are designed to provide access to the electrical connections. This technology can be used for retrofitting activities on the roof of an existing building. [14]

4.5.3 Atrium systems

In this application type, BiPV is a glass element that provides different degrees of shading and can be designed to enhance indoor thermal comfort as well as daylighting. [14]

The photovoltaic atrium roof application produces electricity, provides weather protection, prevents excess heat gain and also modulates direct sunlight and diffuse sunlight and diffused natural light; therefore, it acts as a shading device. This modulation can be controlled according to the density of the solar cells. An atrium application with PV is showed in Figure 4.7.

Figure 4.7 : PV-atrium application [46]

4.5.4 Shading systems

Solar radiation should be kept out in summer while it should be let in through the windows as much as possible in winter, for the radiation control. When PV modules are used as shading devices on buildings for solar control, the solar energy gain during summer decreases and this excess and unwanted solar energy is converted into electricity by photovoltaics. The location and orientation of photovoltaics must be well analysed and designed for the maximum energy efficiency both of excess solar gain prevention and electricity production. At the same time, designed PV system should let solar radiation enter the building during winter. As an example, the shading system of Solar-Fabrik building can be seen in Figure 4.8.

Figure 4.8 : PV-shading device application [47]

A variety of PV materials can be mounted onto a façade in aesthetic manner to serve as awnings. [14] There is a growing need for carefully designed shading systems for the building market due to an increasing use of large windows and curtain walls in today's architecture. Photovoltaic modules of different shapes can be used as shading elements above windows or as part of a roof structure. Since many buildings already provide some sort of structure to shade windows, the use of photovoltaic shades should not involve any additional load for the building structure. The exploitation of this synergetic effect helps to reduce the total costs of such a photovoltaic installation and to create added value to the building and its shading system. Photovoltaic shading devices may additionally use one way trackers to tilt the photovoltaic array for maximum power generation and at the same time provide a variable degree of shading. [23]

4.6 Aesthetics of BiPV Systems

An important architectural consideration is aesthetics, and PV modules do differ in appearance.

- Single crystalline PV modules are dense blue (almost black), with a flat, uniform appearance.

- Polycrystalline PV modules are multicoloured, having variety of sparkling blue tones.

- Thin-film amorphous silicon PV modules are reddish-brown to black; the surface may appear uniform or nonuniform, depending on how the modules are made.

Consequently, typical system colours are blues, browns, and black. However, some PV manufacturers can fill special orders for colours such as gold, green and magenta. These colour variations will result in some loss in performance efficiencies. [14] Architects can choose among these different colour varieties (Figure 4.9) to design a BiPV system. They also should remember that photovoltaic integration into a building is a way to show their sensitivity and consciousness about environment and global warming.

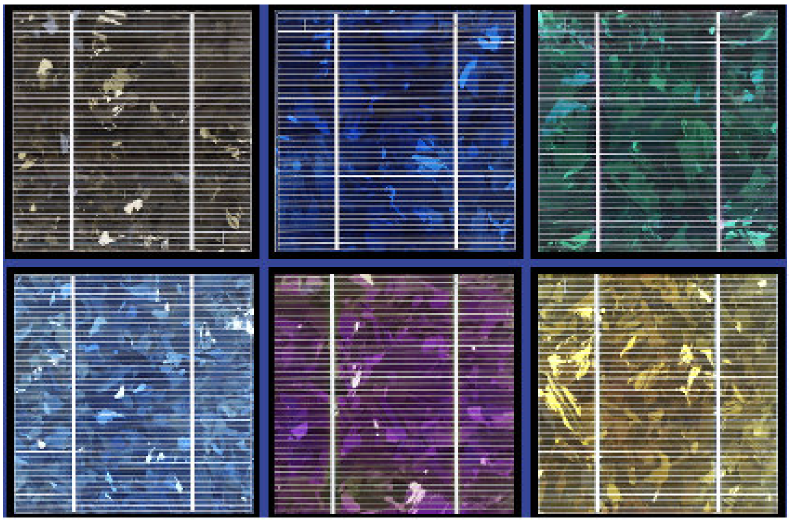


Figure 4.9 : Polycrystalline colour samples [48]

4.7 Cost of BiPV Systems

Next to benefits of BiPV, of course costs are important matter. The BiPV system cost depends on the type and size of the system, on current PV technology, and on whether a custom product or a standardized product is used. Some of façade cladding materials and PV costs are given in Figure 4.10. As seen in the figure, cost of photovoltaic application changes between 500$ and 1500$ per m². [21]

BiPV application is available for both new construction and renovation projects. BiPV façade systems products, such as laminated and patterned glass, curtain wall glazing materials, cladding and awning systems can displace traditional construction materials. Roofing system's products such as BiPV shingles, tiles, metal roofing and atrium or laminate roof systems can be used instead of traditional construction materials or be sold as enhanced construction materials. [21]

Figure 4.10 : Reference cost of façade cladding materials [21]

Cost of BiPV system reduces when it substitutes traditional materials. Stand-off façade and integrated façade cost of PV panels can be seen in Table 4.1. The integrated façade system's cost is lower than stand-off façade systems.

Table 4.1: Cost comparison between Stand-off and Integrated Façade PV panels[21]

(USD/Wp)	Stand-off Facade	Integrated Facade
Modules	3	3
Bos & Installation	1.11	(0.50)
Central Inverter & accessories	1.71	1.71
Total	5.83	4.21

4.8 BiPV Application Samples in the World

Photovoltaics is one of the most indispensable elements for the energy efficient and/or intelligent building design. Hundreds of BiPV applications are available throughout the world, from Australia to The United States of America, from China to Europe.

Unfortunately, in Turkey, photovoltaic applications are limited. Nevertheless researches on photovoltaic technologies is carried out by some universities and private companies. A few of the most valuable and important applications all around the world and their noticeable properties will be given below.

4.8.1 GreenPix – Zero Energy Media Wall

Location : Xicui Road, Beijing, China

Date Completed : 2008

Architect : Simone Giostra & Partners Architects

Façade Engineers : Arup

Solar Technology R&D : Schüco International – SunWays AG

PV Module Manufacturer: Suntech China

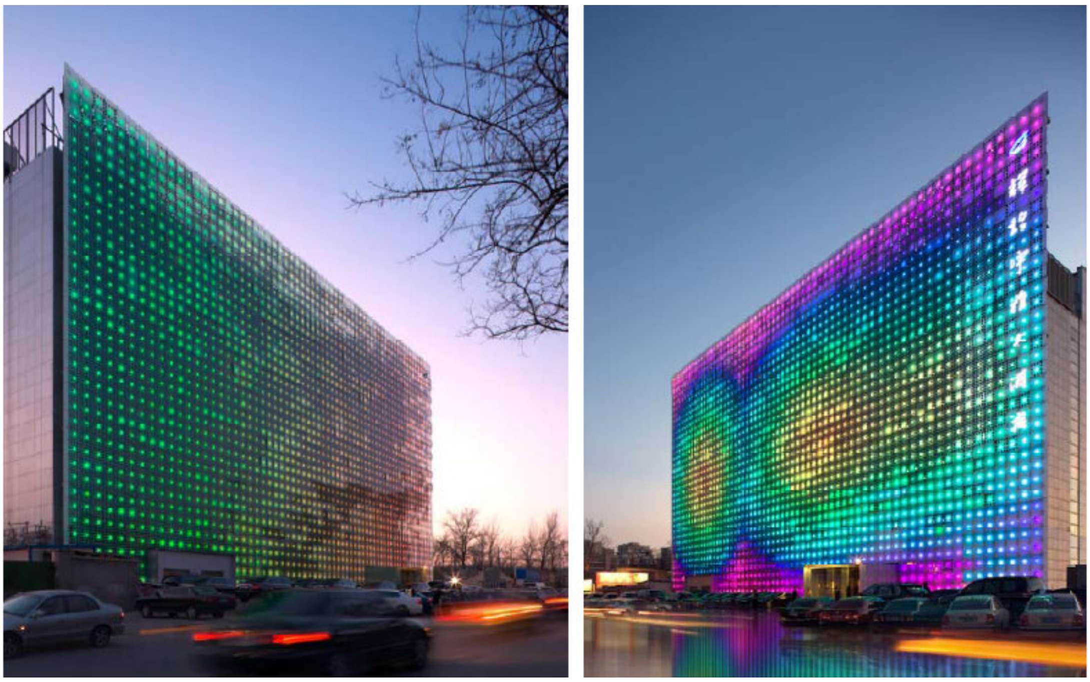


Figure 4.11 : GreenPix – Zero Energy Media Wall [49]

Featuring the first photovoltaic system integrated into a glass curtain wall in China and the largest coloured LED display worldwide, the BiPV performs as a self-sufficient organic system, harvesting solar energy by day and using it to illuminate the screen night-time, mirroring a day's climatic cycle. Figure 4.11 shows the façade of Zero Energy Media Wall. Additionally, photovoltaic panels on the façade can be seen in Figure 4.12.

Figure 4.12 : Photovoltaic Panels of GreenPix – Zero Energy Media Wall [49]

The polycrystalline photovoltaic cells are laminated within the glass of the curtain and placed with different density on the entire building's skin. The density pattern increases building's performance, allowing natural light when required by interior program, while reducing heat gain and transforming excessive solar radiation into energy for the media wall.

GreenPix is a large-scale display comprising of 2,292 color (RGB) LED's light points comparable to a 24.000 sq. ft. (2.200m²) monitor screen for dynamic content display. The very large scale and the characteristic low resolution of the screen enhances the abstract visual qualities of the medium, providing an art-specific communication form in contrast with the commercial applications of high resolution screens in conventional media facades. [49]

(The area and capacity of photovoltaic panels haven't been reached in the official website of GreenPix – zero energy media wall.)

4.8.2 Solar – Fabrik Zero Emission Factory

Location : Freiburg, Germany

Date Completed : 1998

Architect : Rolf + Hotz Architects

PV Area : 575 m²

PV Production Capacity : 45.000 kWh/a

Solar-Fabrik is an important PV manufacturer company whose office building is also a PV panel factory which has the capacity to produce 53MW of peak power solar panel modules per year. It is approximately 53.000m² of panels. [50]

Figure 4.13 : View from the west of Solar-Fabrik [47]

The Solar Fabrik factory is Europe's first zero-emissions solar module factory and uses only renewable energy sources for electricity and heat. Figure 4.13 shows Solar-Fabrik building.

The PV modules cover the entire facade. 575 m² of solar power modules supply around one-fifth of the electricity needed in the zero-emissions factory. 210 m² are fixed in front of the south-facing wall. The modules are positioned at an angle to shade the glass building when the sun is at its highest position during summer. In winter, the low-lying sun penetrates deep into the building and helps to heat the foyer. [47]

4.8.3 Mont – Cenis Academy

Location : Herne Sodingen, Germany

Sunshine Hours : 1.454 hours/year, 3,98 hours/day

Date Completed : 1999

Architect : Jourda Architects, HHS Planer+Architekten BDA

PV Engineers : Flabec Solar International, Abakus Energiesysteme

PV Area /Total Roof Area : 8.400 m² / 12.600 m²

Total Electrical Power : 1 MWp

PV Production Capacity : 750.000 kWh/a

Number of Roof Panels : 2.904 panels with 5 degree incline angle

Number of Façade Panels : 280 panels with 90 degree incline angle

Number of Inverters : 569

Figure 4.14 : Mont-Cenis Academy [52]

On the roof of the building, 925 kWp of semi-transparent PV modules are oriented with 5 degree inclination angle to south. On façade, 75 kWp of semi-transparent PV modules are used with 90 degree inclination angle to west. Three types of cells are used, all polycrystalline silicon from the manufacturers Solarex and ASE. Figure 4.14 shows the building that includes photovoltaics on its façade and roof. [52,53]

4.8.4 Solar Office Doxford International

Location : United Kingdom

Date Completed : 1998

Architect : Studio E Architects Ltd

PV Design : Studio E Architects + Rybka Battle

PV Area on South Façade : 532 m²

Total Electrical Power : 73 kWp

PV Production Capacity : 113.000 kWh/a

Number of Panels : 352 panels on South-face with 60 degree

Type of Cell Technology : Monocrystalline square cells

PV Module Manufacturer : Kyocera

Figure 4.15 : Solar Office Doxford International [52]

The Solar Office, showed in Figure 4.15, is the first speculatively constructed office building to incorporate BiPV and the resulting solar façade is the largest so far constructed in Europe. It is one of the few BiPV projects to adopt a holistic energy strategy. The designed of a speculative office building fully meets the requirements of the commercial market. It also required the building to be designed to fit the best practice low energy principles. The client supported the initiatives taken by the architect to include a worthwhile PV installation, but would only agree to include it if it was completely funded by outside sources and it did not extend the design and construction program. [52]

4.8.5 4 Times Square

Location : New York, USA

Date Completed : 1999

Architect : Fox & Fowle Architects

PV Design : Kiss + Cathcart Architects

PV Area on South Façade : 287 m²

Total Electrical Power : 14 kWp

PV Production Capacity : 13.800 kWh/a

PV Module Efficiency : 6%

Type of Cell Technology : Amorphous silicon

PV Module Manufacturer : Energy Photovoltaics, Inc.

Figure 4.16 : 4 Times Square [52]

Figure 4.16 shows 4 Times Square building that was the tallest skyscraper built in New York City in 1990s with 48-story office tower. The south and east facades between the 37th and the 43rd floors were designed as the sites for the photovoltaic "skin." BiPV was incorporated into the design after the tower's general appearance had already been decided upon, so the installation was made to harmonize with the established design concept.

The PV modules are attached to the building structure in exactly the same way that standard glass is attached. The glass units are attached with structural silicone adhesive around the back edge to an aluminium frame. [14]

4.8.6 ECN Building 42

Location : Petten, Netherlands

Sunshine Hours : 1.477 hours/year, 4,05 hours/day

Date Completed : 2002

Architect : BEAR Architecten BV

PV Area on South Façade : 400 m²

Total Electrical Power : 43 kWp

Number of PV Modules : 570

PV Module Efficiency : 16,5%

Type of Cell Technology : Monocrystalline silicon

PV Module Manufacturer : BP Solar

PV System Cost : 384.352 Euro

Figure 4.17 : ECN Building 42 [52]

As renewable and low-energy material, it was decided to build the conservatory with a laminated wooden construction. Two curved glued timber beams are interconnected with small round shaped steel profiles to form strong beams. On top steel-profiles aluminium glazing profiles are placed to hold the PV-modules horizontally and vertically.

The greenhouse construction company Allicon was chosen as a partner to develop the PV-glazing and glass-facades. Glass profiles developed for greenhouses are used for the conservatory roof. The conservatory glazing is carried out as single glazing, as the conservatory space should function as a buffer zone without heating. [54]

4.9 Conclusion

In Chapter 4, basic of BiPV system such as usage type in buildings, connection properties have been clarified with important applications around the world. According to global warming issues and the decrease of fossil sources, even petroleum companies are interested in renewable energy technologies particularly photovoltaics. Figure 4.18 shows BP Solar Showcase building located in Birmingham, UK.

Figure 4.18 : BP Solar Showcase [55]

The examples could continue more and more, but the important thing is what the development of technology and aesthetic in BiPV system application is. In Figure 4.19, one of the first example(on the left) and a new BiPV project design from Dubai (on the right) are shown and it can be seen that the integration of photovoltaics into buildings has developed a lot.

Figure 4.19 : Two PV Applications [56,57]

In the next chapter, a case-study BiPV application from Italy will be described and simulated for its performance evaluation.

5. DESCRIPTION OF CASE-STUDY: ATC BUILDING

In this chapter, ATC Building, which is a part of Polycity Project, will be introduced as a case-study. Firstly; Polycity Project and its three parts will be explained, then the Italian site of Polycity Project, and in particular ATC office building and its photovoltaic system will be described with details.

5.1 Definition of Sites of Polycity Project

POLYCITY is a project of the CONCERTO[1] initiative, co-funded by the European Commission. In the course of the Polycity Project, three large urban areas in Germany, Spain and Italy will be developed, particularly in the field of energy optimisation and the use of renewable energies.

The German project is the Scharnhauser Park in Ostfildern, a former military area. Cerdanyola del Vallès in Spain is a development area planned for 50.000 inhabitants north of Barcelona. The Arquata in Turin – Italy, is an industrial district which is restored according to ecological criteria. [26]

5.2 Italian Site of Polycity Project

The Italian project Arquata, coordinated by the Fiat Research Centre, is part of a larger initiative aimed at promoting integrated energy systems based on distributed generation which means co-generation and renewable energies. The initiative involves the relevant stakeholders in the region, such as public administrations, utilities, research centres and users.

The overall Arquata District Contract is a detailed programme including several measures of urban and social requalification such as the refurbishment of the council buildings, the realisation of green areas, the creation of common spaces dedicated to social activities, social and occupational development of the district, the improvement of mobility, the creation of small commercial spaces. Such measureshave been completely approved and funded by the contractors. [26]

[1] Concerto : Concerto is a new major European Union initiative which will support local communities in developing concrete initiatives that are both sustainable and highly energy efficient.

Arquata district consists of 30 residential building and 1 high rise office building called ATC. This building will be analyzed in this study. In Arquata district, approximately 2500 people live in 622 dwellings. [24] The map of Arquata district is given in Figure 5.1.

Figure 5.1: The map of Arquata District [58]

The energy efficient energy supply system of Arquata District consists of:

- A Combined Heat and Power (CHP) unit (0.9MWel, 1.1MWth) to be installed in the basement floor of the ATC office building.
- An absorption chiller, thermally coupled to the co-generation plant, placed in the ATC office building that provides cold for the climatisation of the ATC building itself.
- Modification of the district heating distribution grid to provide heat storage for peak management.
- Photovoltaic modules to be integrated in the facade of the ATC office building as sun-shading devices with a total peak power of 50 kW.
- Additional photovoltaic modules to be installed on the roofs of the council buildings with a total peak power of 100 kW. [27]

Furthermore, the reduction of energy needs for ATC office building and Arquata residential building is summarized below:

- Substitution of 500 conventional glazing with low emittance glazing for ATC-owned dwellings of north eastern and south western facades.
- Substitution of windows glasses with low emittance glazing in north eastern facade of ATC office building.
- Insulation of thermal bridges in the walls and balconies, with the application of wooden fiber panels. [24]

5.3 ATC Office Building

In this section, ATC office building's architectural characteristics, office hours and schedules, electrical equipments of building, retraining steps and particularly, photovoltaic system will be explained.

5.3.1 Description of ATC office building

ATC office building is the headquarters of "Agenzia Territoriale per la Casa della Provincia di Torino (ATC)", and is located in Dante Street in Turin. It is a tower that stands out compared to the surrounding buildings because of its height and the facade that is mostly glassed. It consists of 2 basement floors and 10 floors above ground. The photo of ATC building is shown in Figure 5.2.

The building can be considered as made of 2 main blocks. The first part, which consists of 10 office floors, is used by ATC and is about 35m high.

The second part consists of the ground floor and the first 2 floors, these 3 floors are larger than the ATC office areas. Ground floor is a public area, the first floor is used for office and the second floor is the former consortium. [28]

Figure 5.2: ATC Office Building, Turin [28]

The first floor plan (1.047m²) and the type floor plan (643m²) can be seen in Figure 5.3. Total area of ATC building is 7.531m².

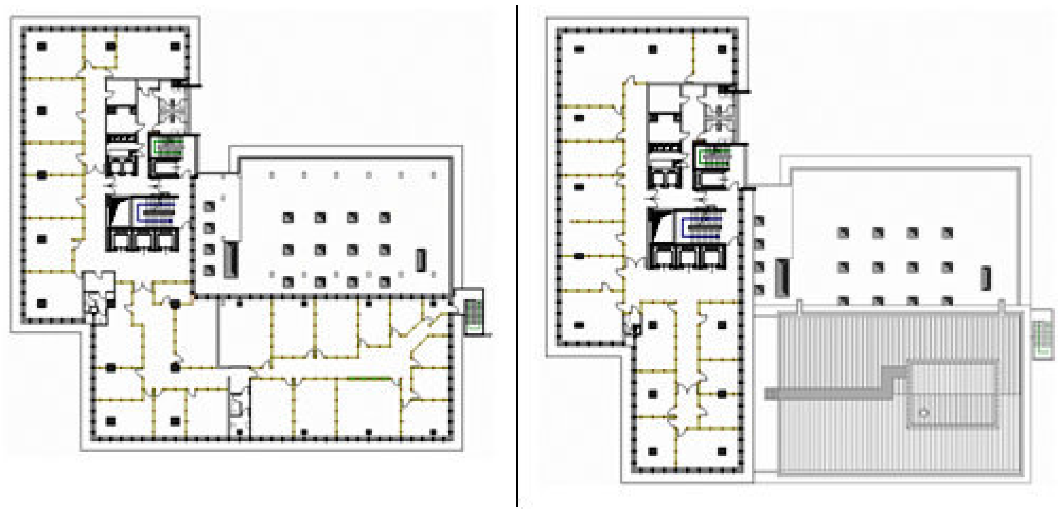


Figure 5.3: First Floor Plan – Type Floor Plan of ATC Building [28]

5.3.2 Renovation steps of ATC office building

ATC building has been renovated during these years. The most important results of the renovation are here summarized:

- Photovoltaic system integrated in the South western and South eastern facades with a total peak power of 49kW
- Because of substitution of glazing of North eastern facade's windows, U-factor has decreased from 3,8 to 1,9W/m²K
- Due to insulation of thermal bridges, thermal fluxes have been reduced from 1,2 to 0,7W/K
- Installation of a Combined Heat and Power Generator Unit (CHP) that supplies heat for ATC building and the district network [24]

5.3.3 Schedules of ATC office building

Schedules of ATC Building include working hours, HVAC and lighting systems schedules and electrical aquipment's features. They are collected in Appendix A.

Table A.1 is the occupancy schedule.

Table A.2 shows the cooling schedule of the building and the set-point temperature is 26ºC.

Table A.3 is the heating schedule of building and the set-point temperature of the heating system is 20ºC.

Table A.4 is the lighting system schedule of ATC building.

Table A.5 gives information about the electrical office equipments used in the building and their electricity consumptions.

All tables are organized from Reference 28 and these schedules and the electrical equipment features are used as input data for the simulations of ATC building.

5.3.4 Photovoltaic system of ATC building

The building integration of photovoltaic is a particular way to achieve energy savings, that is one of the most important aims of Polycity Project. The photovoltaic modules have been installed above the windows of ATC building so that they can simultaneously satisfy two purposes:

- Production of electrical energy,
- Shading of the offices (Saving on summer cooling of the building).

The photovoltaic modules are used as shading devices, and have a total size of 49,14kW peak power. They are mounted along 7 floors on south western facade and along 3 floors on south eastern facade of ATC building. The rendering of ATC building with its photovoltaic system is shown in Figure 5.4. [25]

Figure 5.4: Rendering of ATC Building with Photovoltaic Panels - South west and South east Façade [25]

The Photovoltaic modules are 210W peak power each one, and they are produced by the German Company Heckert Solar. The position of the photovoltaic modules on the type floor plan is shown in Figure 5.5.

