ΤΕΙ ΠΑΤΡΩΝ
ΣΧΟΛΗ ΤΕΧΝΟΛΟΓΙΚΩΝ
ΕΦΑΡΜΟΓΩΝ

Πτυχιακή Εργασία:

''Ανάπτυξη Λογισμικού Για Τη Διαστασιολόγηση Φωτοβολταϊκών Συστήματων''

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Abstract

The aim of this project is to examine photovoltaic systems and their application for residential use. Two different locations will be chosen in order to size a photovoltaic system to cover a house's energy needs and observe the differences in size and economics. The locations chosen are in Greece and Scotland. The sizing of the systems will be with the help of software written for Excel. The software will calculate the available solar energy in a given location, the average daily energy required by the load, the number of panels and batteries needed by the system and finally it will include a life cycle cost estimation.

The first chapter of the report will include an introduction to solar energy and its applications, concentrating on photovoltaic systems. The Sun – Earth geometric relations are presented in the second chapter, along with an approach of calculating the incident radiation on a tilted surface. Chapter 3 discusses the solar cell technology (how solar cells work, materials etc). The main parts of a photovoltaic system are presented in the fourth chapter. In the fifth chapter a method for sizing a system is presented and is applied in practice in chapter 6. Chapter 7 includes an economic evaluation of the systems discussed in chapter 6 and a comparison to other sources of energy. Chapter 8 includes conclusions and final comments.

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1 CHAPTER

Solar Energy - An Introduction

1.1 Renewable Energy

The world currently relies heavily on coal, oil, and natural gas for its energy. Fossil fuels are non-renewable, that is, they are finite resources that will eventually diminish, becoming too expensive or too environmentally damaging to retrieve. In contrast, renewable energy resources – such as wind and solar energy – are constantly replenished and will never run out. Most renewable energy comes either directly or indirectly from the sun.

Sunlight, or solar energy, can be used directly for heating and lighting homes and other buildings, for generating electricity, and for hot water heating, solar cooling, and a variety of commercial and industrial uses. The sun's heat drives the winds, whose energy is captured with wind turbines.

But not all renewable energy resources come from the sun. Geothermal energy taps the Earth's internal heat for a variety of uses, including electric power production, and the heating and cooling of buildings. The energy of the ocean's tides comes from the gravitational pull of the moon and the sun upon the Earth. In fact, ocean energy comes from a number of sources. In addition to tidal energy, there's the energy of the ocean's waves, which are driven by both the tides and the winds. The sun also warms the surface of the ocean more than the ocean depths, creating a temperature difference that can be used as an energy source. All these forms of ocean energy can be used to produce electricity.

1.2 Solar Energy

With the term solar energy, we mean all the energy that reaches the earth from the sun. It provides daylight, makes the earth warm and is the source of energy for the plants to grow.

Even though solar energy has been available since prehistoric times, we have only recently began to discover its potential and use it effectively. Solar energy is the least polluting and most inexhaustible of all known energy sources. The sun is a giant nuclear fusion reactor and the energy it supplies, is truly enormous. It converts 4 million tons of hydrogen per second to helium. The energy falling in earth is 5.4 x 10^{24} J per year equal to 170x10^{9} kilowatts, which is about 27000 the amount of energy produced by all human made systems in the world [1]. Indeed, it is the energy of sunlight assimilated by biological organisms over millions of years that has made possible the industrial growth as we know it today. Most of the other renewable means of power generation also depend on the Sun as the primary source: hydroelectric, wind and wave power all have the same origin.