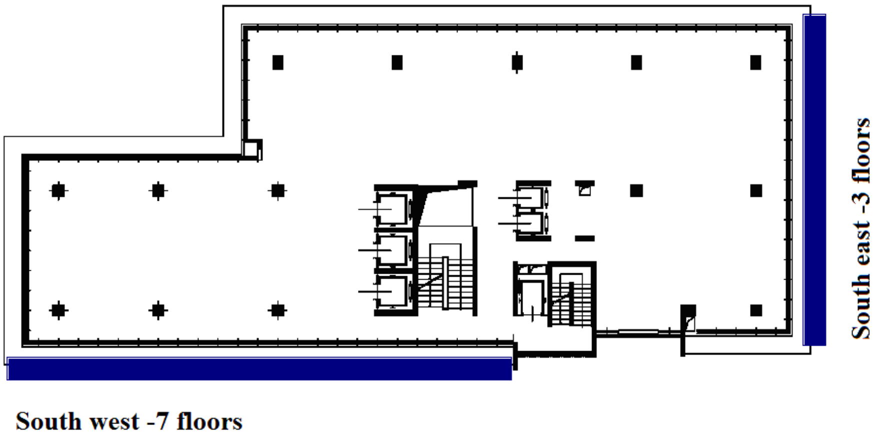


Figure 5.5: Position of the photovoltaic modules on the type floor plan of ATC Building [28]

The photovoltaic modules have been mounted on the existing shading device as the second shading devices with an orientation angle of 35° as shown in Figure 5.6.

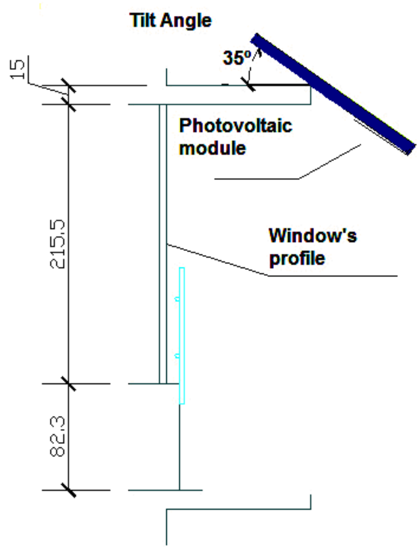


Figure 5.6: Orientation Angle of Photovoltaic Module [28]

The total photovoltaic panel area is 342m². The configuration of the photovoltaic modules can be seen in Figure 5.7.

The photovoltaic modules and inverters properties have been changed before the installation and the updated photovoltaic system information is taken from Electrical Engineering Department of Politecnico di Torino and is given below.

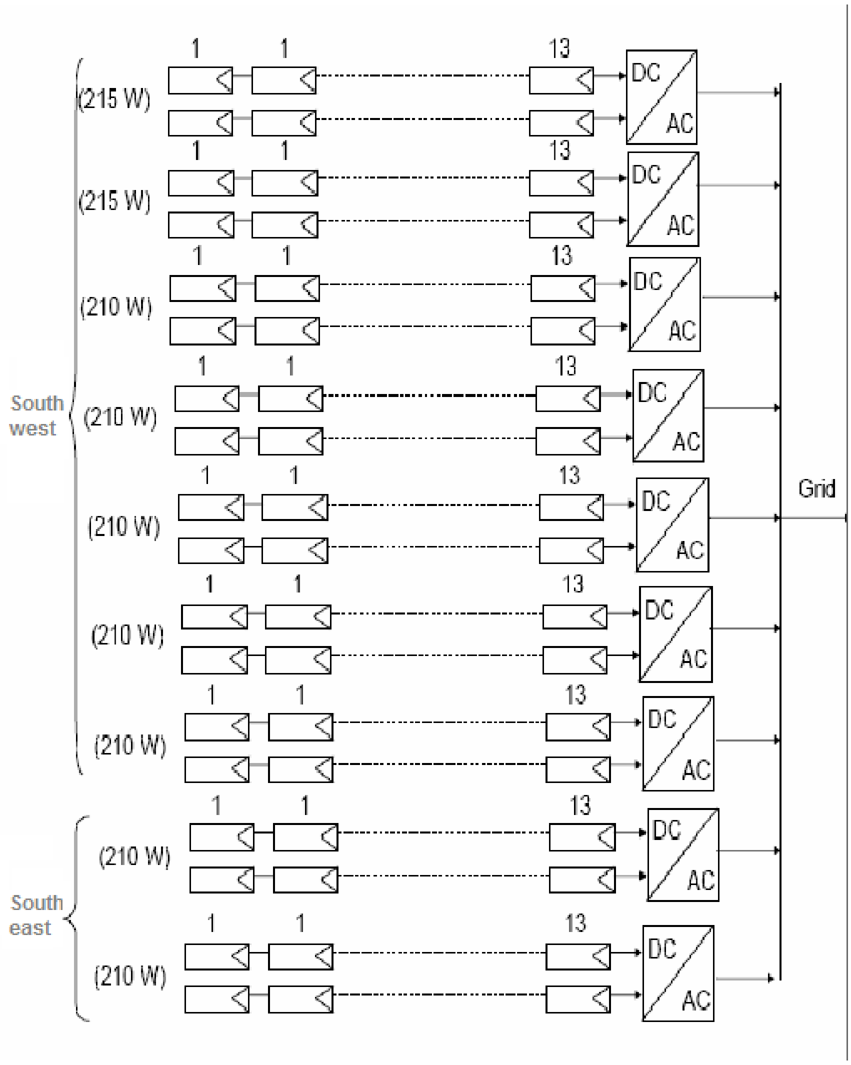


Figure 5.7: Configuration of Photovoltaic Modules in the ATC Building [64]

The configuration of photovoltaic panels is summarized in the following lines.

South-west Facade consists of :

- 182 modules subdivided on 7 levels,
- Every level has 26 modules managed by 1 inverter,
- Every inverter manages 2 strings which are connected in parallel and composed by 13 series modules.

South-east Facade consists of :

- 52 modules subdivided on 3 levels,
- 2 levels have 17 modules and 1 level has 18 modules managed by 2 inverters.
- Every inverter manages 2 strings, each one composed by 13 modules connected in series.

5.3.4.1 Heckert Solar Photovoltaic Panels

234 photovoltaic panels are used in ATC office building. They are produced by Heckert Solar Company. The module type is HS-PXL-Series 210W. The detailed performance and general features of the modules are explained in Figure 5.8.

Performance data HS-PXL-Series (typically)

	HS-PXL 190	HS-PXL 195	HS-PXL 200	HS-PXL 205	HS-PXL 210	HS-PXL 215
Maximum Power	190 W_p	195 W_p	200 W_p	205 W_p	210 W_p	215 W_p
Tolerance	+/- 2%	+/- 2%	+/- 2%	+/- 2%	+/- 2%	+/- 2%
Number of cells	54	54	54	54	54	54
Cell size	156 x 156 mm	156 x 156 mm	156 x 156 mm	156 x 156 mm	156 x 156 mm	156 x 156 mm
Nominal voltage	24 V	24 V	24 V	24 V	24 V	24 V
Bypass diods	3	3	3	3	3	3
Short circuit current I_{SC}	8.20 A	8.25 A	8.30 A	8.35 A	8.40 A	8.45 A
Open circuit voltage U_{OC}	31.78 V	32.25 V	32.70 V	33.20 V	33.68 V	34.10 V
Voltage at maximal load U_{MPP}	24.65 V	25.13 V	25.60 V	26.07 V	26.55 V	27.00 V
Current at maximal load I_{MPP}	7.71 A	7.76 A	7.81 A	7.86 A	7.91 A	7.96 A
Maximal system voltage	1.000 VDC	1.000 VDC	1.000 VDC	1.000 VDC	1.000 VDC	1.000 VDC

General data

Dimensions	990 x 1480 mm
Dimensions (excluding frame)	985 x 1475 mm
Height	38 mm
Height (excluding frame)	5 mm
Weight	18.7 kg
Weight (excluding frame)	16.5 kg
Glass	4 mm highly transparent solar glass
Cells	54 polycrystalline 6"
Frame	38 mm anodized aluminium frame
Temperature coefficient A_{SC}	0.05 %/K
Temperature coefficient V_{OC}	-0.31 %/K

Figure 5.8: Performance and General Data's of Heckert Solar Photovoltaic Panel is used in ATC building [59]

5.3.4.2 SolarMax 6000C Inverters

9 inverters, which are used for converting the DC electricity produced by the photovoltaic modules into AC electricity, are produced by Sputnik Engineering from Switzerland. The type is SolarMax 6000C. The detailed information of the inverter can be seen in Figure 5.9.

Technical data SolarMax 6000C

	SolarMax 6000C
Input side (DC)	
Max. input voltage**)	600 V_{DC}
MPP control range	90 ... 560 V_{DC}
Max. generator output*)	6000 W_{STC}
Maximum current	22 A_{DC}, 16 A_{DC} max. per input connector
Output side (AC)	
Rated output	4600 W
Maximum output	5060 VA
Mains voltage	196 ... 253 V_{AC}
Power factor	>0.98
Mains frequency	49.8 ... 50.2 Hz
Harmonic distortion	< 3 %
System data	
Maximum efficiency	97 %
European efficiency	96.2 % (Udc: 400 V) / 95.5 % (Udc: 300 V)
Night-time consumption	0 W
Ambient op. temp.	- 20 °C ... + 50 °C
Rel. humidity	0 ... 98 %, no condensation
Heat dissipation	convection, active cooling (fan) if required
Protection type	IP 54
Circuit type	transformerless, two-stage (no galvanic isolation)
Mains monitoring	ENS according to VDE 0126
Fault current monitoring for personal and system protection	all-current-sensitive fault current monitoring according to VDE 0126
Display	2-line LC display with background illumination
Housing	Heat sink and cover mad from cast aluminium
Weight	16.3 kg
Dimensions (W*H*D)	554 x 260 x 190 mm
CE-compliant according to	EN 61000-6-3, EN 61000-6-1, EN 61000-3-2, EN 61000-3-3, EN 50178
Mark of conformity	TÜV type approved

*) with recommended oversizing of 15 % (Fraunhofer ISE study)
**) calculated at 1000 W/m^2 and –10 °C (applies to central Europe). For systems in exposed locations temperatures <-10 °C are to be expected.

Figure 5.9: Technical Data of SolarMax 6000C Inverter used in ATC Building [60]

6. PERFORMANCE EVALUATION OF THE CASE STUDY BUILDING

In the case - study of ATC office building, photovoltaic panels are used as second shading devices, because every floor in ATC building has 1m horizontal shading devices in every direction of the facades. The photo of ATC building with these shading devices can be seen in Figure 5.2. Therefore, when the panels product the electricity, they affect the cooling, heating and lighting loads of ATC building through their shading effect.

Because of the shading effect of the panels, while cooling loads decrease during summer, heating loads during winter and general lighting loads increase.

The numerical simulations have focused on the assessment of the utility ratio of the PV system (that is the ratio of the electricity produced by the PV system to the building total electricity consumption) and the electrical energy production of the PV panels. Moreover the effect of the PV panels, mounted as shading devices, on the cooling, heating and lighting demands has been determined, in comparison with the same building without the PV system. All the analysis have been carried out with the following commercial software:

- PVSYST - for electricity production,
- DesignBuilder - for cooling and heating loads,
- EnergyPlus - for lighting loads.

6.1 Electricity Production of Photovoltaic Panels of ATC Building

The PVSYST program is used for the simulation of the electrical performance of the photovoltaic modules. The electricity production of ATC building is simulated by using PVSYST version 4.33.

6.1.1 Simulating with PVSYST

The PVSYST is developed by the collaboration of Group for Energy (CUEPE) from University of Geneva, Enercad and Meteonorm and the program is suitable for grid-connected, stand-alone, pumping and DC-grid (public transport) systems.

The program asks the user to define the PV system to be analysed. Orientation and location of the PV panels are entered. Then, types and sizes of photovoltaic modules and inverters can be chosen from PVSYST libraries. With this input data, the program is ready for the simulation that calculates the electricity production of the panels. More information can be found on the official website of PVSYST. (http://www.pvsyst.com/) The interfaces of PVSYST program can be seen in Figure 6.1 and Figure 6.2

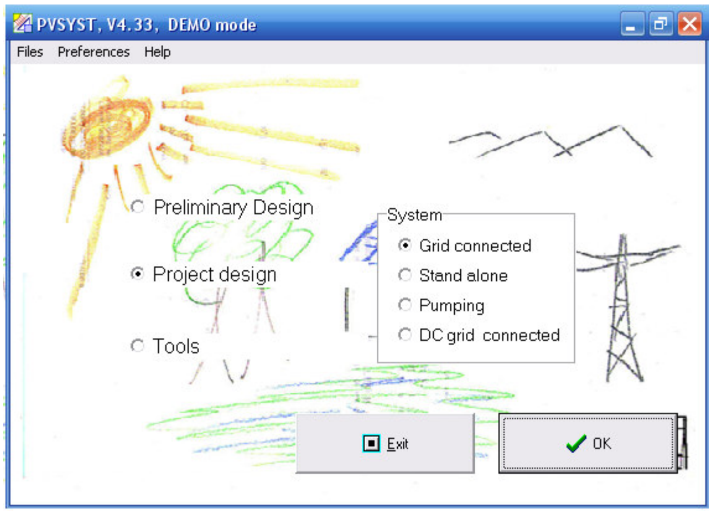


Figure 6.1: Opening Screen of PVSYST Program

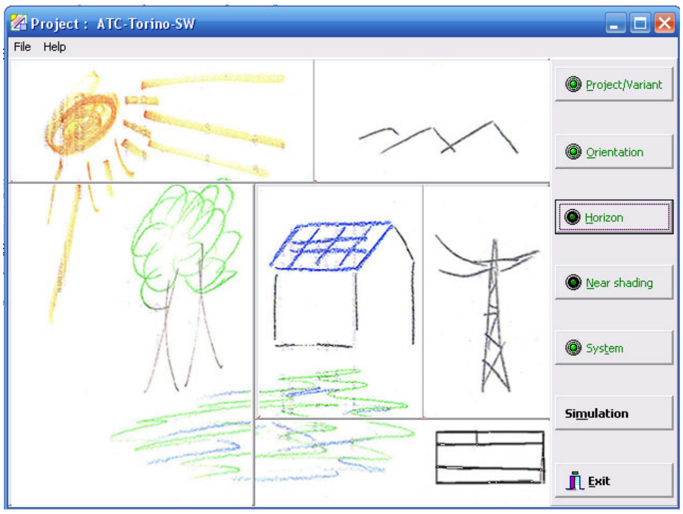


Figure 6.2: Grid Connected Project Design Categories of PVSYST Program

The PV system of ATC building has been explained in Chapter 5. According to this information, PV electricity production will be calculated in two parts.

- Production of PV panels on the south-west façade

- Production of PV panels on the south-east façade

6.1.2 Electrical production of PV panels on the South-west facade

On 7 floors of the south-west facade are installed 182 PV modules managed by 7 inverters.

Heckert Solar polycrystalline photovoltaic cells with 210Wp and SOLARMAX 6000C inverters, which are the current PV devices in ATC building, are used in the simulations.

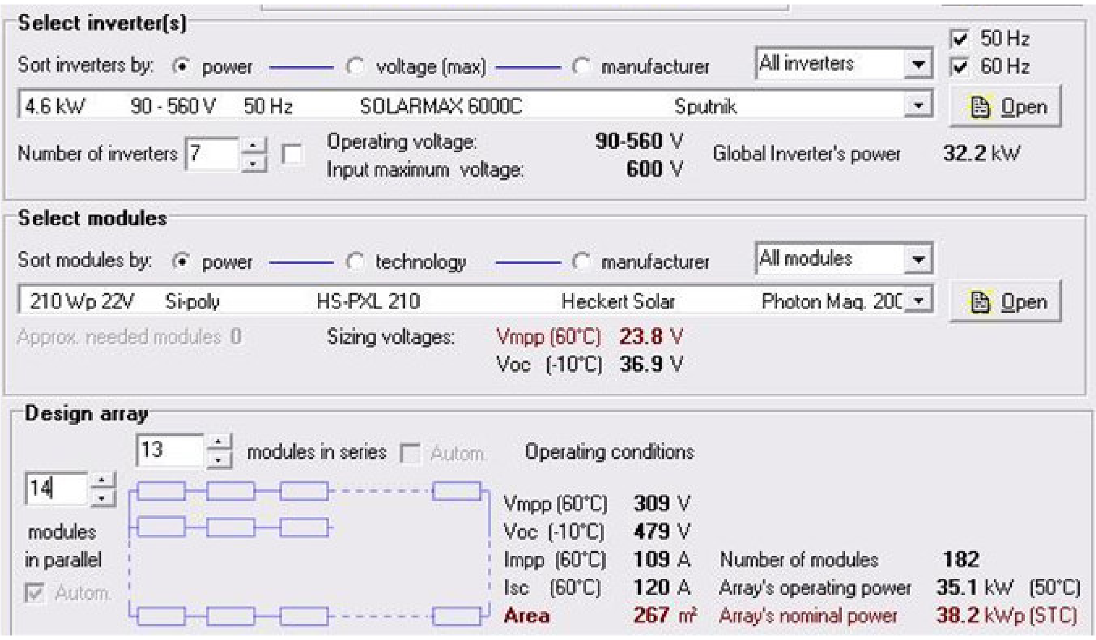


Figure 6.3: Input File (Grid System Definition) for the South-west Facade

Figure 6.3 shows the most important input window for the PV system in PVSYST programme. As seen in the figure, 7 units of SOLARMAX 6000C inverter and Heckert Solar - HS-PXL 210 polycrystalline PV modules are selected. Furthermore, 14 strings connected in parallel, each of them composed by 13 series modules are simulated according to ATC PV system. Photovoltaic panel area is 267m² and the PV array power is 38.2kWp for the south-west facade.

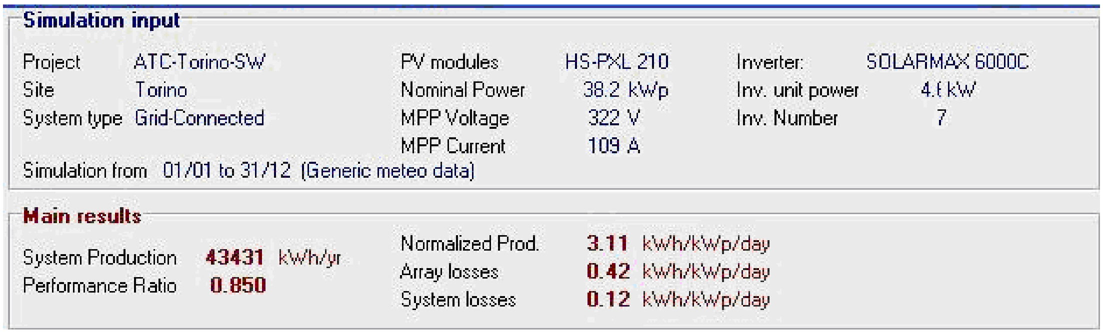


Figure 6.4: Output File (Annual Electricity Production) of South-west Facade

Figure 6.4 shows the output file of PVSYST for the south-west façade: on the top of the window the input data (location, system, data, etc.) are summarized. The annual electricity production of the PVmodules is **43.431kWh/yr**.

In order to calculate the seasonal electricity production of the PV array, the system has been simulated for the summer and winter seasons. Winter period has been split in two parts, because of the current weather file of Turin in PVSYST. It should be taken into consideration that PVSYST always gives annual results.

6.1.2.1. Summer production of PV panels on the South-west façade

The input file is the same, but the simulated period is different: summer period starts from April 1st and finishes September 30th.

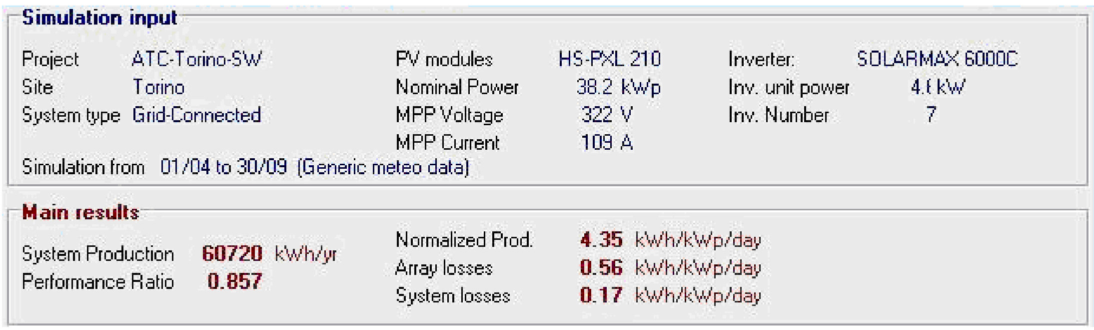


Figure 6.5: Annual Electricity Production of the South-west Facade in Summer Conditions

In Figure 6.5, the annual production value is 60.720kWh/yr for the summer season. It must not be forgotten that the programme calculates the electrical production as annual and considering that summer lasts 6 months (April 1st - September 30th), in order to obtain the summer production of the PV panels the annual production value is divided into 2.

60.720 kWh/yr / 2 = **30.360 kWh (for 6 months)**

6.1.2.2. Winter production of PV panels on the South-west façade

Winter Period is divided in 2 parts because of the current weather file of Turin in PVSYST program. The first part goes from January 1st and March 31st while the second part goes from October 1st to December 31st.

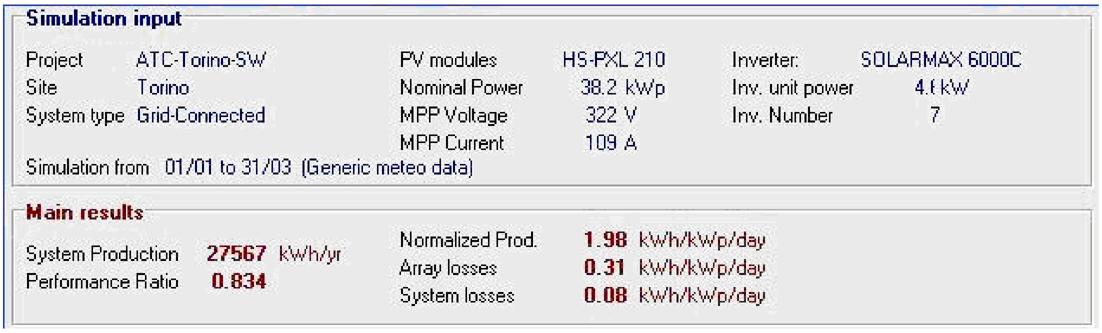


Figure 6.6: Annual Electricity Production of South-west Facade in the 1st part of Winter Conditions

In Figure 6.6, the annual electrical production of the PV array is 27.567 kWh/yr. As the first part of winter lasts 3 months (January 1st –March 31st), the production of the PV panels during the first part of winter is thereby calculated by dividing the annual production by 4.

27.567 kWh/yr / 4 = **6.891 kWh ((for 3 months)**

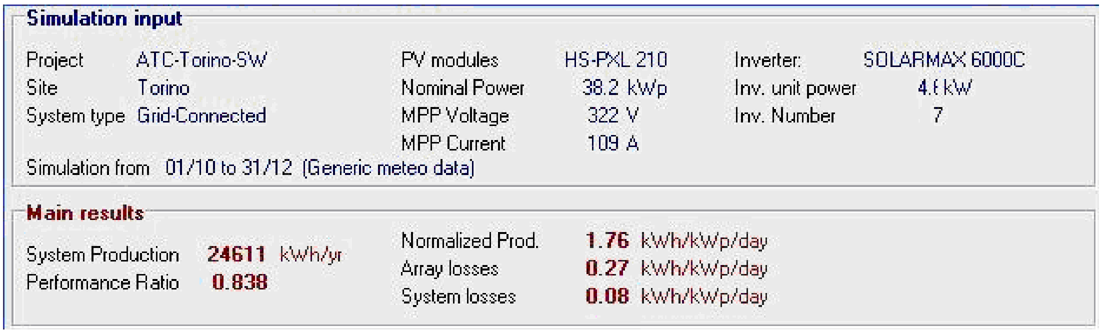


Figure 6.7: Annual Electricity Production of South-west Facade in the 2nd part of Winter Conditions

In Figure 6.7, the annual production of the PV array is 24.611 kWh/yr. As the second part of winter lasts 3 months (October 1st –December 31st), the production of the PV panels during the second part of winter is thereby calculated by dividing the annual production by 4.

24.611 / 4 = **6.152 kWh (for 3 months)**

The electricity production of south western PV modules during winter is calculated below.

Total winter production : 6.891kWh + 6.152kWh = **13.043kWh (for 6 months)**

The annual electricity production of south west façade's PV Panels is summarized in Table 6.1.

Table 6.1: Annual Electricity Production of the PV Panels on the South-west Façade

ATC BUILDING	SUMMER CONDITIONS	WINTER CONDITIONS	TOTAL
SOUTHWEST FAÇADE ELECTRICITY PRODUCTION (kWh/yr)	**30.360**	**13.043**	**43.431**

(Due to PVSYST results, there is a difference, -28kWh/yr, between the annual PV production and sum of the seasonal production and it has been ignored.)

6.1.3 Electrical production of PV panels on the South-east facade

South eastern facade is composed by 52 modules along 3 floors.

Input and output files can be seen in Figure 6.8 and Figure 6.9.

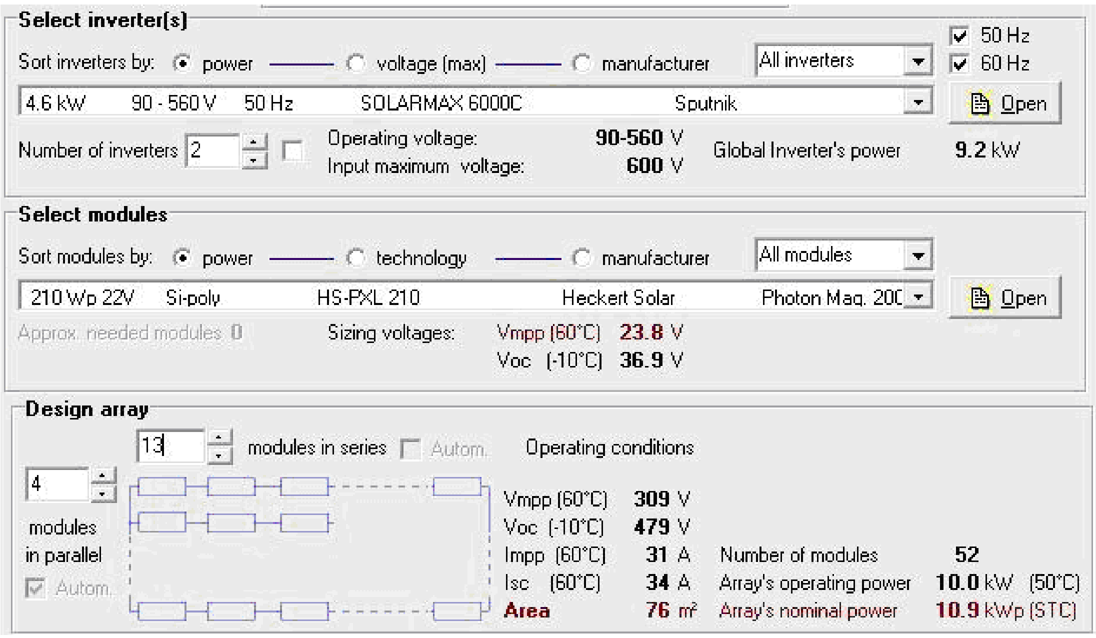
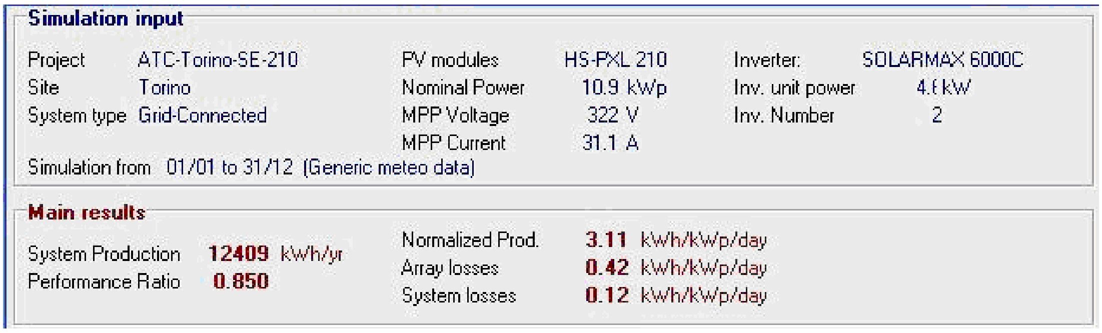


Figure 6.8. Input file (Grid System Definition) of the South-east Facade

Figure 6.8 refers to the input file of the south-east façade's PV modules. As seen in the figure, 2 units of SOLARMAX 6000C inverter and Heckert Solar - HS-PXL 210 polycrystalline PV modules are selected. Besides, 4 strings of PV modules connected in parallel, each of them composed by 13 series modules are considered. The photovoltaic panel area is 76m² and the array power is 10.9kWp for the south-east facade.


Simulation input

Project	ATC-Torino-SE-210	PV modules	HS-PXL 210	Inverter:	SOLARMAX 6000C
Site	Torino	Nominal Power	10.9 kWp	Inv. unit power	4.6 kW
System type	Grid-Connected	MPP Voltage	322 V	Inv. Number	2
		MPP Current	31.1 A		

Simulation from 01/01 to 31/12 (Generic meteo data)

Main results

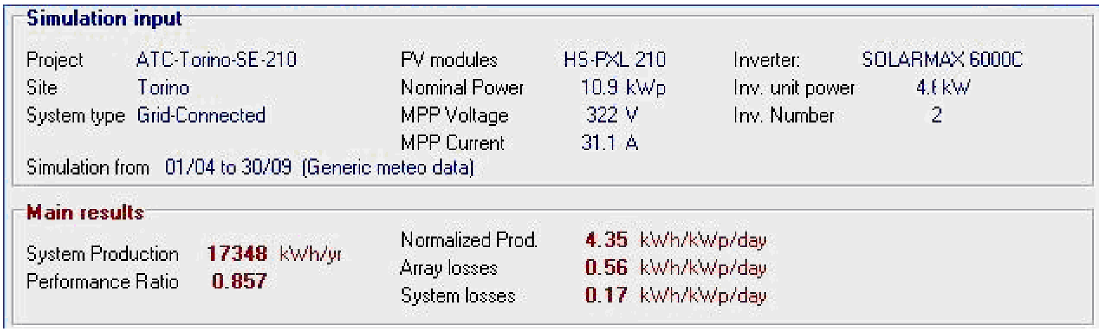
System Production	12409 kWh/yr	Normalized Prod.	3.11 kWh/kWp/day
Performance Ratio	0.850	Array losses	0.42 kWh/kWp/day
		System losses	0.12 kWh/kWp/day

Figure 6.9: Output File (Annual Electricity Production) of South-east Facade

As seen in Figure 6.9, the electrical production of the PV array is **12.409kWh/yr**.

6.1.3.1. Summer production of the PV panels on the South-east façade

Summer period starts on April 1st and finishes on September 30th.


Simulation input

Project	ATC-Torino-SE-210	PV modules	HS-PXL 210	Inverter:	SOLARMAX 6000C
Site	Torino	Nominal Power	10.9 kWp	Inv. unit power	4.6 kW
System type	Grid-Connected	MPP Voltage	322 V	Inv. Number	2
		MPP Current	31.1 A		

Simulation from 01/04 to 30/09 (Generic meteo data)

Main results

System Production	17348 kWh/yr	Normalized Prod.	4.35 kWh/kWp/day
Performance Ratio	0.857	Array losses	0.56 kWh/kWp/day
		System losses	0.17 kWh/kWp/day

Figure 6.10: Annual Electricity Production of the South-east Facade in Summer Conditions

In Figure 6.10, the electrical annual production of the PV panels is 17.348 kWh/yr for the summer season. It must not be forgotten the programme calculates the production as annual and considering that summer lasts 6 months (from April 1st to September 30th), in order to obtain the summer production of the PV panels, the annual production value is divided into 2.

17.348 kWh/yr / 2 = **<u>8.674 kWh (for 6 months)</u>**

6.1.3.2. Winter production of the PV panels on the South-east façade

As seen in paragraph 6.1.1.2, the winter period is divided in 2 parts because of the current weather file of Turin in PVSYST. The first part goes from January 1st to March 31st, and the second part includes the period from October 1st to December 31st.

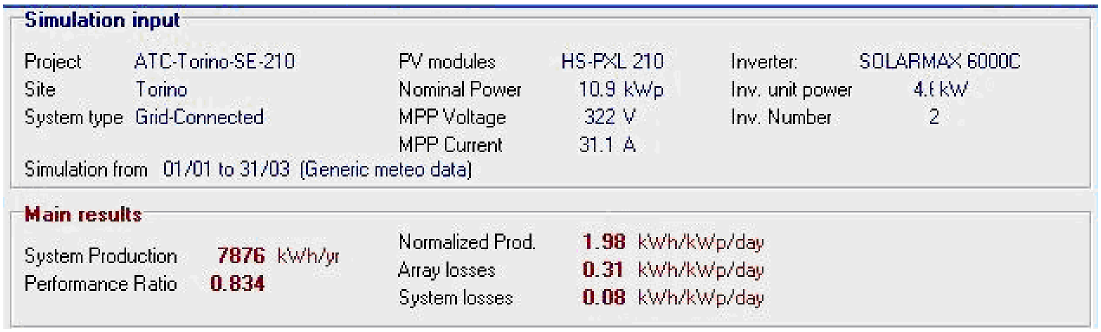


Figure 6.11: Annual Electricity Production of the South-west Facade in the 1st part of Winter Conditions

In Figure 6.11, the annual electrical production of the PV array is 7.876 kWh/yr. As the first part of winter lasts 3 months (January 1st –March 31st), in order to calculate the production of the PV panels for the first part of the winter season, the annual production value is divided by 4.

7.876 kWh/yr / 4 = **<u>1.969 kWh ((for 3 months)</u>**

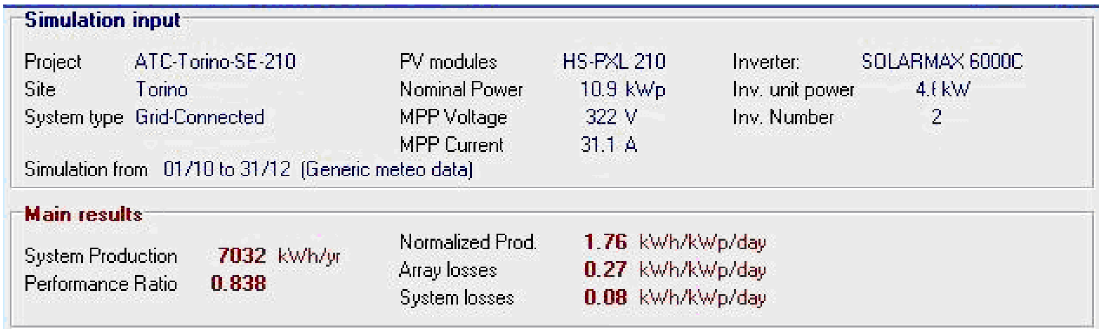


Figure 6.12. Annual Electricity Production of the South-west Facade in the 2nd part of Winter Conditions

In Figure 6.12, the annual production value is 7.032 kWh/yr. As the second part of winter lasts 3 months (October 1st –December 31st), the production of the PV panels during the second part of winter is calculated below.

7.032 / 4 = **<u>1.758 kWh (for 3 months)</u>**

The total electrical production of the South-east PV panels during winter is calculated below.

1.969kWh + 1.758kWh **= <u>3.727kWh (for 6 months)</u>**

The annual electricity production of the PV panels on the south-east façade is summarized in Table 6.2.

Table 6.2: Annual Electricity Production of the PV Panels on the South-east Façade

ATC BUILDING	SUMMER CONDITIONS	WINTER CONDITIONS	TOTAL
SOUTHEAST FACADE ELECTRICITY PRODUCTION (kWh/yr)	**8.674**	**3.727**	**12.409**

(Due to PVSYST results, there is a difference, -8kWh/yr, between the annual production and the total of the seasonal production, and it has been ignored.)

6.1.4 Evaluation of the PV electricity production

When the electricity production is categorized by season and orientation, Table 6.3. is obtained.

Table 6.3: Annual Electricity Production of PV System

ATC BUILDING'S PHOTOVOLTAICS	SUMMER CONDITION	WINTER CONDITION	**TOTAL**
SOUTHWEST FAÇADE (kWh/yr)	30.360	13.043	**43.431**
SOUTHEAST FAÇADE (kWh/yr)	8.674	3.727	**12.409**
TOTAL(kWh/yr)	**39.034**	**16.770**	**55.840**

As seen in the table 6.3, the total electricity production of ATC building's PV system is 55.840kWh in a year. South-west façade produces 44.431kWh while South-east façade produces 12.409kWh but, for these results, it must be taken into consideration the different size of the PV systems. Additionally; the electricity production during summer is bigger than during winter: while the electricity production during summer is 39.034kWh/yr, the electricity production during winter is 16.770kWh/yr.

The specific annual electricity production of ATC building's photovoltaic system has been calculated by referring the annual production to the total building area, and it is shown below.

Table 6.4: Specific Annual PV Electricity Production

ANNUAL PRODUCTION	55.840 kWh/yr
TOTAL BUILDING AREA	7.531 m²
SPECIFIC ANNUAL PV ELECTRICITY PRODUCTION	**7,41 kWh/m²**

This value will be used in the next simulations, to compare the energy loads of the building and the electricity production of ATC photovoltaic system.

6.2 Cooling and Heating Loads of ATC Building

As specified in the previous chapter, the installation of photovoltaic modules as shading devices not only produces the electricity, but also affects the cooling, heating and lighting loads of ATC building.

Due to the shading effect of the panels, the cooling loads decrease during summer, while the heating loads during winter and the lighting loads increase.

In order to evaluate the utility ratio of the photovoltaic panels, the electricity production of the PV system has been calculated in section 6.1.

In this section, the shading effect of PV panels on the cooling and heating demand will be calculated by using “DesignBuilder” version 1.5.

DesignBuilder is the most comprehensive user interface for “EnergyPlus”, that will be used in the next chapter for the lighting demand.

6.2.1 Simulating with DesignBuilder

DesignBuilder is built on the EnergyPlus data requirements. EnergyPlus is the U.S. DOE building energy simulation program for modelling building heating, cooling, lighting, ventilating, and other energy flows.

EnergyPlus is a stand-alone simulation program without a 'user friendly' graphical interface – that DesignBuilder has.

DesignBuilder has been specifically developed around EnergyPlus and it includes most of the EnergyPlus libraries. Databases of building materials, constructions, window panes, window gas, glazing units and blinds are provided.

HVAC is modelled using the Compact HVAC descriptions now offered by EnergyPlus. These allow a number of predefined HVAC system types to be defined parametrically without the need for complex system layouts. These compact descriptions are automatically expanded behind-the-scenes into full HVAC simulation data sets prior to simulation. [61]

DesignBuilder program has a user-friendly interface and requires the definition of the most important parameters of the building. Firstly; the building is drawn like the other architectural designing programs and the location is chosen. Then, zones, architectural elements, materials, working schedules etc. are defined. After these sections, the program is ready for the simulation that calculates the heating, cooling loads for variable time alternatives, from the design day to whole year. It is a dynamic simulation model and makes calculations 4 times per hour.

The simulated area of the case study building is 7.531m², and includes the 10 upper storeys of ATC building. The photovoltaic panels are installed on 3 floors on the south-east façade and on 7 floors on the south-west facade.

Moreover, the cooling and heating loads of ATC building have been performed by considering two conditions:

- ATC building without PV panels (before the renovation)

- ATC building with PV panels (after the renovation)

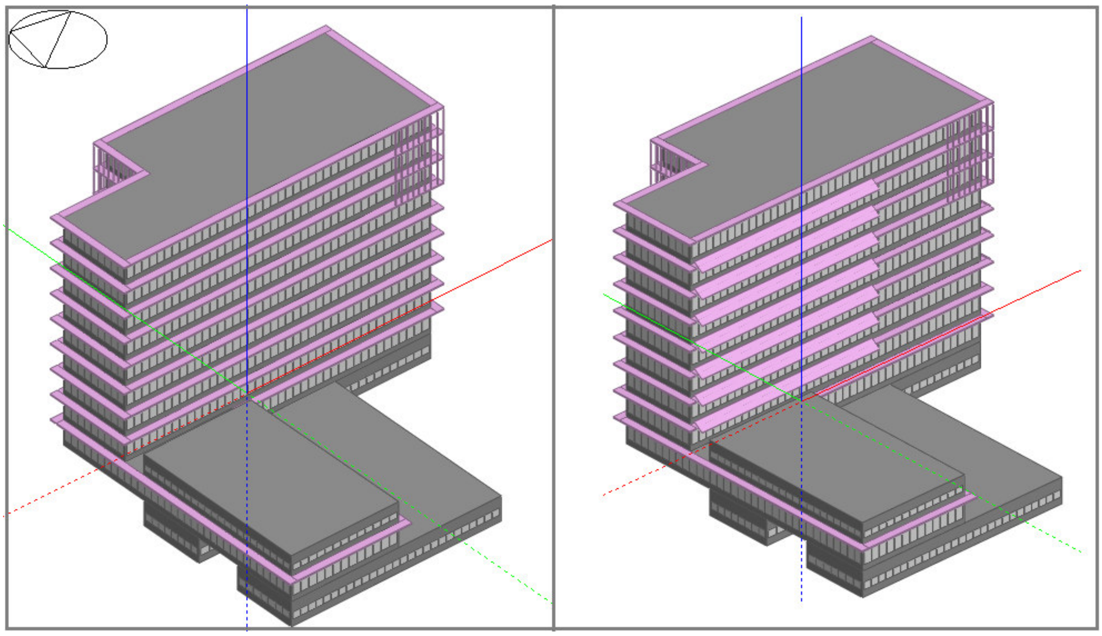


Figure 6.13: ATC Building renderings for without PV and with PV

Figure 6.13 shows ATC building without PV on the left and with PV (after the renovation) on the right.

6.2.2 Input files of DesignBuilder

The input file includes lighting, activity, construction, openings and HVAC system; they are explained in the next pages. Input files of ATC Building are the same with PV and without PV; the unique difference between these two conditions is the PV panels on the south-west and south-east facades. Figure 6.14 shows the general view of DesignBuilder program for ATC building.

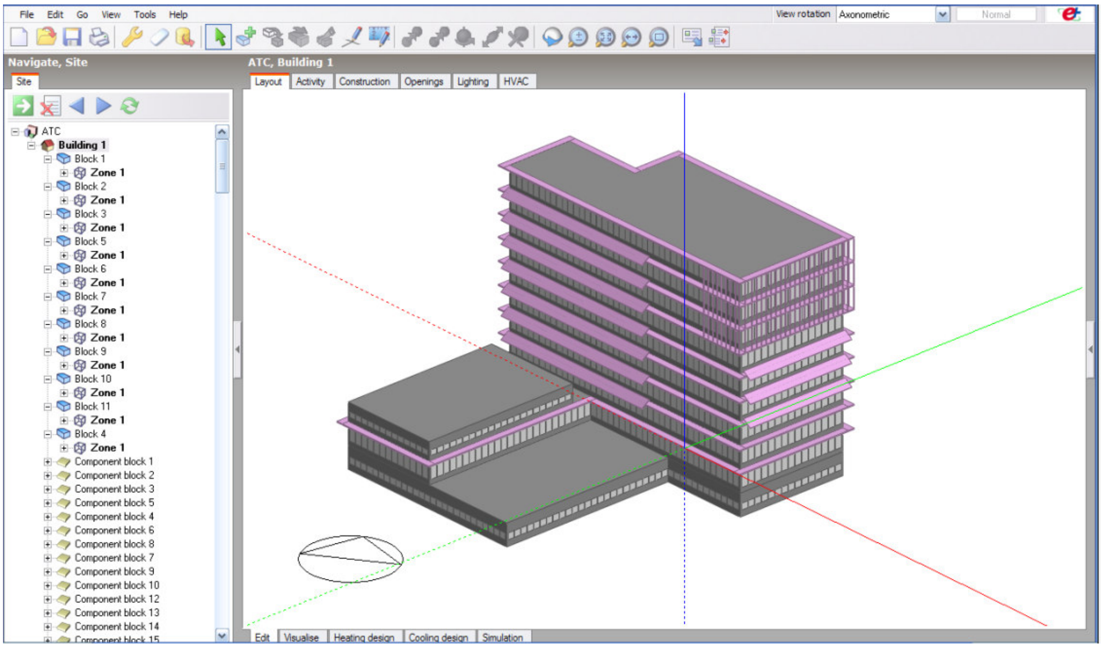


Figure 6.14: General View of DesignBuilder Program for ATC Building

6.2.2.1. Lighting

Lighting specific load for ATC building is 25W/m² and it can be seen in Figure 6.15. It is calculated by using data of Table A.5.

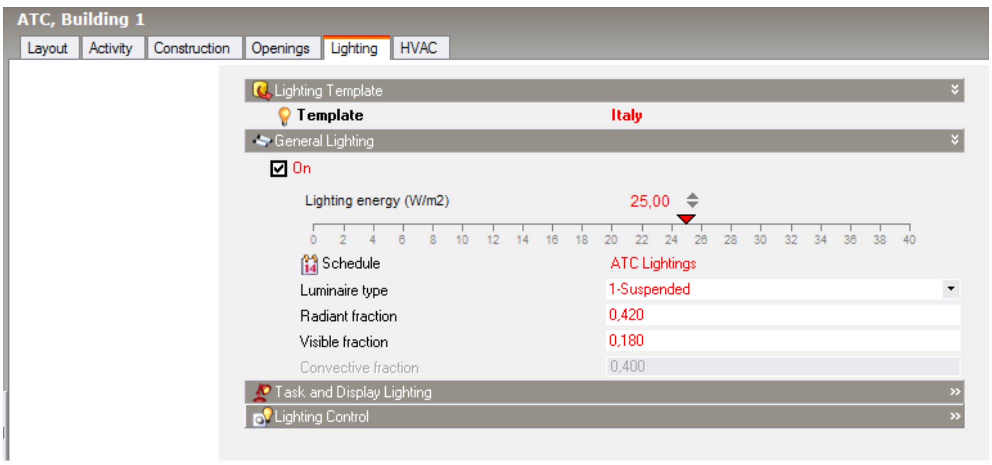


Figure 6.15: Lighting Values for ATC Building

6.2.2.2. Activity

Activity tab includes the occupancy, metabolic, holidays, environmental control (that is heating, cooling and ventilation setpoint temperatures), electricity consumption of computers and office equipments, which must be specified for simulation. The usage type of the building is defined as "office" for ATC Building.