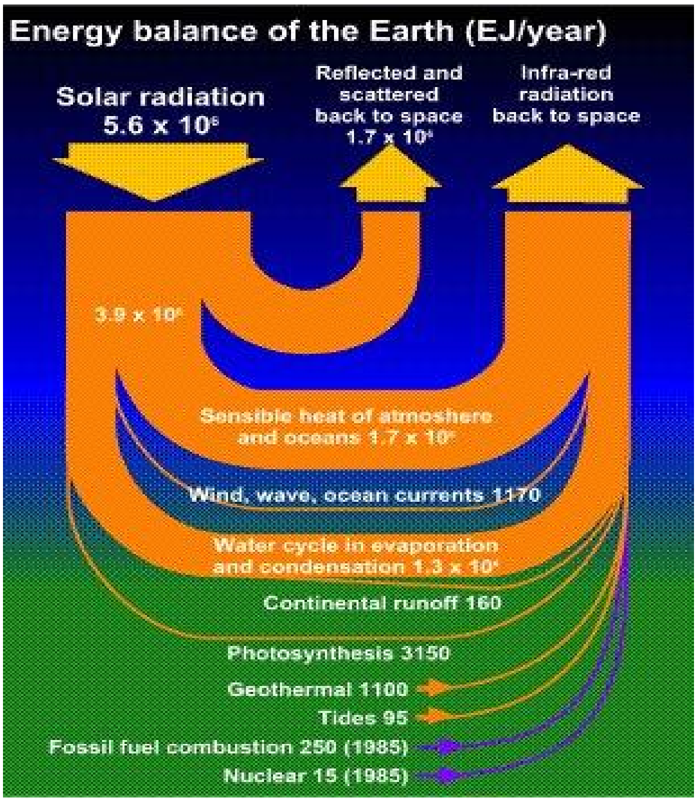


Figure 1-1-Energy balance of the Earth (EJ/year), from I. Dostrovsky, Energy and the Missing Resource

1.3 The Challenges of Solar Energy

The availability of solar energy at the Earth's surface varies in several different ways, and on different time scales. Most uses of energy require both constant and easily available energy. The greatest challenge to the designer of solar energy systems is first to forecast the availability of that solar energy at some time in the future, and then to provide means to capture and store the energy when necessary, so that it will be available when needed. Some of this variation is precisely predictable. These are: diurnal variation (due to the rotation of the Earth on its axis), seasonal variation, (due to the tilt of the Earth's axis), and annual variation, (due to the elliptical orbit of the Earth about the Sun). Other variations are only predictable statistically (for example as the average over a long time period), such as the variations due to clouds and to atmospheric pollution, dust or haze.

It is true that the actual output of the sun varies slightly due to the occurrence of sunspots, and possibly some other phenomenon, but this variation is so small compared to the above-mentioned effects that designers of solar systems ignore it. In fact, we call the amount of energy received at the Earth (outside the Earth's atmosphere) the "Solar Constant" because it changes so little. The solar constant and other radiation will be discussed in the second chapter.

The second great challenge is to make a device to capture the solar energy in the form of radiation, and to convert it to a useful form of energy. The amount of energy falling on a flat level surface one-metre square over the course of one day is roughly 5-kilowatt hours [2]. This averages in 24 hours to about 0.2 kWh/m2. When compared to other modern energy sources, this is not very concentrated. For example a 100-Watt light bulb at its surface has an intensity of about 12 kW/m^2 and an electric stove (500W burner) has an intensity of about 25 kW/m^2. Thus solar energy systems need to have collectors over a relatively large area compared to uses of energy that we are familiar with.

The third great challenge is economic. While the concepts of collection and storage of solar energy are simple, those collectors and that storage must be built with real materials, and must compete economically in a world, which already has fairly inexpensive energy sources at today's prices.

In spite of these challenges, solar energy is today making real progress towards supplying a major fraction of the world's energy.

1.4 Solar energy applications

Even though solar energy is plentiful and inexhaustible, it is thinly distributed over a wide area; so large collector areas are required in order to utilize the solar energy for useful purposes. Solar energy is put to two types of use to help our lives directly: solar heating and solar electricity, the second being the subject of this project. The solar thermal systems convert the radiant energy of the sun into heat, and then use that heat energy as desired. This application has been used for centuries for drying crops, bricks and pots and to make salt from seawater.

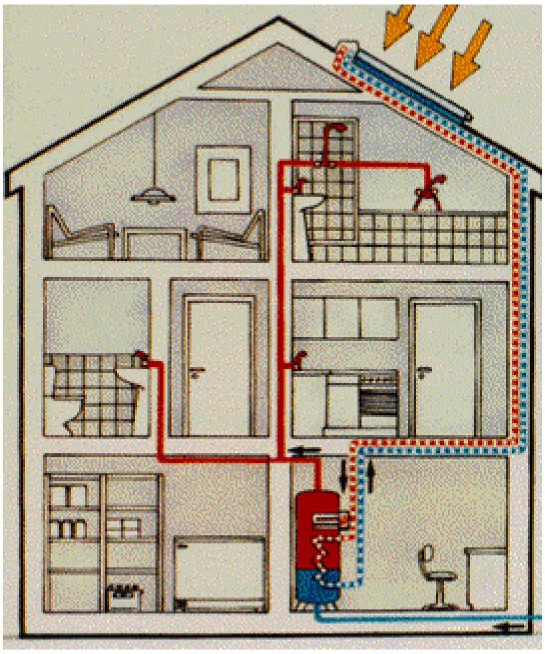


Figure 1-2 -Solar thermal systems for residential use. Source [3]

Solar energy is also used for space heating and cooling, industrial process heating and other applications. When people hear of solar power, they usually think of solar water heaters, now quite common for domestic use in some places of the world.

Solar electric systems convert the radiant energy of the sun directly into electrical energy, which can then be used as most electrical energy is used today. This electricity is generated from sunlight using photovoltaic (PV) cells.

1.5 What are Photovoltaics?

Photovoltaics, or PV refers to an electric voltage caused by light. The term "photo" is a stem from the Greek "phos," which means "light." "Volt" is named for Alessandro Volta (1745-1827), a pioneer in the study of electricity. "Photo-voltaics," then, could literally mean "light-electricity." Photovoltaics are a high-technology approach to converting sunlight directly into electrical energy. The electricity is direct current and can be used that way, converted to alternating current or stored for later use. Conceptually, in its simplest form a photovoltaic device is a solar-powered battery whose only consumable is the light that fuels it. Because sunlight is universally available, photovoltaic devices have many additional benefits that make them usable and acceptable to all inhabitants of our planet. Photovoltaic systems are modular, and so their electrical power output can be engineered for virtually any application, from low-powered consumer uses-wristwatches, calculators and small battery chargers-to energy-significant requirements such as generating power at electric utility central stations. Moreover, incremental power additions are easily accommodated in photovoltaic systems, unlike more conventional approaches such as fossil or nuclear fuel, which require multimegawatt plants to be economically feasible.

1.6 History of photovoltaics

French physicist Edmond Becquerel first described the photovoltaic (PV) effect in 1839, but it remained a curiosity of science for the next three quarters of a century. At only 19, Becquerel found that certain materials would produce small amounts of electric current when exposed to light. Heinrich Hertz in the 1870s first studied the effect in solids, such as selenium. Soon afterward, selenium PV cells were converting light to electricity at 1% to 2% efficiency. As a result, selenium was quickly adopted in the emerging field of photography for use in light-measuring devices. A comprehensive understanding of these phenomena, however, had to await the progress of science towards the quantum theory in the early parts of this century. Twentieth-century physicists, including Albert Einstein, found that tiny photons, or particles of sunlight, can interact with the electron shell surrounding the nucleus of an atom. The interaction causes a free stream of electrons--the basis of electricity.