The density of ATC building is 0,05, that is 30 people work in each floor. Working hours is given in Table A.1 as occupancy schedule. The heating setpoint temperature is 20°C while the cooling setpoint temperature is 26°C. Figure 6.16 shows activity values of DesignBuilder programme for ATC building.

Table A.1, Table A.2, Table A.3 and Table A.4 are used as schedules. The number and electricity consumption of computers and office equipments can be seen in Table A.5.

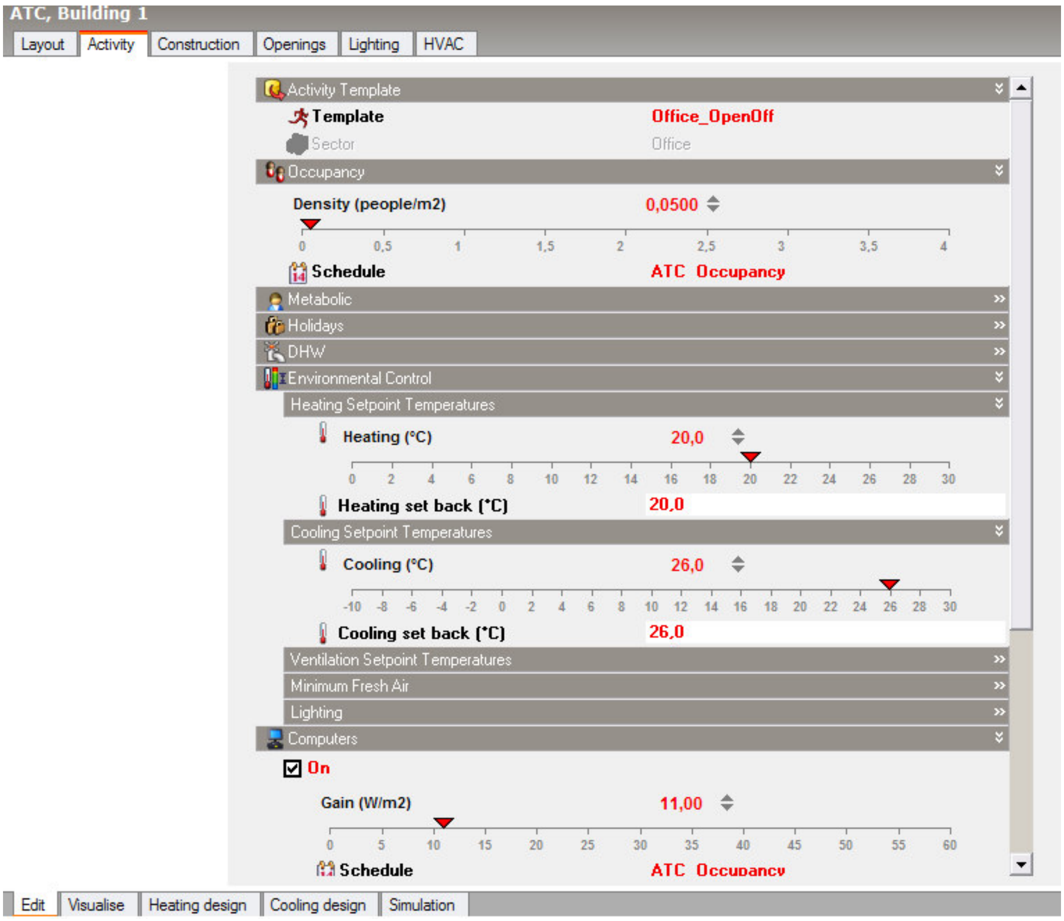


Figure 6.16: Activity Values for ATC Building

6.2.2.3. Openings

In this tab, properties of windows, doors and roof windows are specified. ATC Building envelope is formed mostly (66% of the surface) by glass. However, this percentage differs among the floors; for example, the window to wall percentage is 26% in the ground floor while it is 66% for the type-floors that are seven. Figure 6.17 shows a snapshot of DesignBuilder opening tab for ATC building.

The glass type is double glass and its layers are:

- 4 mm clear glass
- 12 mm argon gas
- 4 mm clear glass

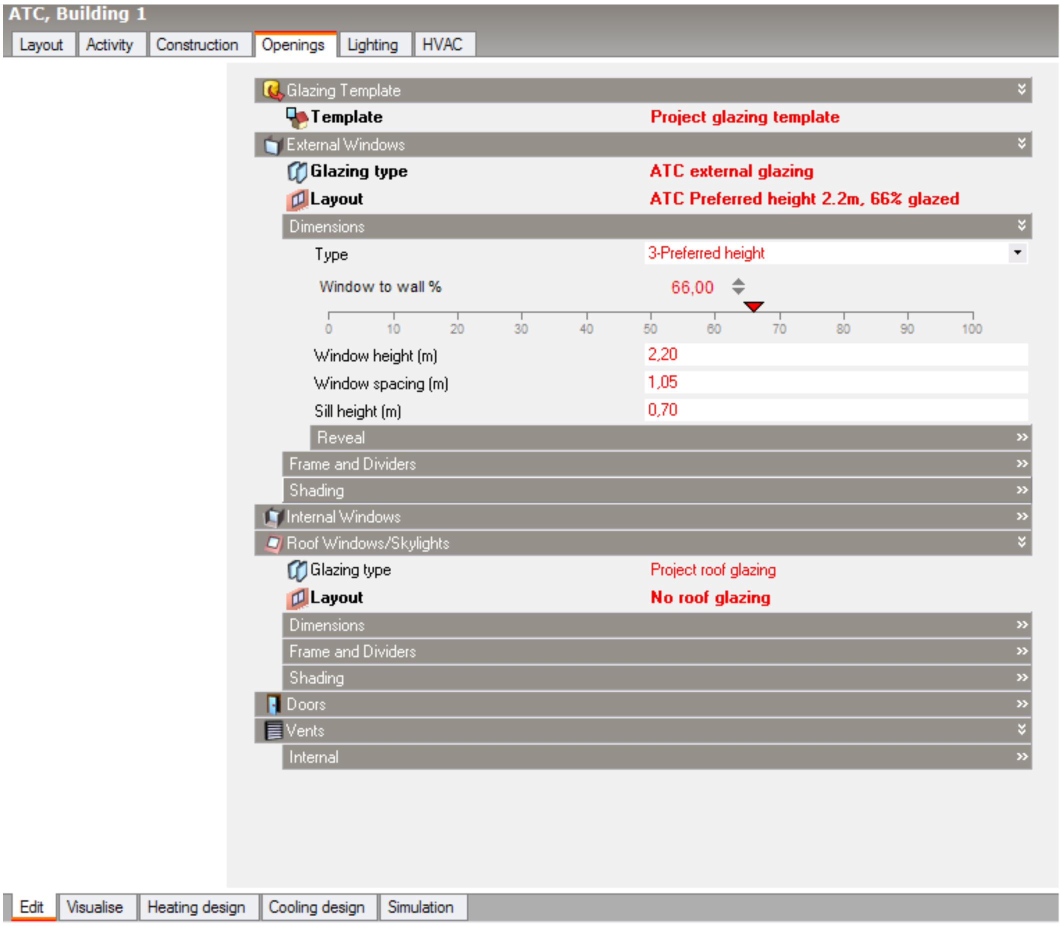


Figure 6.17: Opening Values for ATC Building

6.2.2.4. HVAC system

HVAC System tab is divided in the following sections: heating system, cooling system, mechanical and natural ventilation. ATC Building is heated by using natural gas and the heating system CoP (Coefficient of Performance) value is 0,890; the heating system schedule can be seen in Table A.3. The building is cooled by using electricity and the cooling system CoP is 4,4 and the schedule of cooling system has been given in Table A.2. Besides the building doesn't have any mechanical ventilation system, it is ventilated only by natural ventilation and the air change is 2 for an hour during the working hours. Figure 6.18 shows a snapshot of HVAC tab.

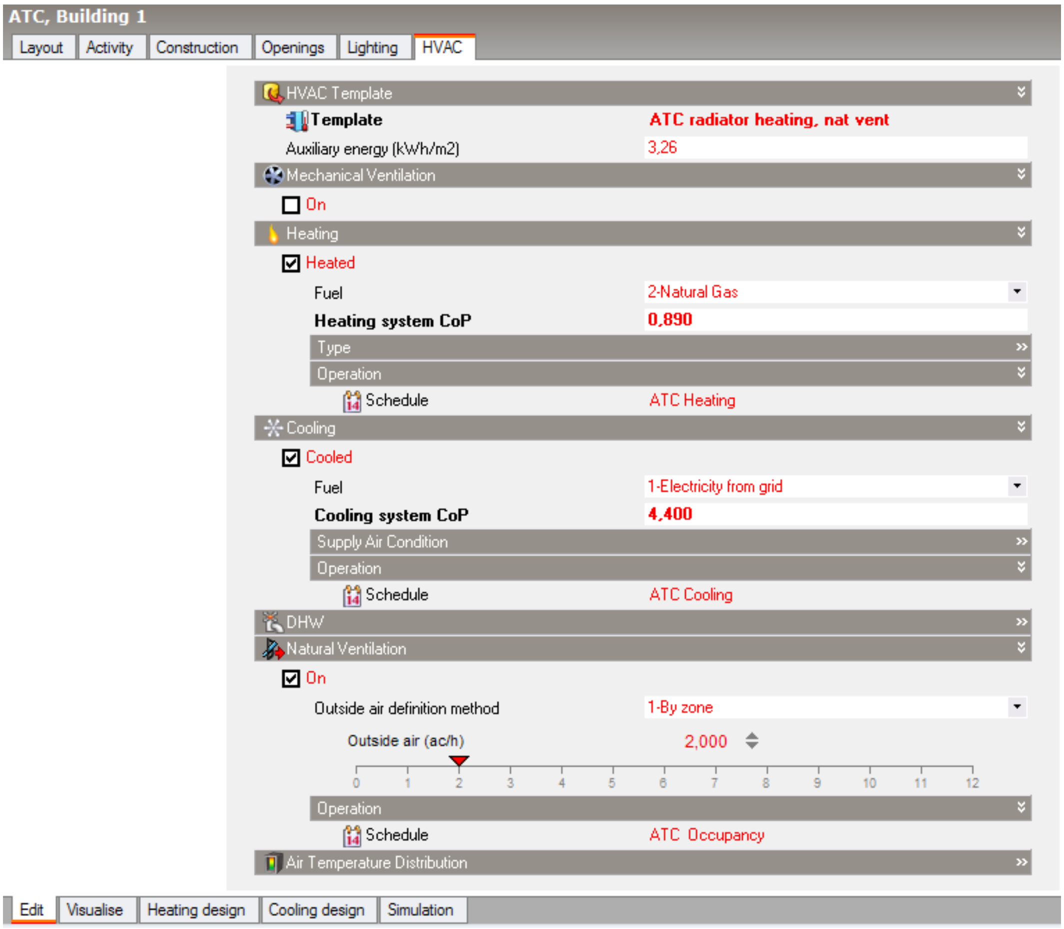


Figure 6.18: HVAC System Values for ATC Building

6.2.3 Output files of DesignBuilder

With DesignBuilder it is possible to obtain the results of site data, comfort values, internal gains, fabric and ventilation data, fuel breakdown(analysis), fuel totals, CO_2 emission and system loads for variable time periods (from one day to a year). However, only the annual fuel analysis is of interest in this study, in order to calculate the shading effect of the PV panels to the annual cooling and heating loads. Monthly simulation outputs without PV are given in Appendix B, monthly simulation outputs with PV (as shading devices, without electricity production) conditions are given in Appendix C.

Firstly, the results for the condition without PV panels are given, then they are given for the conditions with PV, and a comparison between these two conditions is explained.

The fuel analysis includes electrical equipmant consumption (room electricity), lighting, electricity consumption of the chiller and gas consumption for heat generation. In this part, the PV effect on the heat generation and chiller demands are evaluated for the two following conditions:

- ATC building without PV panels
- ATC building with PV panels

Figure 6.19 shows the annual fuel analysis of ATC building without PV. Figure 6.20 shows the annual fuel analysis of ATC building with PV panels. Table 6.5 shows the comparison of the annual fuel analysis of ATC building, with and without PV conditions. As expected while the heating loads increase, the cooling loads decrease. Unfortunately, DesignBuilder does not calculate detailed lighting according to the day light this is why “lighting” values are same without and with conditions.

Table 6.5: Comparison of the annual fuel analysis for without and with PV

ATC BUILDING ANNUAL FUEL ANALYSIS	WITHOUT PV CONDITION	WITH PV CONDITION
Electrical Equipment Consumption (kWh/m²)	37,58	37,58
Lighting (kWh/m²)	23,25	23,25
Heat generation (gas) (kWh/m²)	20,60	20,73
Chiller (electricity) (kWh/m²)	4,69	4,62

The annual electricity consumption results from the sum of all values, heat generation excluded.

- Annual electricity consumption without PV: 65,52 kWh/m²

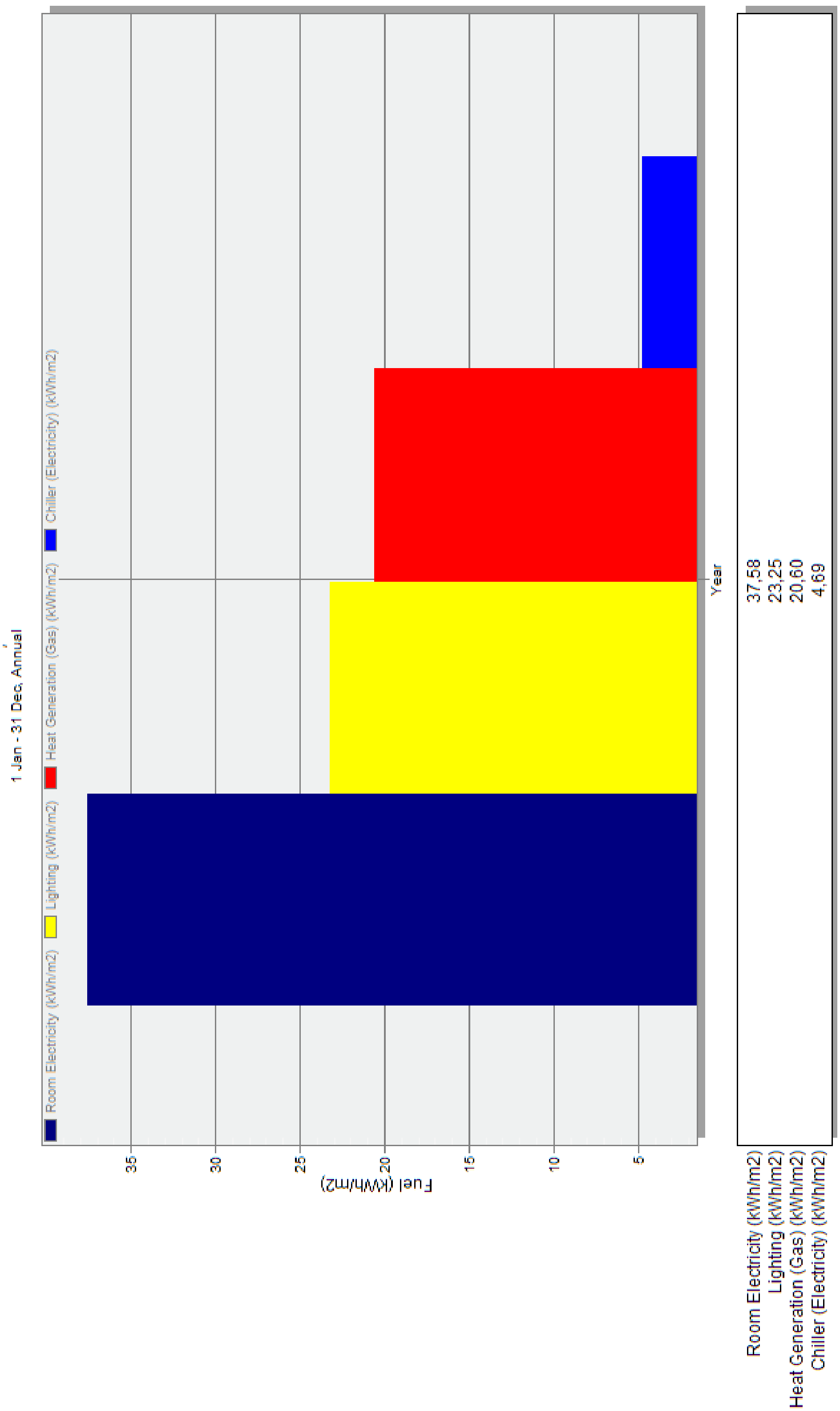


Figure 6.19: Annual Fuel Analysis for ATC Building without PV

- Annual electricity consumption with PV : 65,45 kWh/m²

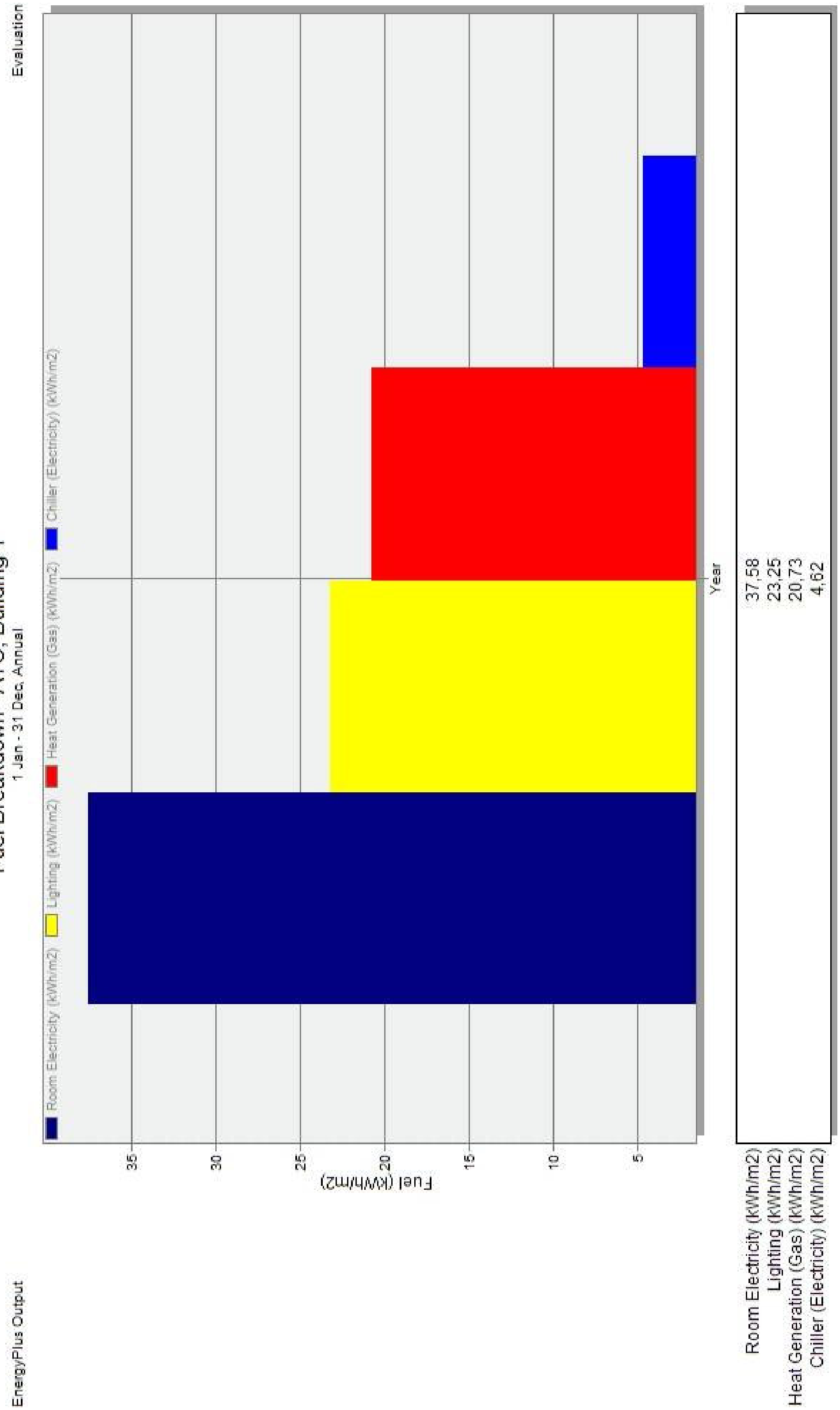


Figure 6.20: Annual Fuel Analysis for ATC Building with PV

6.2.4 Change ratios of the cooling and heating loads

Before renovation, ATC building already had shading devices at every floor for 1m all around the façade. Therefore, PV panels (installed during the renovation of the building) are the second shading devices on the South-west and South-east facades that is why difference is less without PV and with PV conditions. The original structural shading devices already contribute to reduce the cooling loads and also to increase the heating loads. The PV shading effect on the cooling and heating loads can be seen in Table 6.6. The change ratio of lighting loads will be calculated with EnergyPlus simulation tool, because DesignBuilder does not make detailed lighting calculation according to the day light.

Appendix D shows internal gains without PV and with PV conditions and particularly, it focuses on solar gains from exterior windows for summer and winter design days. It aims at explaining that why the difference is less without PV and with PV conditions as annual results. PV panels affect solar gains -1,52% both summer and winter design days, but when the results are analysed together as annual, the seasons are balanced themselves and the change ratios of cooling and heating (annual) has become less than change ratios of design days. Another reason of small change ratios is that PV panels are installed on south-west and south-east façade of building because of the orientation of the case-study building. However, the horizontal shading devices are not enough to get well solar protection on south-west and south-east orientation.

6.3 Lighting Loads of ATC Building

As specified in the previous chapter, the installation of photovoltaic modules as shading devices not only produces the electricity, but also affects the cooling, heating and lighting loads of ATC building. While the shading effect of the panels decreases the cooling loads, it increases the heating and lighting loads. The electricity production of the PV system and the change ratios of the cooling and heating loads have been calculated in sections 6.1 and 6.2.

In this section, the shading effect of PV panels on the lighting demand will be examined by using "EnergyPlus" simulation tool, version 2.2.

6.3.1 Simulating with Energyplus

EnergyPlus models heating, cooling, lighting, ventilating, and other energy flows as well as water in buildings. While originally based on the most popular features and capabilities of BLAST and DOE-2, EnergyPlus includes many innovative simulation capabilities such as time steps of less than an hour, modular systems and plant integrated with heat balance-based zone simulation, multizone air flow, thermal comfort, water use, natural ventilation, and photovoltaic systems. [62]

EnergyPlus is a stand-alone simulation program without a 'user friendly' graphical interface. EnergyPlus reads input and writes output as text files.

Unfortunately, EnergyPlus hasn't got a user-friendly interface. DesignBuilder is the most comprehensive user interface for EnergyPlus. In this section, the input file of EnergyPlus called "IDF file" is exported from DesignBuilder to EnergyPlus. After this exportation, two reference points, are chosen in the darkest area of the plan, are defined for each floor in the "Daylighting" component of EnergyPlus. These two reference points in the zone at which horizontal daylighting illuminance are calculated based on input data. It is assumed that the photocells that control the overhead electric lighting respond to the light levels at the specified reference points. Then, some modifications have been done about input and output properties in IDF file. After it, the IDF file is ready for the simulation and shown in Figure 6.21.

Also for calculation of the lighting loads, the simulations consider two scenarios, as for the calculation of the cooling and heating loads. These are:

- ATC building without PV panels

- ATC building with PV panels

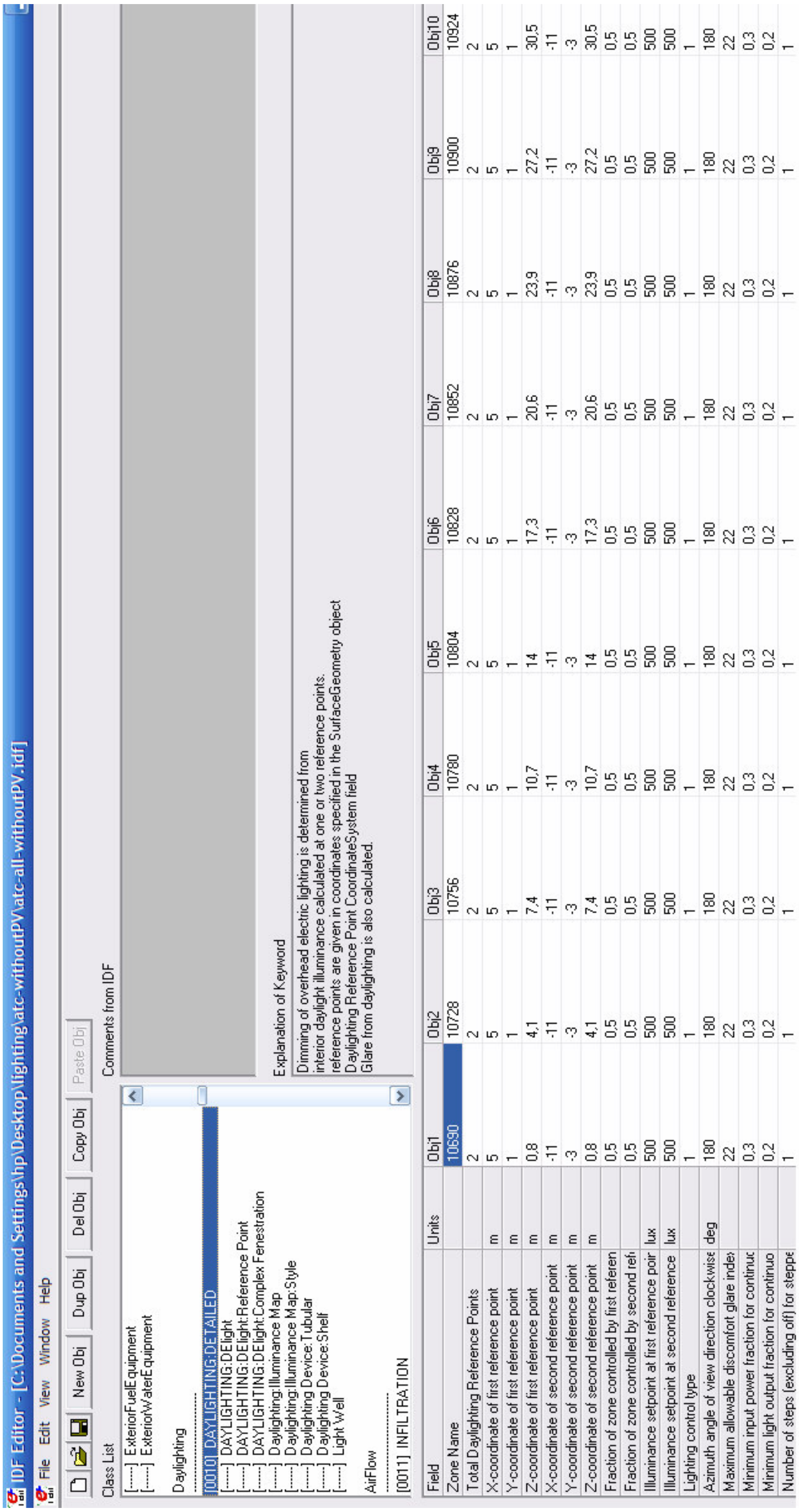


Figure 6.21: EnergyPlus Input File for Daylighting

6.3.2 Results on lighting without and with PV

The following figures have been taken from the "Annual Building Utility Performance Summary", which is an output of EnergyPlus.

Utility Use Per Total Floor Area

	Electricity Intensity (kWh/m2)
Lighting	10.96
HVAC	0.00
Other	37.45
Total	48.41

Figure 6.22: Electricity Intensity without PV

As seen in Figure 6.22, the electricity consumption due to lighting is 10,96 kWh/m². This value refers to ATC Building without PV. Figure 6.23 has been obtained considering the PV panels installed on the building.

Utility Use Per Total Floor Area

	Electricity Intensity (kWh/m2)
Lighting	11.10
HVAC	0.00
Other	37.45
Total	48.55

Figure 6.23: Electricity Intensity with PV

As seen in Figure 6.23, lighting intensity has increased to 11,10 kWh/m² as expected. The shading effect of the PV panels has increased the lighting loads of +1,27%.

6.4 Conclusion

When the results of all simulations (electricity production of PV panels, change ratios of cooling, heating and lighting loads refer to part 6.1, part 6.2, part 6.3) are considered together, the utility ratio of the Photovoltaic System of ATC building can be calculated, and the summary of all simulations is shown in Table 6.6 and Table 6.7.

Table 6.6: Calculation of the Shading Effect to Cooling-Heating and Lighting Loads

ATC BUILDING	WITHOUT PV CONDITION	WITH PV CONDITION	CHANGE RATIO
COOLING LOADS (kWh/m²)	4,69	4,62	**- 1,49%**
HEATING LOADS (kWh/m²)	20,60	20,73	**+ 0,63%**
LIGHTING LOADS (kWh/m²)	10,96	11,10	**+ 1,27%**

Table 6.6 shows the cooling, heating and lighting loads without and with PV and also the change ratio of these values because of the shading affect of the PV panels. As seen in the table cooling loads reduce from 4,69 kWh/m² to 4,62 kWh/m², so the change ratio is -1,49%. Heating loads increase from 20,60 kWh/m² to 20,73 kWh/m², with a change ratio of +0,63%. Finally, lighting loads increase from 10,96 kWh/m² to 11,10 kWh/m² with a change ratio of +1,27%.

Table 6.7: Calculation of Actual Utility Ratio of PV Panels

ATC BUILDING	WITHOUT PV CONDITION	WITH PV CONDITION	CHANGE RATIO
ANNUAL ELECTRICITY CONSUMPTION (kWh/m²)	65,52	65,45	
PV ELECTRICITY PRODUCTION (kWh/m²)	0	7,41	
TOTAL CONSUMPTION (kWh/m²)	65,52	58,04	**- 11,41%**
EFFECT RATIO OF THE PV PANELS	-	-	**+ 1,27%**
UTILITY RATIO OF THE PV PANELS : - 10,14%			

Total electricity consumption decreases 11,41% due to electricity production of PV panels and and this percentage includes the PV effect on the cooling and heating loads (DesignBuilder results). Therefore, when also the shading effect to lighting loads is added to this value, utility ratio of the PV can be calculated with all the contributions (electricity production and shading effect to the cooling, heating and lighting loads.

The utility ratio of the PV panels is described the ratio of the electricity produced by PV panels to annual electricity consumption of the case-study building. The utility ratio of PV panels is -10,14%. In other words, the electricity produced by photovoltaic panels meets 10,14% of the annual electricity requirement of ATC building. It should be noticed that the PV arrays are installed only on 3 floors on the southeast façade and on 7 floors on the southwest facade, while ATC building consists of 10 storeys, and the first two floors are larger than the upper ten storeys. Another reason is that PV panels is not most properly located on the building considering orientation and tilt angle.

7. PERFORMANCE EVALUATION OF THE CASE STUDY BUILDING FOR ISTANBUL CONDITIONS

Unfortunately, building integrated photovoltaic systems are not common in Turkey, although researches on photovoltaic technology are done in universities and private companies. When the importance of renewable energies will be recognized and supported by the Laws, the photovoltaic sector will grow and photovoltaic installations will spread.

In Chapter 7, ATC Building is simulated with the same strategy for Istanbul site, weather and solar radiation data, in order to evaluate the difference in the photovoltaic utility ratio for two different climates. The comparisons of air temperature, relative humidity and daily solar radiation on the horizontal for Turin and Istanbul are shown in Figure 7.1, Figure 7.2 and Figure 7.3.

This chapter mirrors chapter 6. Therefore, the simulations carried out for Istanbul conditions are:

- Electricity production of PV panels,
- Shading effect of PV panels on the cooling and heating loads,
- Shading effect of PV panels on the lighting loads.

The input files for the simulation programs are not given in this chapter because the input values are the same of Chapter 6 except the site data. Site data is here defined as Istanbul instead of Turin.

The results for Turin and Istanbul conditions will be compared and the difference in the PV utility ratios will be avaluated.

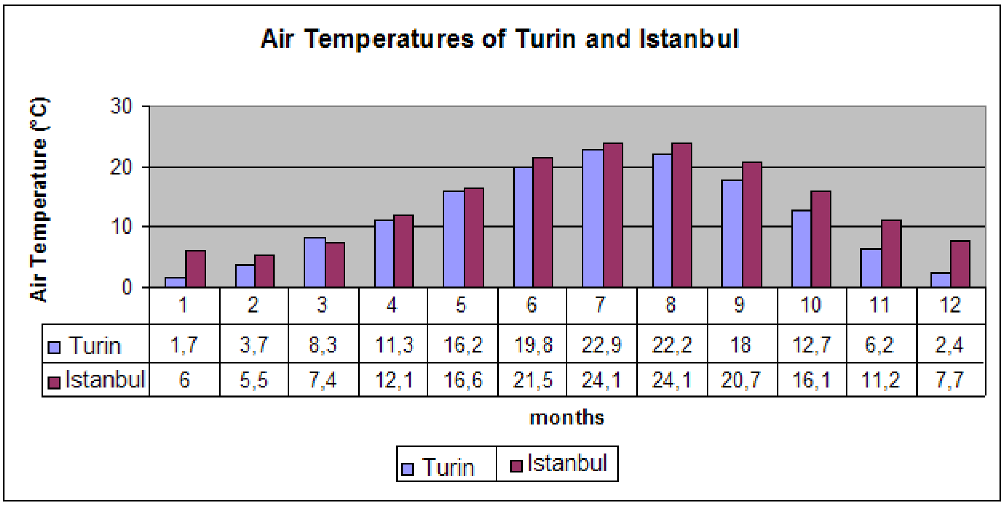


Figure 7.1. Air Temperature for Turin and Istanbul [51]

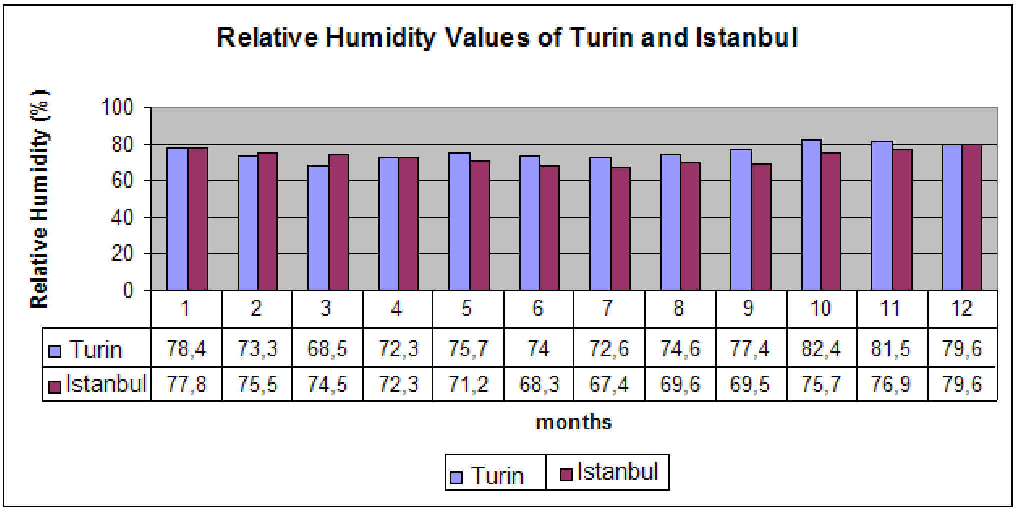


Figure 7.2: Relative Humidity (%) for Turin and Istanbul [51]

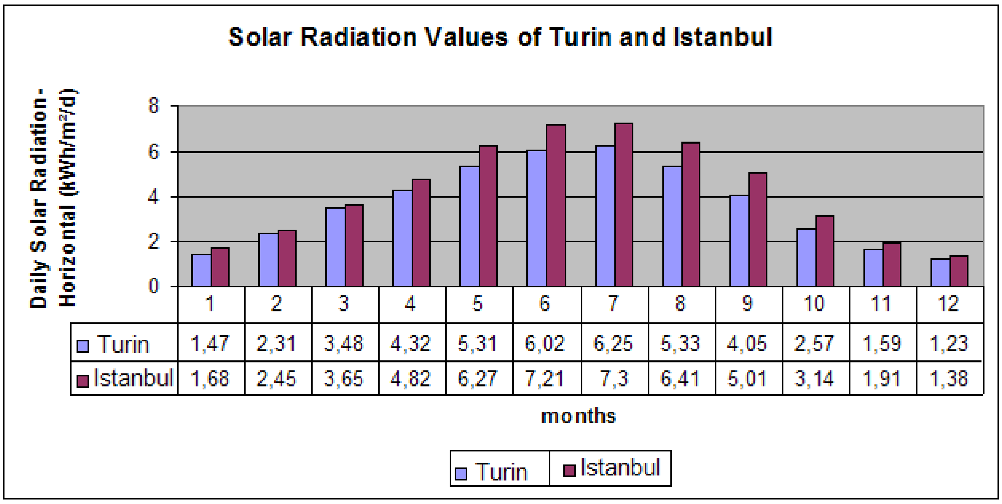


Figure 7.3: Daily Solar Radiation on the Horizontal for Turin and Istanbul [51]

7.1 Electricity Production of Photovoltaic Panels in Istanbul

The PVSYST program is used for electricity production of the building. The system is the same with previous chapter that consists of Heckert Solar PV modules with 210W peak power and SolarMax 6000C inverters and includes 182 modules managed by 7 inverters on south west façade and 52 modules manage by 2 inverters on south east façade.

7.1.1 Electrical production of PV panels on the South-west façade in Istanbul

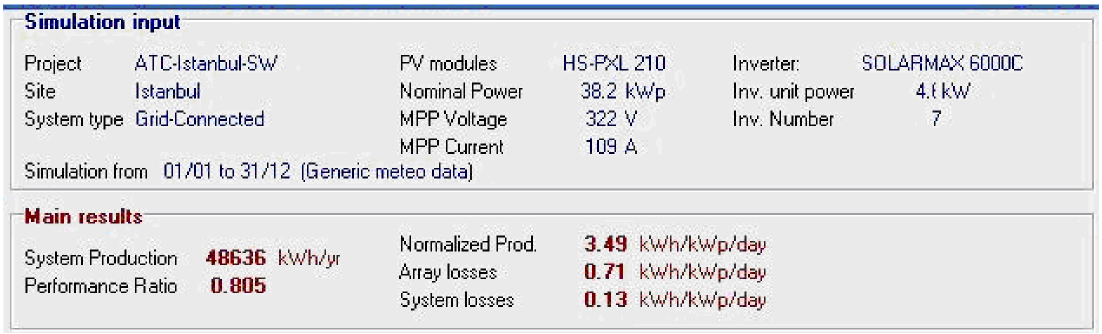


Figure 7.4: Annual Electricity Production of South-west Façade in Istanbul

Figure 7.4 shows the output file of PVSYST programme for the south-west façade on the top the project site can be seen as Istanbul. System production of modules is **48.636 kWh/yr**.

In order to understand of electricity production depends on the seasons, the system has been simulated categorized by summer and 2 winter seasons (because of the current weather file of Istanbul in PVSYST program) in the next part like Chapter 6.

7.1.1.1. Summer production of PV panels on the South-west façade

Summer period starts from April 1st and finishes on September 30th.

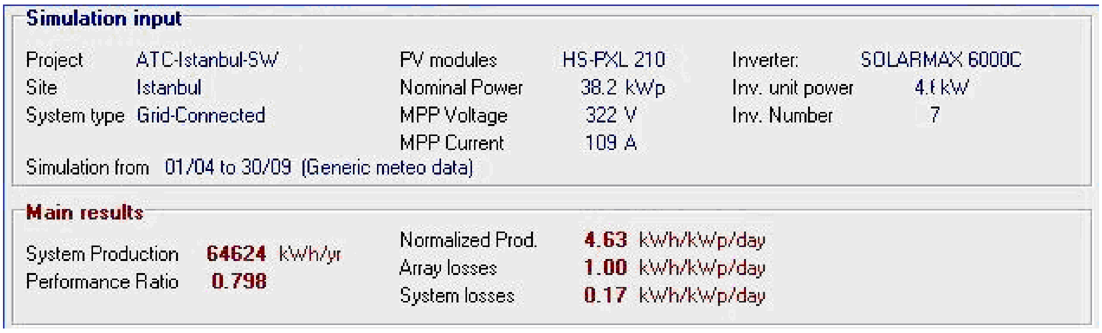


Figure 7.5: Annual Electricity Production of South-west Facade in Summer Period for Istanbul Condition

In Figure 7.5, the annual production value is 64.624kWh/yr for summer season. It must not be forgotten the programme calculates production as annual and considering summer term April 1st to September 30th as 6 months, in order to calculate the summer production of the PV panels the annual production value is divided into 2.

64.624 kWh/yr / 2 = **<u>32.312 kWh (for 6 months)</u>**

7.1.1.2. Winter production of PV panels on the South-west façade

Winter period is divided by 2 parts because of the current weather file of Istanbul in PVSYST program. The first part consists of the term between January 1st and March 31st and the second part includes the term from October 1st to December 31st.

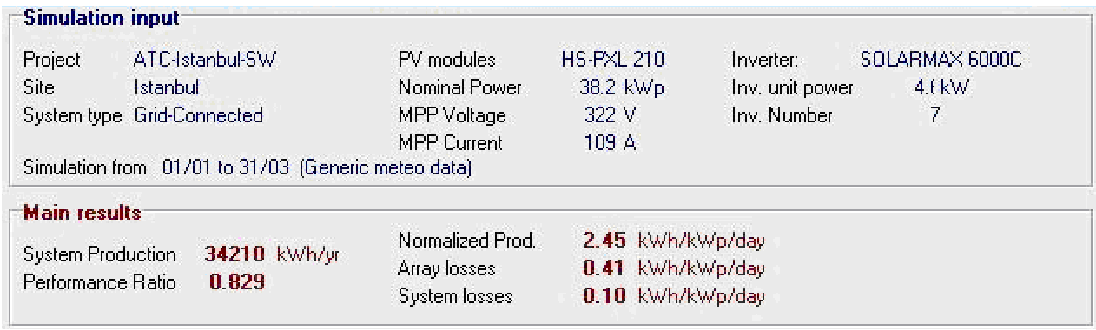


Figure 7.6: Annual Electricity Production of South-west facade in the 1st part of Winter Period for Istanbul Condition

In Figure 7.6, the annual electrical production of the PV array is 34.210 kWh/yr. As the first part of winter lasts 3 months (January 1st –March 31st), the production of the PV panels during the first part of winter is thereby calculated by dividing the annual production by 4.

34.210 kWh/yr / 4 = **8.552,5 kWh ((for 3 months)**

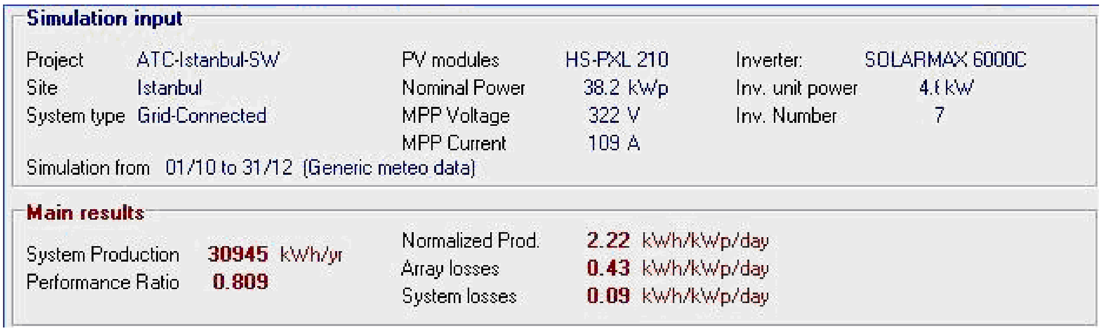


Figure 7.7: Annual Electricity Production of South-west facade in the 2nd part of Winter Period for Istanbul Condition

In Figure 7.7, the annual production value is 30.945 kWh/yr. Considering second part of winter (October 1st –December 31st) as another 3 months, the second part of winter production of the PV panels is calculated thereby dividing annual production by 4.

30.945 / 4 = **7.736 kWh (for 3 months)**

Total winter production: 8.552,5kWh+7.736kWh **=16.288,5 kWh (for 6 months)**

The annual electricity production of south-west façade's PV Panels is clarified in Table 7.1.

Table 7.1: Annual Electricity Production of the PV Panels on the South-west Façade in Istanbul

ATC BUILDING IN ISTANBUL	SUMMER CONDITIONS	WINTER CONDITIONS	TOTAL
SOUTHWEST FAÇADE ELECTRICITY PRODUCTION (kWh/yr)	**32.312**	**16.288,5**	**48.636**

(Due to PVSYST results, there is a difference, -35,5kWh/yr, between annual production and total of seasonal production and it has been ignored.)

7.1.2 Electrical production of PV panels on the South-east facade

Simulation input

Project	ATC-Istanbul-SE-210	PV modules	HS-PXL 210	Inverter:	SOLARMAX 6000C
Site	Istanbul	Nominal Power	10.9 kWp	Inv. unit power	4.6 kW
System type	Grid-Connected	MPP Voltage	322 V	Inv. Number	2
		MPP Current	31.1 A		

Simulation from 01/01 to 31/12 (Generic meteo data)

Main results

System Production	13924 kWh/yr	Normalized Prod.	3.49 kWh/kWp/day
Performance Ratio	0.807	Array losses	0.70 kWh/kWp/day
		System losses	0.13 kWh/kWp/day

Figure 7.8: Annual Electricity Production of South-east Facade in Summer Period in Istanbul

As seen in Figure 7.8, system's annual production of modules is **13.924kWh/yr**.

7.1.2.1. Summer production of the PV panels on the South-east facade

Summer period starts from April 1st and finishes September 30th.

Simulation input

Project	ATC-Istanbul-SE-210	PV modules	HS-PXL 210	Inverter:	SOLARMAX 6000C
Site	Istanbul	Nominal Power	10.9 kWp	Inv. unit power	4.6 kW
System type	Grid-Connected	MPP Voltage	322 V	Inv. Number	2
		MPP Current	31.1 A		

Simulation from 01/04 to 30/09 (Generic meteo data)

Main results

System Production	18511 kWh/yr	Normalized Prod.	4.64 kWh/kWp/day
Performance Ratio	0.800	Array losses	0.99 kWh/kWp/day
		System losses	0.17 kWh/kWp/day

Figure 7.9: Annual Electricity Production of South-east facade in Summer Period in Istanbul

In Figure 7.9, the annual production value is 18.511 kWh/yr for summer season. It must not be forgotten the programme calculates production as annual and considering summer term April 1st to September 30th as 6 months, in order to calculate the summer production of the PV panels the annual production value is divided by 2.