Figure 1-3 Bell Laboratories PV researchers, measure the response of an early solar cell to light. Source [4]

Major steps toward commercializing PV were taken in the 1940s and early 1950s, when the Czochralski process was developed for producing highly pure crystalline silicon. In 1954, scientists at Bell Laboratories (figure 1-3) depended on the Czochralski process to develop the first crystalline silicon photovoltaic cell, which had an efficiency of 4%. Solar cells did not have to wait long to find an application. American scientists in the late 1950s were searching for a lightweight, long-lasting power source for satellites. PV cells were the answer; they could take advantage of the continuous sunlight of space (figures 1-4 and 1-5).

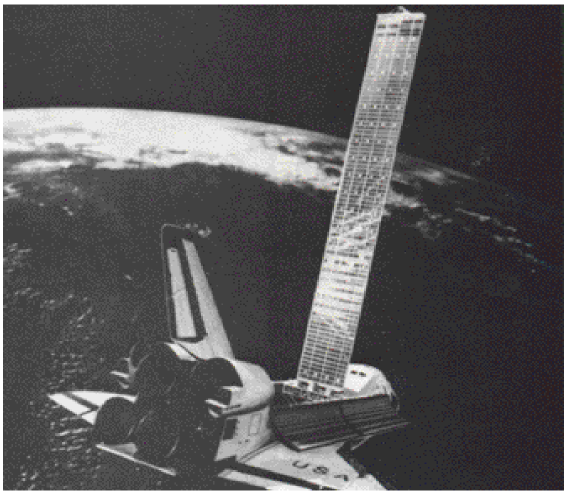


Figure 1-4-PV in space program. Source [5]

The year 1958 witnessed the launch of Vanguard 1 the first satellite to use electricity from the sun. The satellite carried a small array of PV cells to power its radio.

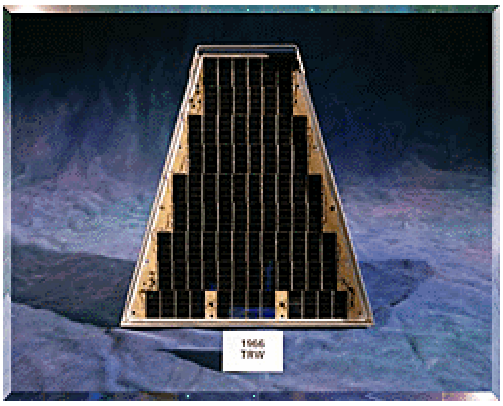


Figure 1-5 PV panel, developed by TRW for a communications satellite in 1966 [7]

The cells worked so well that PV technology has been part of the space program ever since. Achievements in solar-cell research during the peak years of the space program included a major increase in efficiency and a reduction in cost to $200 per watt by 1970. The technology has been developing ever since. Much interest in solar electricity appeared particularly in the wake of the oil crisis in the early 1970s. Today, the direct conversion of light into electricity, or *photovoltaics*, is becoming accepted as an important form of power generation. Solar cells power virtually all satellites, including those used for communications, defense, and scientific research.

Today's commercial PV systems can convert from 7% to 17% of sunlight into electricity. They are highly reliable and last 20 years or longer. The cost of PV-generated electricity has dropped 15- to 20-fold, and PV modules now cost around $6 per watt (W) and produce electricity for as little as 25 to 50 cents per kilowatt-hour [6].

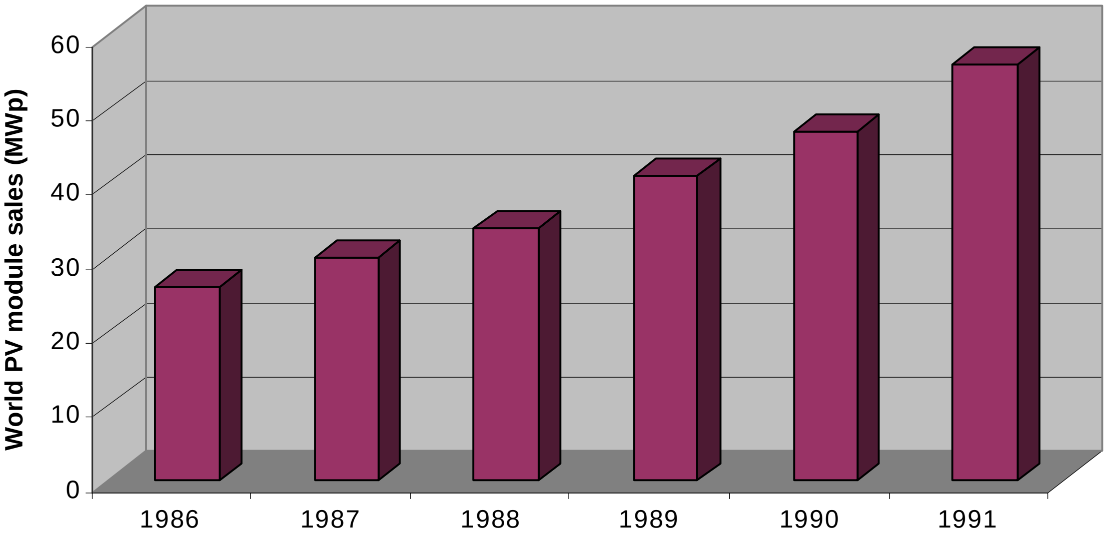


Figure 1-6 World PV module sales [8]

Almost 90 megawatts of photovoltaic power modules were produced in 1996. The production rate has been increasing at almost 20% annually over the last few years, and this trend is likely to continue. At a conservative estimate, the annual production rate will reach hundreds of megawatts by the end of the century and tens of gigawatts in the next 40-50 years [9].

Some dates of relevance to photovoltaic solar energy conversion

1839	Becquerel discovers the photovoltaic effect
1879	Adams and Day observe photovoltaic effect in selenium
1900	Planck postulates the quantum nature of light
1930	Quantum theory of solids proposed by Wilson
1940	Mott and Schottky develop the theory of solid-state rectifier (diode)
1949	Bardeen, Brattain and Shockley invent the transistor
1954	Chapin, Fuller and Pearson announce 6% efficient solar cell
1954	Renolds et al. report solar cell based on cadmium sulphide
1958	First use of solar cells on an orbiting satellite Vanguard 1
1973	Oil crisis spurs growth of terrestrial applications
1982	First photovoltaic power station (1 MW) built at Hysperia, California

Table 1-1 Some important days to PV energy conversion [10]

1.7 Advantages of Photovoltaics

Photovoltaic power has similar benefits to solar thermal power: it’s a clean and inexhaustible source of electricity. In addition the low maintenance required by photovoltaic cells extends their virtues far beyond those of traditional solar thermal collectors. The advantages that photovoltaic systems have over competing power options:

- They have no moving parts and produce power silently.
- They are non-polluting with no detectable emissions or odours, once operational.
- They are inherently stand-alone systems that reliably operate unattended for long periods.

- They require no connection to an existing power source or fuel supply.
- They may be combined with other power sources to increase system reliability (hybrid systems).
- They can withstand severe weather conditions including snow and ice.
- Once operational they consume no fossil fuels - their fuel is abundant and free.
- They can be installed as modular building blocks - as your power demand increases, you may add more photovoltaic modules.

1.8 Environmental benefits of renewable energy systems

Renewable energy technologies are a lot more benign to the environment than conventional energy technologies, which rely on fossil fuels. Fossil fuels contribute significantly to many of the environmental problems we face today – greenhouse gases, air pollution, and water and soil contamination – while renewable energy sources contribute very little or not at all. The so called greenhouse gases – carbon dioxide, methane, nitrous oxide, hydrocarbons, and chlorofluorocarbons – surround the Earth's atmosphere like a clear thermal blanket, allowing the sun's warming rays in and trapping the heat close to the Earth's surface. This natural effect keeps the Earth's average surface temperature at about 33ºC [11]. But the increased use of fossil fuels has significantly increased emissions of these gases, particularly carbon dioxide, creating an enhanced warming effect known as greenhouse effect. According to the U.S. Environmental Protection Agency (EPA), carbon dioxide is responsible for one-half to two-thirds of our contribution to global warming. Renewable energy technologies, however, can produce heat and electricity with a very low or no amount of carbon dioxide emissions.