18.511 kWh/yr / 2 = **9.255,5 kWh (for 6 months)**

7.1.2.2. Winter production of the PV panels on the South-east facade

Like south west façade calculations, winter period is divided by 2 parts because of the current weather file of Istanbul in PVSYST program. The first part consists of the term between January 1st and March 31st and the second part includes the term from October 1st to December 31st.

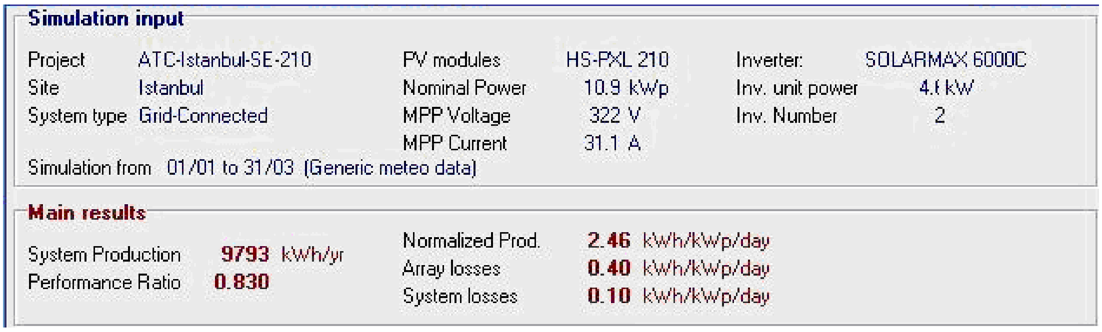


Figure 7.10: Annual Electricity Production of South-east Facade in the 1st part of Winter Period in Istanbul

In Figure 7.10, the annual production value is 9.793 kWh/yr. Considering first part of winter (January 1st –March 31st) as 3 months, in order to calculate the winter production of the PV panels the annual production value is divided by 4.

9.793 kWh/yr / 4 = **2.448 kWh ((for 3 months)**

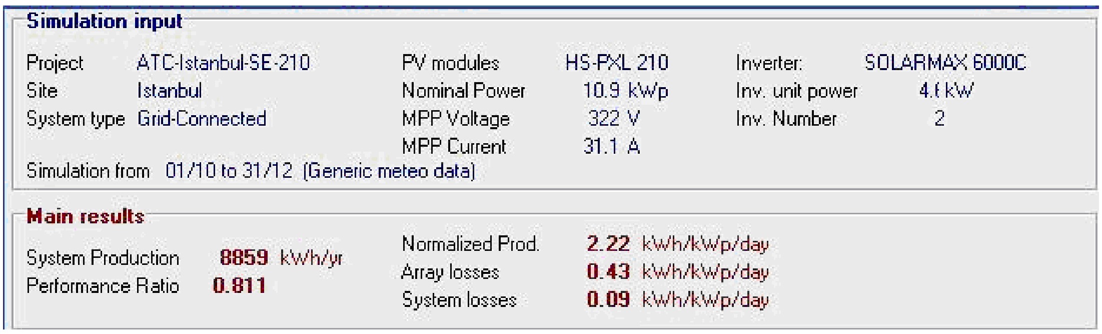


Figure 7.11: Annual Electricity Production of South-east Facade in the 2nd part of Winter Period in Istanbul

In Figure 7.11, the annual production value is 8.859 kWh/yr. Considering the second part of winter (October 1st –December 31st) as 3 months, the winter production of the PV panels is calculated below.

8.859 / 4 = **2.214 kWh (for 3 months)**

Total winter production : 2.448kWh + 2.214kWh **= 4.662 kWh (for 6 months)**

Annual electricity production of south west façade's PV Panels in Istanbul is clarified in Table 7.2.

Table 7.2: Annual Electricity Production of the PV Panels South-east Façade in Istanbul

ATC BUILDING IN ISTANBUL	SUMMER CONDITIONS	WINTER CONDITIONS	TOTAL
SOUTHEAST FACADE ELECTRICITY PRODUCTION (kWh/yr)	**9.255,5**	**4.662**	**13.924**

(Due to PVSYST results, there is a difference, -6,5kWh/yr-, between annual production and total of seasonal production and it has been ignored.)

7.1.3 Evaluation of the PV electricity production in Istanbul

Electricity production is categorized by orientation and comparison between Turin and Istanbul conditions are shown in Table 7.3.

Table 7.3: Annual Electricity Production of PV System in Turin and Istanbul

ATC BUILDING'S PHOTOVOLTAICS	PRODUCTION IN **TURIN**	PRODUCTION IN **ISTANBUL**	**CHANGE RATIO**
SOUTHWEST FAÇADE (kWh/yr)	43.431	48.636	11,98%
SOUTHEAST FAÇADE (kWh/yr)	12.409	13.924	12,12%
TOTAL(kWh/yr)	**55.840**	**62.560**	**12,03%**

While electricity production of PV panels in Turin is 55.840 kWh/yr, it is 62.560 kWh/yr in Istanbul condition. Therefore, electricity production of PV panels in Istanbul condition is 12,03% more than Turin condition. The reason is that Istanbul has more solar radiation.

Table 7.4: Calculation of Specific Annual PV Electricity Production

	IN TURIN	IN ISTANBUL
ANNUAL PRODUCTION	55.840kWh/yr	62.560kWh/yr
TOTAL BUILDING AREA	7.531 m²	7.531 m²
SPECIFIC ANNUAL PV ELECTRICITY PRODUCTION	**7,41 kWh/m²**	**8,30 kWh/m²**

Specific annual PV electricity production is7,41 kWh/m² for Turin and the same value is 8,30kWh/m² in Istanbul condition. Annual PV electricity power value is going to be used in the next simulation to compare energy need of building and electricity production of ATC building's photovoltaic system.

7.2 Cooling and Heating Loads in Istanbul

The DesignBuilder program is used for calculation of cooling and heating loads. The input file is the same with previous chapter except site data. The annual fuel analysis without and with PV are given in Figure 7.12 and in Figure 7.13.

- Annual electricity consumption without PV: 67,50 kWh/m²

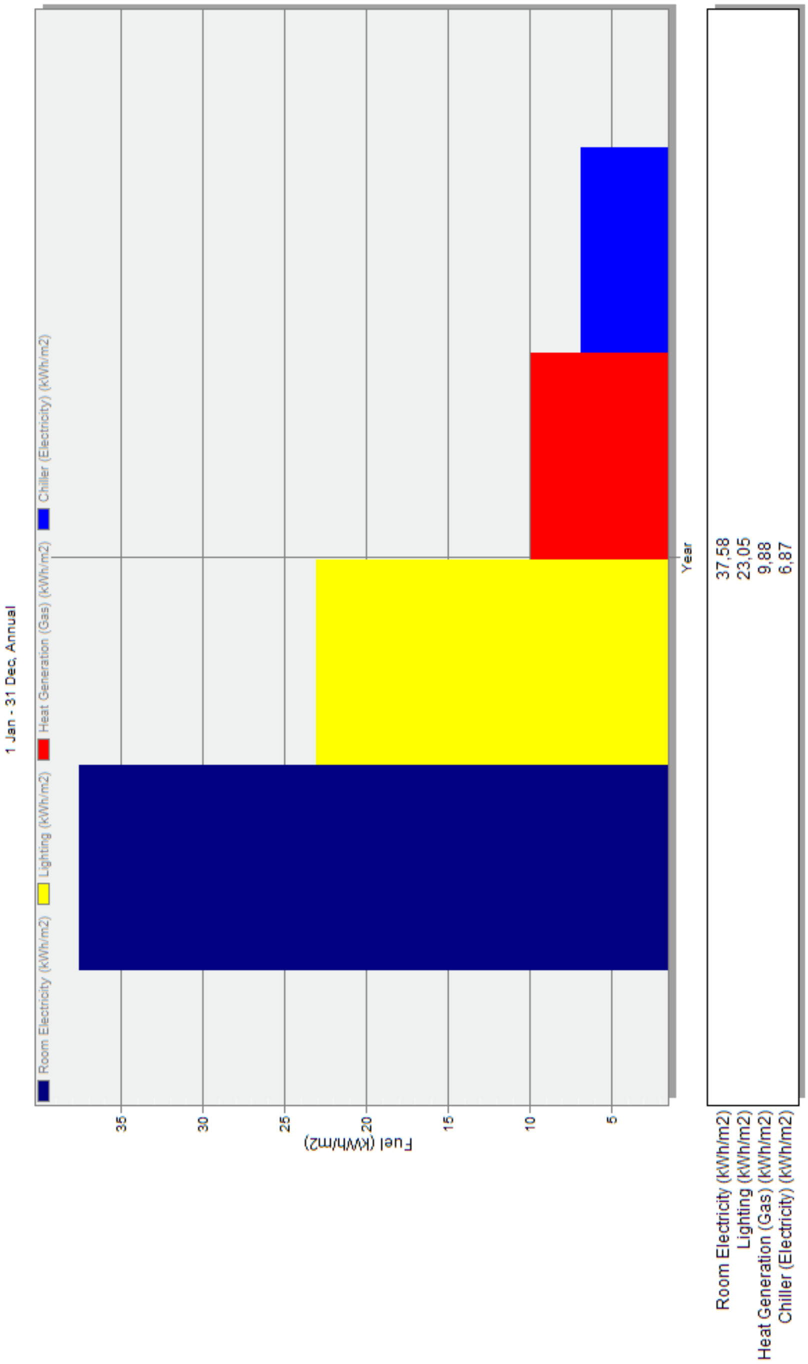


Figure 7.12: Annual Fuel Analysis in Istanbul-without PV

- Annual electricity consumption with PV: 67,41 kWh/m²

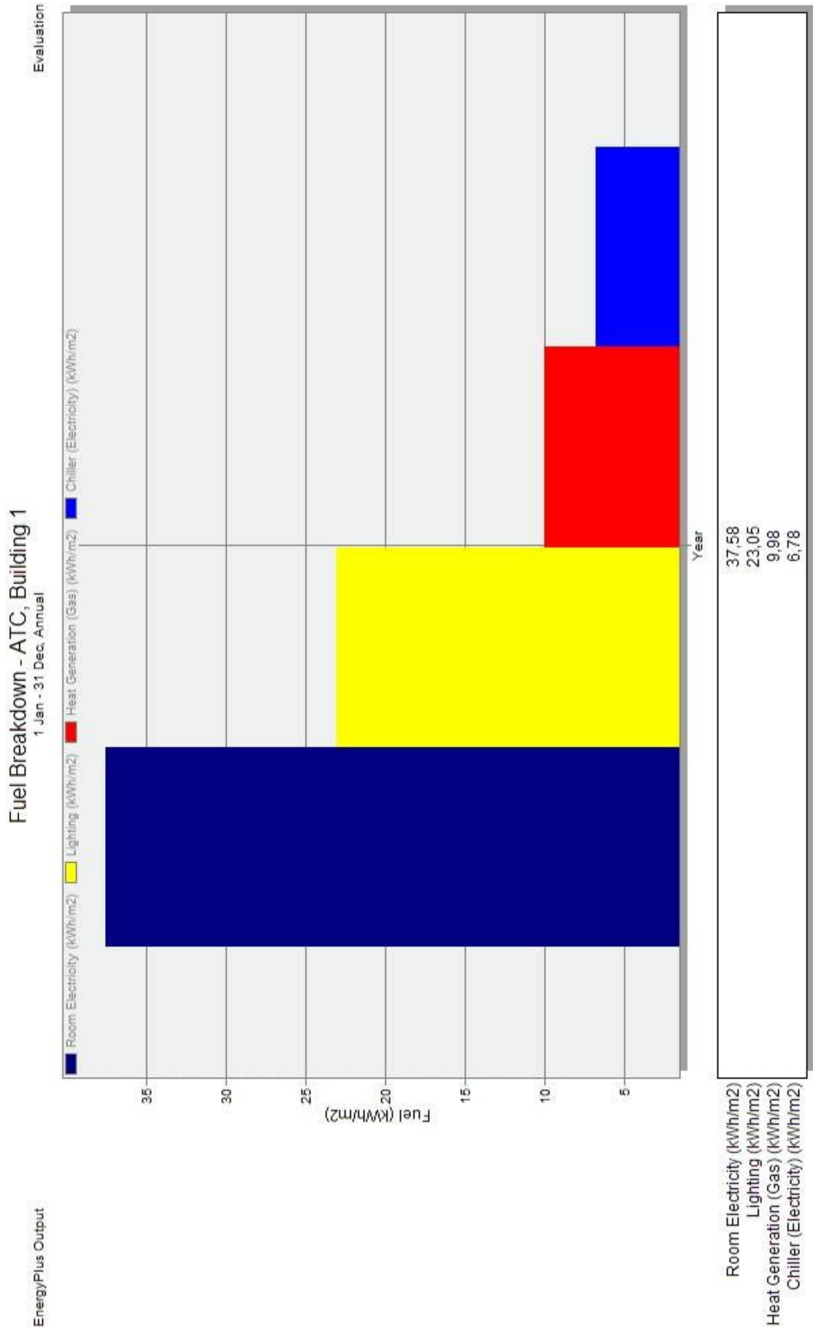


Figure 7.13: Annual Fuel Analysis in Istanbul-with PV

Comparison of annual fuel analysis without and with PV in Istanbul condition is shown in details in Table 7.5.

Table 7.5: Comparison of annual Fuel Analysis without and with PV in Istanbul

ATC BUILDING ANNUAL FUEL ANALYSIS	WITHOUT PV CONDITION	WITH PV CONDITION
Electrical Equipment Consumption (kWh/m²)	37,58	37,58
Lighting (kWh/m²)	23,05	23,05
Heat generation (gas) (kWh/m²)	9,88	9,98
Chiller (electricity) (kWh/m²)	6,87	6,78

7.3 Lighting Loads in Istanbul

EnergyPlus program is used for calculation of lighting loads. The input file is exported from DesignBuilder program and it is the same with previous chapter except site data. Lighting results can be seen in Figure 7.14 and in Figure 7.15.

Utility Use Per Total Floor Area

	Electricity Intensity (kWh/m2)
Lighting	11.04
HVAC	0.00
Other	37.45
Total	48.49

Figure 7.14: Electricity Intensity without PV in Istanbul

As seen in Figure 7.14, electricity consumption of lighting is 11,04 kWh/m².

Utility Use Per Conditioned Floor Area

	Electricity Intensity (kWh/m2)
Lighting	11.17
HVAC	0.00
Other	37.45
Total	48.62

Figure 7.15: Electricity Intensity with PV in Istanbul

As seen in Figure 7.15, lighting intensity has increased to 11,17 kWh/m². The shading effect of PV panels has reflected as change ratio as 1,16% to lighting loads.

7.4 Conclusion

When all simulations that are electricity production of PV panels, change ratio of cooling, heating and lighting loads because of shading effect –have been done in part 7.1, part 7.2, part 7,3- are considered together, the actual utility of Photovoltaic System of ATC building can be calculated with its all effects and the summary of all simulations has been shown in Table 7.6 and Table 7.7.

Table 7.6: Calculation of Shading Effect to Cooling-Heating and Lighting Loads in Istanbul

ATC BUILDING IN ISTANBUL	WITHOUT PV CONDITION	WITH PV CONDITION	CHANGE RATIO
COOLING LOADS (kWh/m²)	6,87	6,78	**- 1,31%**
HEATING LOADS (kWh/m²)	9,88	9.98	**+ 1,01%**
LIGHTING LOADS (kWh/m²)	11,04	11,17	**+ 1,16%**

Table 7.6 shows the cooling, heating and lighting loads for without PV and with PV conditions and also change ratios of these values because of the shading affect of the PV panels. As seen in the table; change ratio of cooling loads is -1,31%, change ratio of heating loads is +1,01% and lastly change ratio of lighting loads is +1,16%.

Utility ratio of PV panels will be calculated with all contributions that are electricity production and shading effect to cooling, heating and lighting loads and Table 7.7 explains it.

Table 7.7: Calculation of Actual Utility Ratio of PV Panels in Istanbul

ATC BUILDING IN ISTANBUL	WITHOUT PV CONDITION	WITH PV CONDITION	CHANGE RATIO
ANNUAL ELECTRICITY CONSUMPTION (kWh/m²)	67,50	67,41	
PV ELECTRICITY PRODUCTION (kWh/m²)	0	8,30	
TOTAL CONSUMPTION (kWh/m²)	67,50	59,11	- 12,42%
EFFECT RATIO OF PV PANELS	-	-	+ 1,16%
UTILITY RATIO OF THE PV PANELS IN ISTANBUL :			**- 11,26%**

The calculated utility ratio of PV panels in Istanbul condition is -11,26% when all the simulated contributions are considered, for same case-study building built in Istanbul. In other words, the electricity produced by photovoltaic panels meets 11,26% of annual electricity requirement of ATC building. It should be noticed that the photovoltaics are used only along 3 floors on southeast façade, along 7 floors on southwest while ATC building consists of 10 floors and the first two floors are larger than type floors.

Utility ratio of PV panels in Turin is calculated as -10,14% in Chapter 6. This value is calculated for Istanbul condition as -11,26%. So, utility ratio of PV panels in Istanbul is 11,04% more than in Turin condition.

8. CONCLUSION

Energy has become a more important and critical issue in recent years. If a country is able to provide its own energy demand, it is rescued external dependence for energy point. Besides; corporations, which produce and import energy, possess power and it is going to be more significant in the near future. Furthermore; almost every country prepares its own national energy policy and publishes and modernizes it every year.

Clean and renewable energy systems seem necessary considering the combination of environmental pollution, global warming and the reduction of fossil fuels. Their diffusion should be fastened and encouraged.

The sun represents the most important clean and renewable energy source, because it is widespread all around the world. Moreover, buildings have a capacity to play pivotal role at solving energy problem, because today they require almost 50% of the primary energy demand. In other words, to solve energy problem of building means to solve a significant value of the world's energy requirements.

Buildings can benefit from the sun in passive or active ways. For an architect, it is a way to show his/her responsibility to give place to passive and active solar energy systems in a building design.

Nowadays, architects can benefit from a big advantage: computer-based simulation tools are able to simulate and calculate energy performance of a building at preliminary design stage and the architect is able to change and organize design parameters according to the simulations' results.

The present work has two main aims:

-To introduce photovoltaic systems (PV) and their integration into buildings (BiPV),

-To evaluate their performance in a case-study building by using different simulation tools and then to get results for further studies in this area.

In the present work, photovoltaic modules are introduced as an active solar system. Photovoltaic technology is developing very fast and it is becoming more aesthetical and efficient day by day. Their cost decreases rapidly while the efficiency increases. Furthermore, many developed countries assist photovoltaic integration into buildings with encouragements in order to make the use of photovoltaic systems widespread and to support to grid. Photovoltaic systems can be installed in different parts of the building envelope, such as roof and façade, and it is also possible to use them on atrium or skylights or as shading devices in buildings. Building integrated photovoltaics systems (abbreviated as BiPV) are considered as multifunctional building materials and they are usually designed to serve more than one function. For instance, a shading device covered by photovoltaics optimizes solar control for unnecessary heat gain, converts this unwanted solar energy into electricity, additionally it is a daylighting element of the building.

The analyzed case-study building is located in Turin, Italy. It is an office building which has undergone a renovation project that included the installation of photovoltaic panels used as shading devices. In the present study, the utility ratio of PV panels, which is the ratio of annual electricity production of the PV system to annual electricity consumption of the case-study building, is calculated by using different simulation tools. These tools are PVSYST to calculate electricity production of the PV system according to the seasons and orientation, DesignBuilder to calculate annual electricity and gas consumption of the building (7.531m²) and the change ratios of cooling and heating loads and the last tool is EnergyPlus to calculate the change ratio of lighting loads. The actual utility ratio of PV panels is -10,14% when all the simulated contributions are considered. In other words, the electricity produced by photovoltaics meets 10,14% of electricity consumption of the case-study building.

Then, the case-study building with same energy management strategies and schedules, is simulated for Istanbul, Turkey weather conditions in order to evaluate the difference in the PV utility ratio and this value is calculated as 11,26% for Istanbul climate. Furthermore, the utility ratio of PV panels in Istanbul is 11,04% higher than in Turin conditions.

However in this example, BiPV application is not very well integrated into the case-study building. Photovoltaic system is oriented to the south-west and south-east because of the building orientation and as known for these directions, the horizontal shading devices are not efficiency to get well solar protection this is why the shading effect is a little value.

As calculated for the case-study building in two different locations, the photovoltaics meets an important value of electricity consumption of the building, in spite of their not very convenience position on the building. It is possible to obtain high utility ratios from photovoltaic systems by designing them carefully according to integration and location, making them suitable for the site conditions, and considering the electricity requirement of the building. Simulation tools strongly contribute to design a photovoltaic system according to the electrical demand, already at a preliminary design stage.

Additionally, photovoltaics systems do not produce any CO_2 emissions. CO_2 emissions for the case study building in Turin are 51,2kg/m², which correspond to 385.6 tons of CO_2 per year. This CO_2 production is reduced of at least the same percentage of the utility ratio of PV panels, that is 10,14% according to reduction of electricity requirement. Therefore the installed PV system avoids the emission of at least 38 tons less CO_2 in the atmosphere.

For all these advantages, BiPV should be strongly supported by governments with economical incentives in order to reduce its payback time, particularly in those countries with high solar radiation such as Turkey and Italy.

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APPENDICES

APPENDIX A

Table A.1 : Occupancy Schedule of ATC Building

Month/Day	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday	Sunday
January	08:00 to 18:00	08:00 to 18:00	08:00 to 18:00	08:00 to 18:00	08:00 to 18:00	08:00 to 13:00	Off
February	08:00 to 18:00	08:00 to 18:00	08:00 to 18:00	08:00 to 18:00	08:00 to 18:00	08:00 to 13:00	Off
March	08:00 to 18:00	08:00 to 18:00	08:00 to 18:00	08:00 to 18:00	08:00 to 18:00	08:00 to 13:00	Off
April	08:00 to 18:00	08:00 to 18:00	08:00 to 18:00	08:00 to 18:00	08:00 to 18:00	08:00 to 13:00	Off
May	08:00 to 18:00	08:00 to 18:00	08:00 to 18:00	08:00 to 18:00	08:00 to 18:00	08:00 to 13:00	Off
June	08:00 to 18:00	08:00 to 18:00	08:00 to 18:00	08:00 to 18:00	08:00 to 18:00	08:00 to 13:00	Off
July	08:00 to 18:00	08:00 to 18:00	08:00 to 18:00	08:00 to 18:00	08:00 to 18:00	08:00 to 13:00	Off
August	08:00 to 18:00	08:00 to 18:00	08:00 to 18:00	08:00 to 18:00	08:00 to 18:00	08:00 to 13:00	Off
September	08:00 to 18:00	08:00 to 18:00	08:00 to 18:00	08:00 to 18:00	08:00 to 18:00	08:00 to 13:00	Off
October	08:00 to 18:00	08:00 to 18:00	08:00 to 18:00	08:00 to 18:00	08:00 to 18:00	08:00 to 13:00	Off
November	08:00 to 18:00	08:00 to 18:00	08:00 to 18:00	08:00 to 18:00	08:00 to 18:00	08:00 to 13:00	Off
December	08:00 to 18:00	08:00 to 18:00	08:00 to 18:00	08:00 to 18:00	08:00 to 18:00	08:00 to 13:00	Off

Table A.2 : Cooling Schedule of ATC Building

Month/Day	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday	Sunday
January	Off	Off	Off	Off	Off	Off	Off
February	Off	Off	Off	Off	Off	Off	Off
March	Off	Off	Off	Off	Off	Off	Off
April	Off	Off	Off	Off	Off	Off	Off
May	Off	Off	Off	Off	Off	Off	Off
June	07:00 to 19:00	07:00 to 19:00	07:00 to 19:00	07:00 to 19:00	07:00 to 19:00	08:00 to 13:00	Off
July	07:00 to 19:00	07:00 to 19:00	07:00 to 19:00	07:00 to 19:00	07:00 to 19:00	08:00 to 13:00	Off
August	07:00 to 19:00	07:00 to 19:00	07:00 to 19:00	07:00 to 19:00	07:00 to 19:00	08:00 to 13:00	Off
September	07:00 to 19:00	07:00 to 19:00	07:00 to 19:00	07:00 to 19:00	07:00 to 19:00	08:00 to 13:00	Off
October	Off	Off	Off	Off	Off	Off	Off
November	Off	Off	Off	Off	Off	Off	Off
December	Off	Off	Off	Off	Off	Off	Off

Table A.3 : Heating Schedule of ATC Building

Month/Day	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday	Sunday
January	02:00 to 18:00	06:00 to 18:00	06:00 to 18:00	06:00 to 18:00	06:00 to 18:00	06:00 to 12:00	08:00 to 10:00
February	04:00 to 18:00	06:00 to 18:00	06:00 to 18:00	06:00 to 18:00	06:00 to 18:00	06:00 to 12:00	20:00 to 22:00
March	04:00 to 18:00	06:00 to 18:00	06:00 to 18:00	06:00 to 18:00	06:00 to 18:00	06:00 to 12:00	20:00 to 22:00
April	Off	Off	Off	Off	Off	Off	Off
May	Off	Off	Off	Off	Off	Off	Off
June	Off	Off	Off	Off	Off	Off	Off
July	Off	Off	Off	Off	Off	Off	Off
August	Off	Off	Off	Off	Off	Off	Off
September	Off	Off	Off	Off	Off	Off	Off
October	04:00 to 18:00	06:00 to 18:00	06:00 to 18:00	06:00 to 18:00	06:00 to 18:00	06:00 to 12:00	20:00 to 22:00
November	04:00 to 18:00	06:00 to 18:00	06:00 to 18:00	06:00 to 18:00	06:00 to 18:00	06:00 to 12:00	20:00 to 22:00
December	02:00 to 18:00	06:00 to 18:00	06:00 to 18:00	06:00 to 18:00	06:00 to 18:00	06:00 to 12:00	08:00 to 10:00

Table A.4 : Lighting Schedule of ATC Building

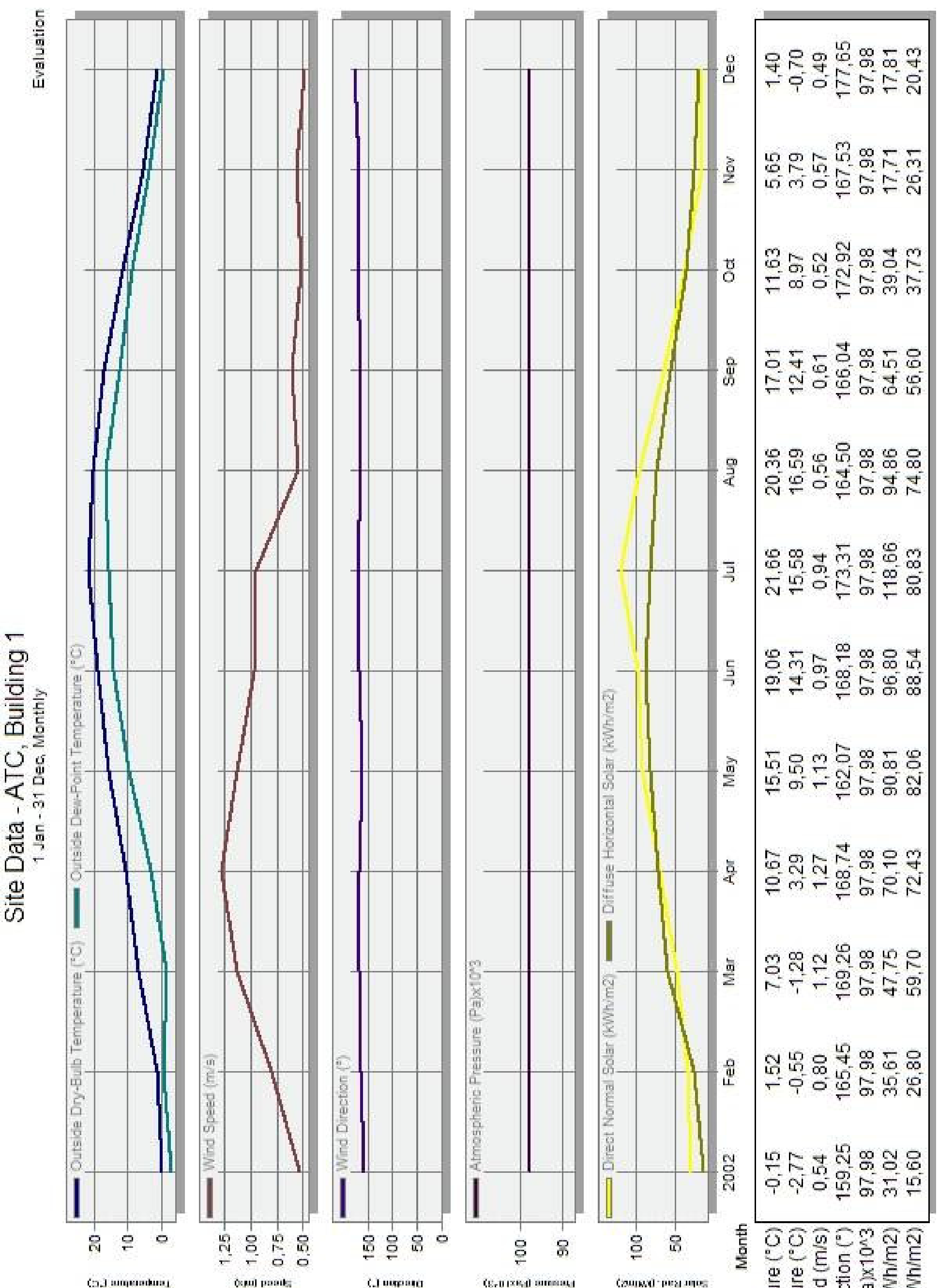
Month/Day	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday	Sunday
January	08:00-16:00 -30% 16:00-18:00-100%	08:00-16:00 -30% 16:00-18:00-100%	08:00-16:00 -30% 16:00-18:00-100%	08:00-16:00 -30% 16:00-18:00-100%	08:00-16:00 -30% 16:00-18:00-100%	08:00-13:00 -30%	Off
February	08:00-16:00 -30% 16:00-18:00-100%	08:00-16:00 -30% 16:00-18:00-100%	08:00-16:00 -30% 16:00-18:00-100%	08:00-16:00 -30% 16:00-18:00-100%	08:00-16:00 -30% 16:00-18:00-100%	08:00-13:00 -30%	Off
March	08:00-16:00 -30% 16:00-18:00-100%	08:00-16:00 -30% 16:00-18:00-100%	08:00-16:00 -30% 16:00-18:00-100%	08:00-16:00 -30% 16:00-18:00-100%	08:00-16:00 -30% 16:00-18:00-100%	08:00-13:00 -30%	Off
April	08:00-18:00-30%	08:00-18:00-30%	08:00-18:00-30%	08:00-18:00-30%	08:00-18:00-30%	08:00-13:00 -30%	Off
May	08:00-18:00-30%	08:00-18:00-30%	08:00-18:00-30%	08:00-18:00-30%	08:00-18:00-30%	08:00-13:00 -30%	Off
June	08:00-18:00-30%	08:00-18:00-30%	08:00-18:00-30%	08:00-18:00-30%	08:00-18:00-30%	08:00-13:00 -30%	Off
July	08:00-18:00-30%	08:00-18:00-30%	08:00-18:00-30%	08:00-18:00-30%	08:00-18:00-30%	08:00-13:00 -30%	Off
August	08:00-18:00-30%	08:00-18:00-30%	08:00-18:00-30%	08:00-18:00-30%	08:00-18:00-30%	08:00-13:00 -30%	Off
September	08:00-18:00-30%	08:00-18:00-30%	08:00-18:00-30%	08:00-18:00-30%	08:00-18:00-30%	08:00-13:00 -30%	Off
October	08:00-16:00 -30% 16:00-18:00-100%	08:00-16:00 -30% 16:00-18:00-100%	08:00-16:00 -30% 16:00-18:00-100%	08:00-16:00 -30% 16:00-18:00-100%	08:00-16:00 -30% 16:00-18:00-100%	08:00-13:00 -30%	Off
November	08:00-16:00 -30% 16:00-18:00-100%	08:00-16:00 -30% 16:00-18:00-100%	08:00-16:00 -30% 16:00-18:00-100%	08:00-16:00 -30% 16:00-18:00-100%	08:00-16:00 -30% 16:00-18:00-100%	08:00-13:00 -30%	Off
December	08:00-16:00 -30% 16:00-18:00-100%	08:00-16:00 -30% 16:00-18:00-100%	08:00-16:00 -30% 16:00-18:00-100%	08:00-16:00 -30% 16:00-18:00-100%	08:00-16:00 -30% 16:00-18:00-100%	08:00-13:00 -30%	Off

Table A.5 : Consumption of electrical equipments of ATC Building

Floors	PC	Printer	Fax	Photocopier	Server	Scanner	Projector	Plotter	Automatic machine	Lighting	Elevator	Ventilation (summer)	Power per floor [W]
Basement Floor										100			15000
Ground Floor	68	7	2	5						250		6	53582
1	80	17	5	4						200		6	48448
2	40	10		4	6					100		6	25695
3	23	7	1	3						100		6	21769
4	45	3	1	3					2	100		6	26180
5	41	5	3	3		1	1	1		100		6	25413
6	46	6	1	3				2		100		6	26283
7	32	5	1	2					2	100		6	23434
8	37	6	4	4						100		6	24779
9	35	5		2			1			100		6	23910
Number of Devices	447	71	18	33	6	1	2	3	4	1350	4	60	[#]
Unit Power	230	50	50	500	50	50	350	50	100	150	2000	300	[W]
Contemporaneity Factor	0.85	0.45	0.3	0.5	1	0.3	0.3	0.4	1	1	1	0.75	[-]
Total Power	**87389**	**1598**	**270**	**8250**	**300**	**15**	**210**	**60**	**400**	**202500**	**8000**	**13500**	**[W]**
Working Hours 10h*22d*12m	2640	2640	2640	2640	2640	2640	2640	2640	2640	2640	2640	880	[h/a]
Annual Consumption	230706	4217	713	21780	792	40	554	158	1056	534600	21120	11880	[kWh/yr]
Specific Consumption	**20.33**	**0.37**	**0.06**	**1.92**	**0.07**	**0.00**	**0.05**	**0.01**	**0.09**	**47.10**	**1.86**	**1.05**	**[kWh m²/yr]**

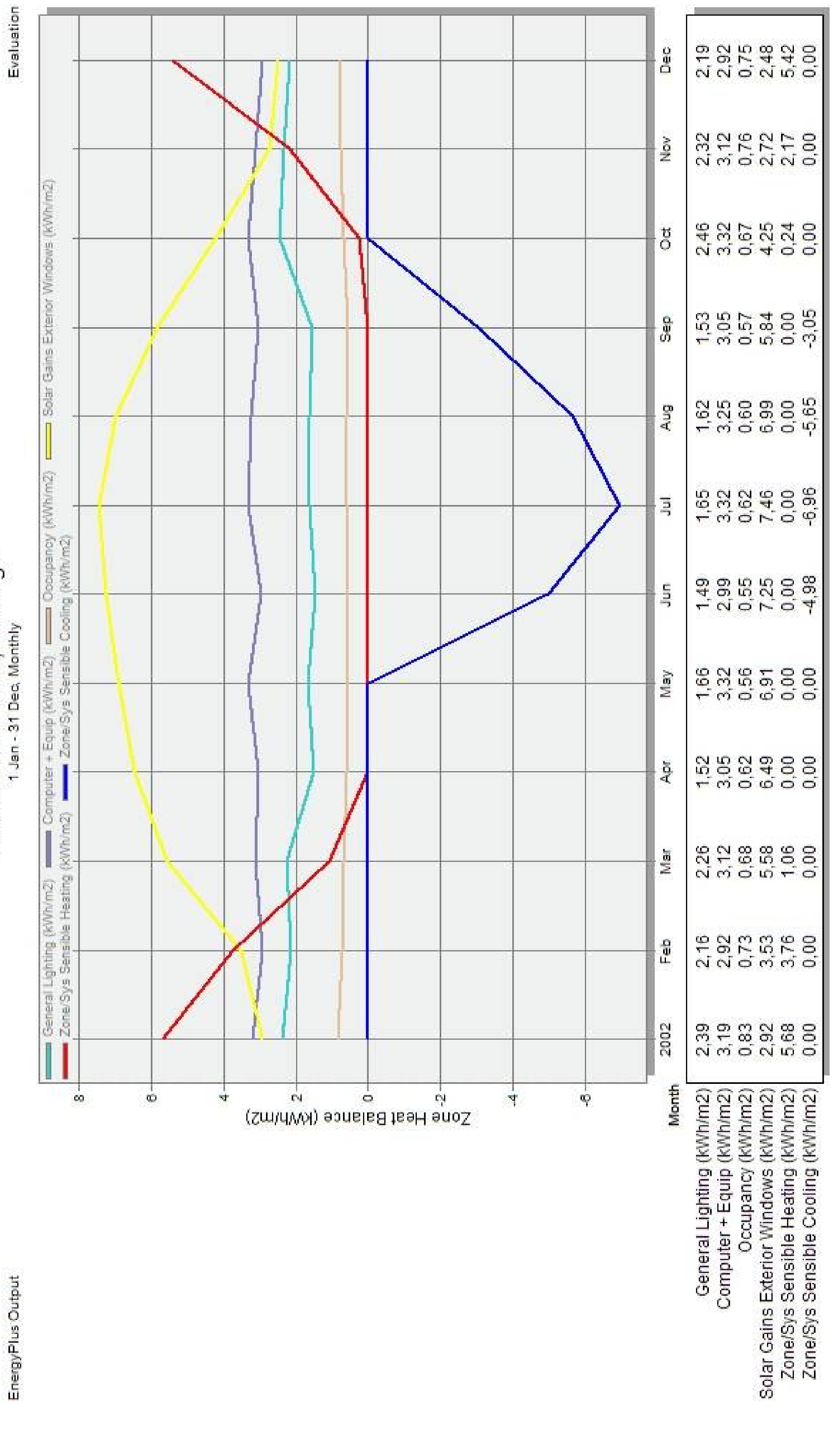
APPENDIX B

Figure B.1 : Monthly Site Data without PV in DesignBuilder



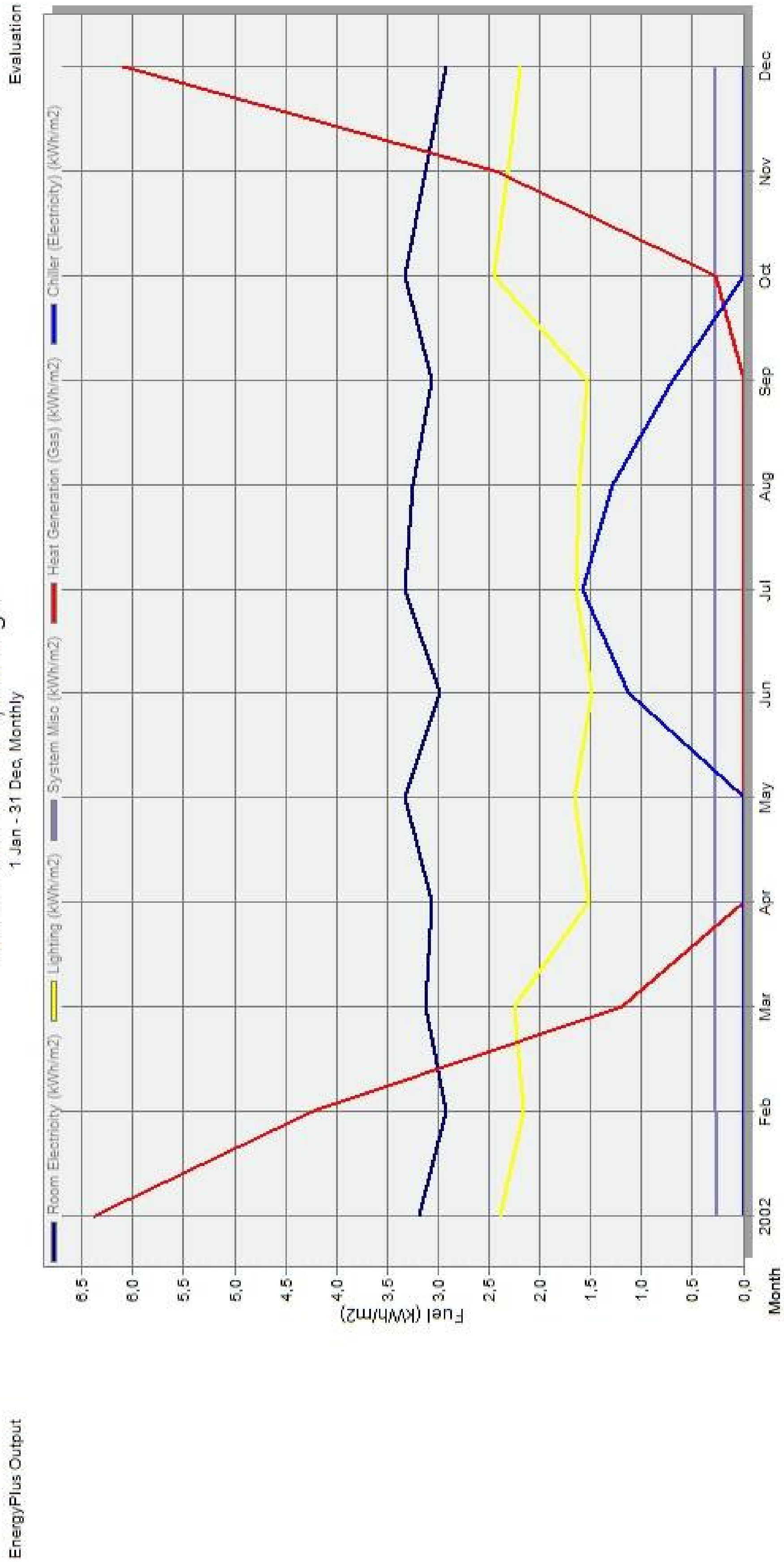
Month	2002	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Outside Dry-Bulb Temperature (°C)	-0,15	1,52	7,03	10,67	15,51	19,06	21,66	20,36	17,01	11,63	5,65	1,40
Outside Dew-Point Temperature (°C)	-2,77	-0,55	-1,28	3,29	9,50	14,31	15,58	16,59	12,41	8,97	3,79	-0,70
Wind Speed (m/s)	0,54	0,80	1,12	1,27	1,13	0,97	0,94	0,56	0,61	0,52	0,57	0,49
Wind Direction (°)	159,25	165,45	169,26	168,74	162,07	168,18	173,31	164,50	166,04	172,92	167,53	177,65
Atmospheric Pressure (Pa)x10^3	97,98	97,98	97,98	97,98	97,98	97,98	97,98	97,98	97,98	97,98	97,98	97,98
Direct Normal Solar (kWh/m2)	31,02	35,61	47,75	70,10	90,81	96,80	118,66	94,86	64,51	39,04	17,71	17,81
Diffuse Horizontal Solar (kWh/m2)	15,60	26,80	59,70	72,43	82,06	88,54	80,83	74,80	56,60	37,73	26,31	20,43

Figure B.2 : Monthly Internal Gains without PV in DesignBuilder



Month	2002	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
General Lighting (kWh/m2)	2,39	2,16	2,26	1,52	1,66	1,49	1,65	1,62	1,53	2,46	2,32	2,19
Computer + Equip (kWh/m2)	3,19	2,92	3,12	3,05	3,32	2,99	3,32	3,25	3,05	3,32	3,12	2,92
Occupancy (kWh/m2)	0,83	0,73	0,68	0,62	0,56	0,55	0,62	0,60	0,57	0,67	0,76	0,75
Solar Gains Exterior Windows (kWh/m2)	2,92	3,53	5,58	6,49	6,91	7,25	7,46	6,99	5,84	4,25	2,72	2,48
Zone/Sys Sensible Heating (kWh/m2)	5,68	3,76	1,06	0,00	0,00	0,00	0,00	0,00	0,00	0,24	2,17	5,42
Zone/Sys Sensible Cooling (kWh/m2)	0,00	0,00	0,00	0,00	0,00	-4,98	-6,96	-5,65	-3,05	0,00	0,00	0,00

Figure B.3 : Monthly Fuel Analysis without PV in DesignBuilder



Month	2002	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Room Electricity (kWh/m2)	3,19	2,92	3,12	3,05	3,32	2,99	3,32	3,25	3,05	3,32	3,12	2,92
Lighting (kWh/m2)	2,39	2,16	2,26	1,52	1,66	1,49	1,65	1,62	1,53	2,46	2,32	2,19
System Misc (kWh/m2)	0,25	0,28	0,27	0,28	0,27	0,28	0,28	0,27	0,28	0,27	0,28	0,28
Heat Generation (Gas) (kWh/m2)	6,38	4,23	1,19	0,00	0,00	0,00	0,00	0,00	0,00	0,27	2,44	6,09
Chiller (Electricity) (kWh/m2)	0,00	0,00	0,00	0,00	0,00	1,13	1,58	1,28	0,69	0,00	0,00	0,00

Figure B.4 : Monthly Fuel Totals without PV in DesignBuilder

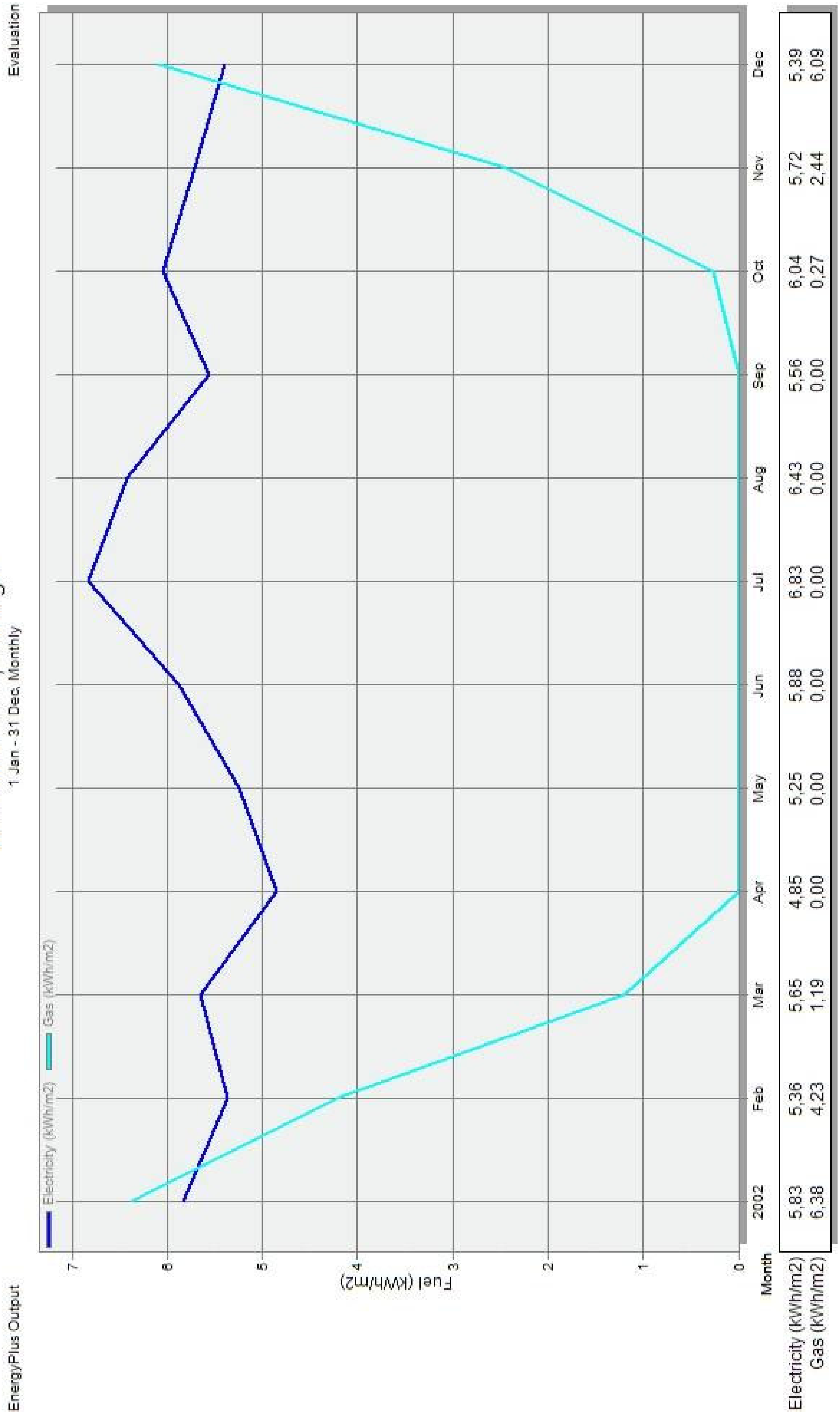
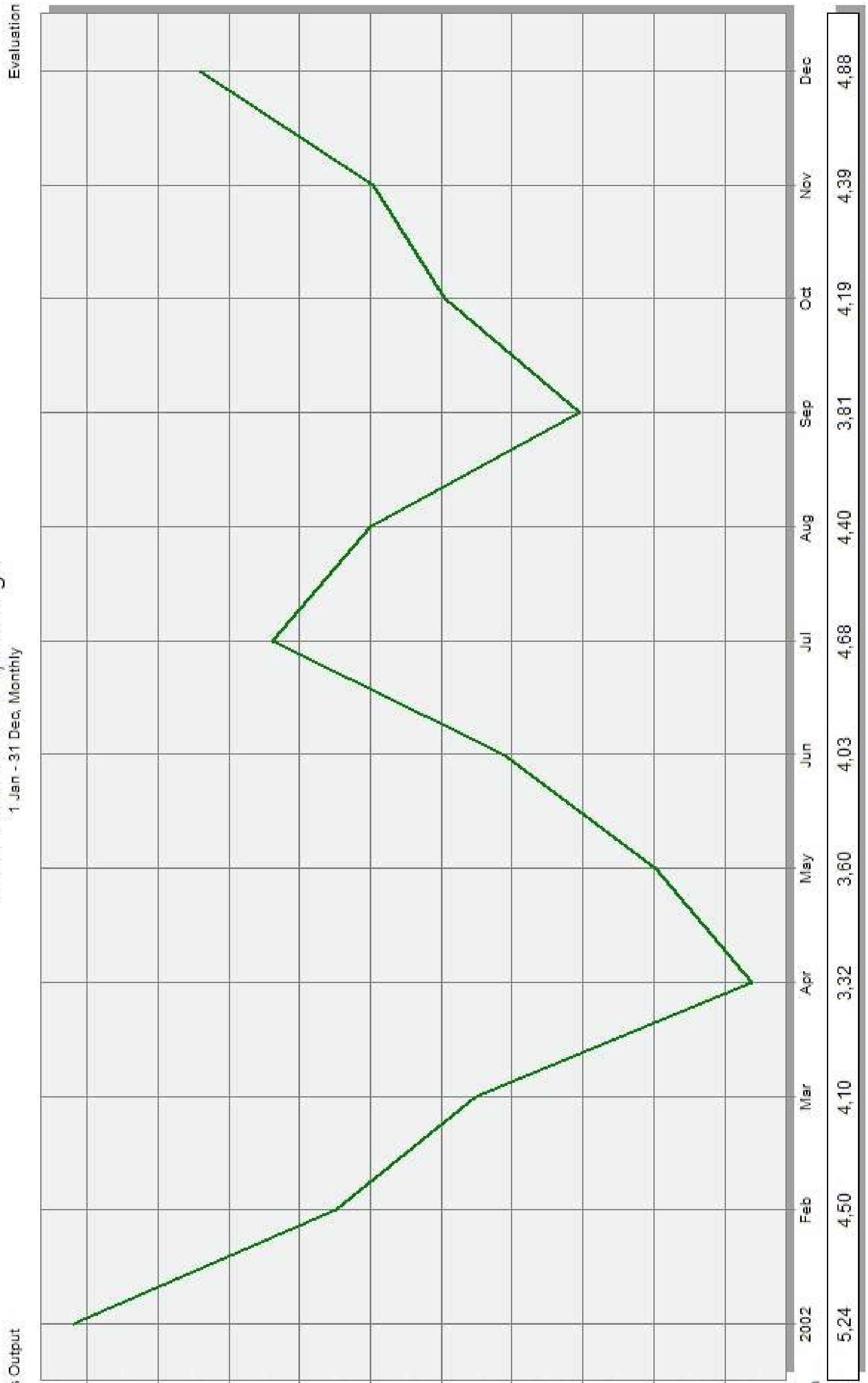
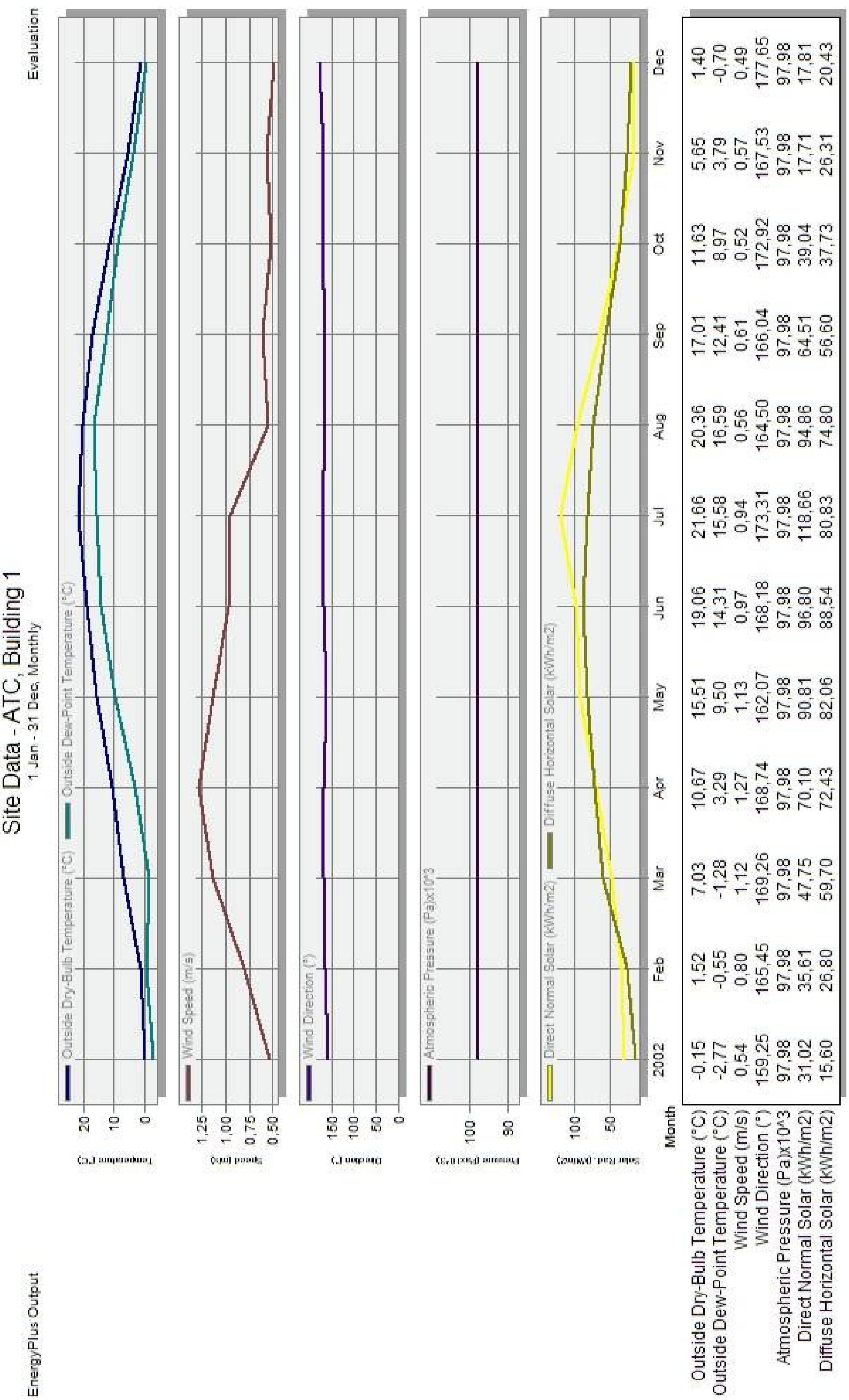


Figure B.5 : Monthly CO2 Production without PV in DesignBuilder



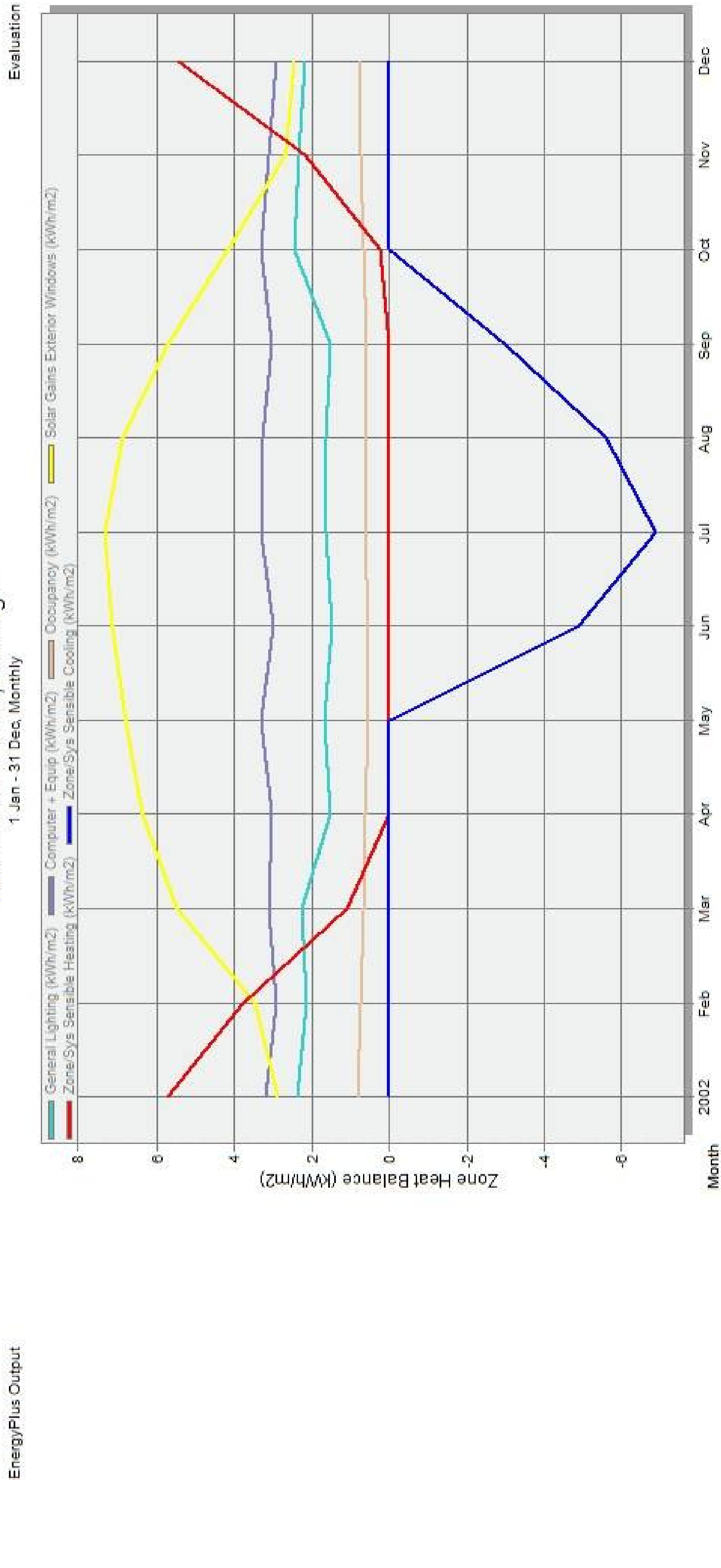
APPENDIX C

Figure C.1: Monthly Site Data with PV in DesignBuilder



Month	2002	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Outside Dry-Bulb Temperature (°C)	-0,15	1,52	7,03	10,67	15,51	19,06	21,66	20,36	17,01	11,63	5,65	1,40
Outside Dew-Point Temperature (°C)	-2,77	-0,55	-1,28	3,29	9,50	14,31	15,58	16,59	12,41	8,97	3,79	-0,70
Wind Speed (m/s)	0,54	0,80	1,12	1,27	1,13	0,97	0,94	0,56	0,61	0,52	0,57	0,49
Wind Direction (°)	159,25	165,45	169,26	168,74	162,07	168,18	173,31	164,50	166,04	172,92	167,53	177,65
Atmospheric Pressure (Pa)x10^3	97,98	97,98	97,98	97,98	97,98	97,98	97,98	97,98	97,98	97,98	97,98	97,98
Direct Normal Solar (kWh/m2)	31,02	35,61	47,75	70,10	90,81	96,80	118,66	94,86	64,51	39,04	17,71	17,81
Diffuse Horizontal Solar (kWh/m2)	15,60	26,80	59,70	72,43	82,06	88,54	80,83	74,80	56,60	37,73	26,31	20,43

Figure C.2: Monthly Internal Gains with PV in DesignBuilder



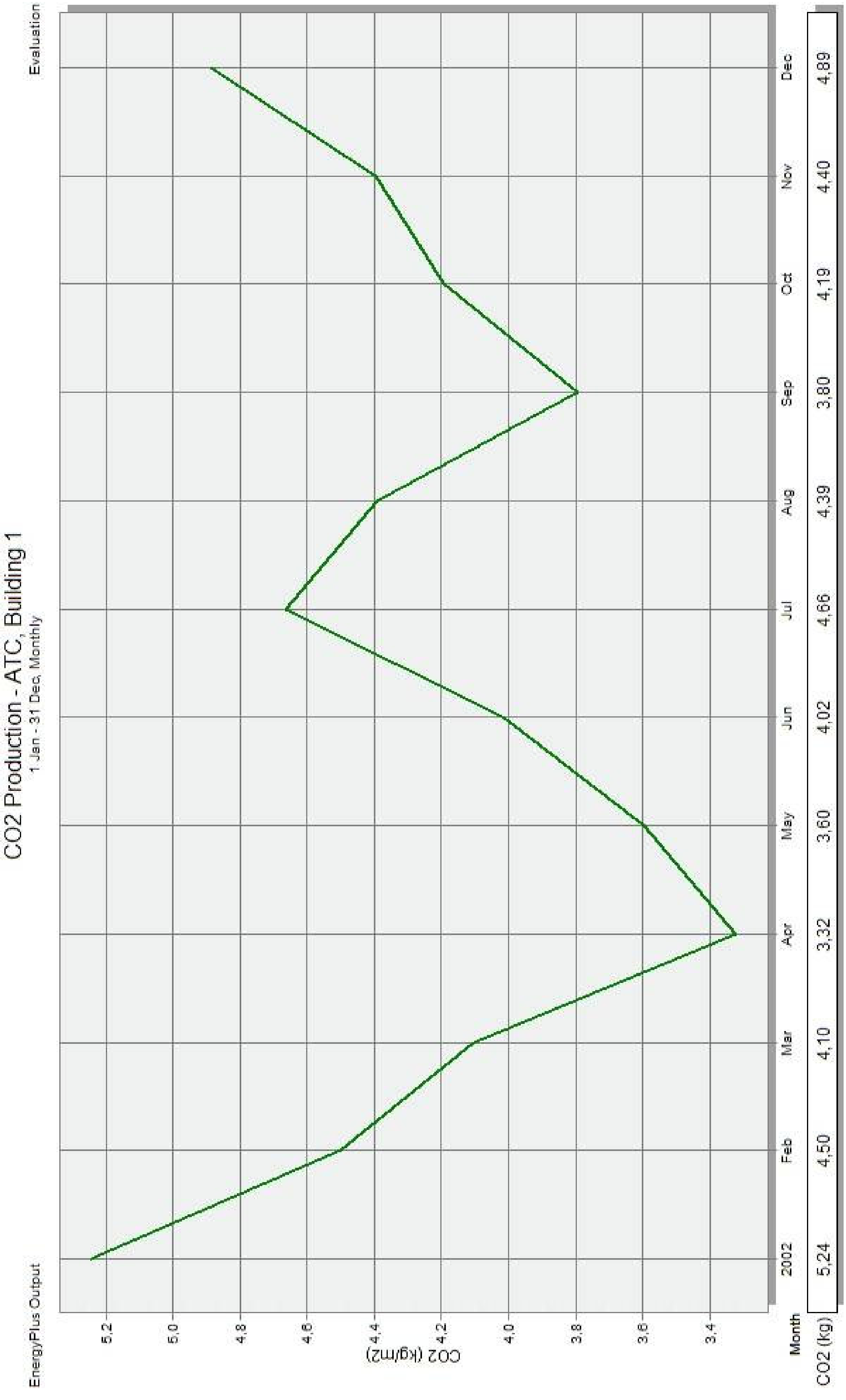
Month	2002	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
General Lighting (kWh/m2)	2,39	2,16	2,26	1,52	1,66	1,49	1,65	1,62	1,53	2,46	2,32	2,19
Computer + Equip (kWh/m2)	3,19	2,92	3,12	3,05	3,32	2,99	3,32	3,25	3,05	3,32	3,12	2,92
Occupancy (kWh/m2)	0,83	0,73	0,68	0,62	0,56	0,56	0,62	0,60	0,57	0,67	0,76	0,75
Solar Gains Exterior Windows (kWh/m2)	2,87	3,47	5,48	6,38	6,82	7,15	7,36	6,88	5,74	4,17	2,68	2,44
Zone/Sys Sensible Heating (kWh/m2)	5,71	3,79	1,08	0,00	0,00	0,00	0,00	0,00	0,00	0,25	2,19	5,44
Zone/Sys Sensible Cooling (kWh/m2)	0,00	0,00	0,00	0,00	0,00	-4,90	-6,88	-5,58	-2,97	0,00	0,00	0,00

Figure C.3 : Monthly Fuel Analysis with PV in DesignBuilder

Month	2002	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Room Electricity (kWh/m2)	3,19	2,92	3,12	3,05	3,32	2,99	3,32	3,25	3,05	3,32	3,12	2,92
Lighting (kWh/m2)	2,39	2,16	2,26	1,52	1,66	1,49	1,65	1,62	1,53	2,46	2,32	2,19
System Misc (kWh/m2)	0,25	0,28	0,27	0,28	0,27	0,28	0,28	0,27	0,28	0,27	0,28	0,28
Heat Generation (Gas) (kWh/m2)	6,41	4,25	1,21	0,00	0,00	0,00	0,00	0,00	0,00	0,28	2,46	6,11
Chiller (Electricity) (kWh/m2)	0,00	0,00	0,00	0,00	0,00	1,11	1,56	1,27	0,67	0,00	0,00	0,00

Figure C.4 : Monthly Fuel Totals with PV in DesignBuilder

Figure C.5 : Monthly CO2 Production with PV in DesignBuilder



APPENDIX D

Figure D.1 : Solar Gains from Exterior Windows in Summer Design Day
without PV conditions (1925,73kW)

Figure D.2 : Solar Gains from Exterior Windows in Summer Design Day
with PV conditions (1896,33kW, -1,52% less than without PV)

General Lighting (kW)	0,00	0,00	0,00	0,00	0,00	0,00	0,00	50,71	49,68	49,01	48,80	48,83	49,04	48,98	49,14	49,48	50,19	0,00	0,00	0,00	0,00	0,00	0,00	0,00
Computer + Equip (kW)	0,00	0,00	0,00	0,00	0,00	0,00	0,00	100,01	100,01	100,01	100,01	100,01	100,01	100,01	100,01	100,01	100,01	0,00	0,00	0,00	0,00	0,00	0,00	0,00
Occupancy (kW)	0,00	0,00	0,00	0,00	0,00	0,00	0,00	18,53	18,52	18,52	18,52	18,52	18,52	18,52	18,52	18,52	18,52	0,00	0,00	0,00	0,00	0,00	0,00	0,00
Solar Gains Exterior Windows (kW)	0,00	0,00	0,00	0,00	0,00	46,36	100,40	137,58	139,19	144,38	148,91	153,25	155,84	159,69	177,66	174,84	154,54	115,95	63,03	24,71	0,00	0,00	0,00	0,00
Zone/Sys Sensible Cooling (kW)	0,00	0,00	0,00	0,00	0,00	0,00	-38,15	-88,10	-116,00	-151,03	-188,39	-228,90	-271,19	-300,61	-291,86	-275,43	-253,02	-133,93	0,00	0,00	0,00	0,00	0,00	0,00

Figure D.3 : Solar Gains from Exterior Windows in Winter Design Day

without PV conditions (1109,75kW)

Time/Date																								
General Lighting (kW)	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	53,13	51,70	50,50	49,80	49,84	50,37	51,23	52,22	173,92	178,57	0,00	0,00	0,00	0,00	0,00	0,00
Computer + Equip (kW)	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	100,01	100,01	100,01	100,01	100,01	100,01	100,01	100,01	100,01	100,01	0,00	0,00	0,00	0,00	0,00	0,00
Occupancy (kW)	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	26,49	26,49	26,49	26,38	25,69	24,58	23,62	23,01	21,76	20,98	0,00	0,00	0,00	0,00	0,00	0,00
Solar Gains Exterior Windows (kW)	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	25,20	74,49	128,96	169,40	194,07	195,12	163,90	109,98	48,63	0,00	0,00	0,00	0,00	0,00	0,00	0,00
Zone/Sys Sensible Heating (kW)	0,00	0,00	0,00	0,00	0,00	0,00	334,40	218,71	86,52	64,15	34,61	8,38	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00

Figure D.4 : Solar Gains from Exterior Windows in Winter Design Day
<u>with PV conditions </u>(1092,78kW, -1,52% less than without PV)

CURRICULUM VITA

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