Energy use from fossil fuels is also a primary source of air, water, and soil pollution. Pollutants – such as carbon monoxide, sulphur dioxide, nitrogen dioxide, particulate matter, and lead – contribute dramatically by polluting further our environment (figure 1-7). On the other hand, most renewable energy technologies produce little or no pollution.

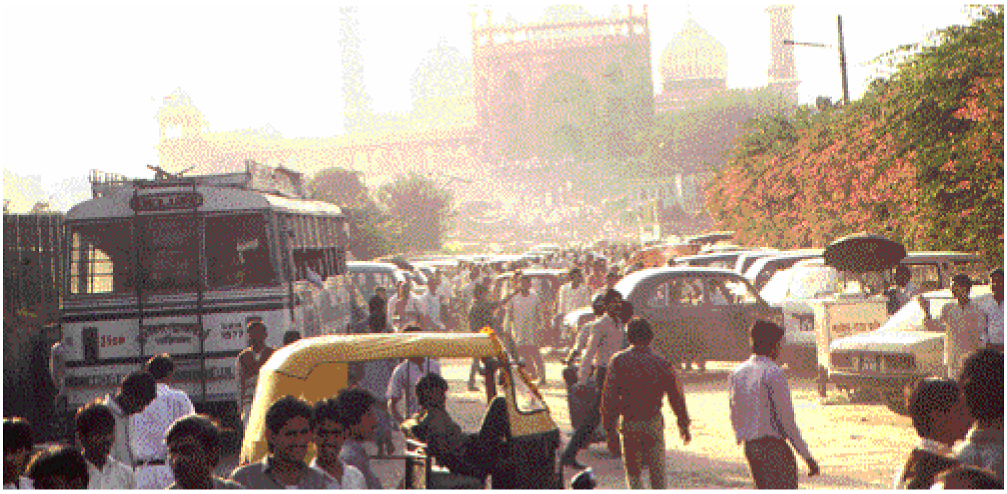


Figure 1-7 Air pollution in modern cities

Both pollution and global warming pose major health risks to humans. According to the American Lung Association, air pollution contributes to lung disease – including asthma, lung cancer, and respiratory tract infections – and close to 335,000 people in the United States die from it every year [12]. Meanwhile, the long-term effects associated with global warming may be even more devastating. Deaths due to extreme weather could increase, and diseases could have a greater potential to thrive as temperatures rise. Ultimately, renewable energy technologies could help us break our conventional pattern of energy use to improve the quality of our environment.

1.9 Applications of Photovoltaics

Today, solar-generated electricity serves people living in the most isolated spots on earth as well as in the center of our biggest cities. First used in the space program, PV systems are now generating electricity to pump water, light up the night, activate switches, charge batteries, supply the electric utility grid, and other applications where they are viewed as the best option for electricity supply. Applications include [13]:

- Rural Electrification
    - Lighting and power supplies for remote buildings
    - Battery charging stations
    - Portable power for nomadic people

- Water Pumping and Treatment systems
    - Pumping for drinking water
    - Pumping for irrigation
    - Water purification

- Health Care Systems
    - Lighting in rural Clinics
    - Vaccine refrigeration
    - Blood storage refrigerators

- Communications
    - Radio repeaters
    - Rural telephone Kiosks
    - Emergency telephones

- Agriculture
    - Livestock watering

- Transport Aids
    - Road sign lighting
    - Railway crossing signals
    - Navigation buoys

- Security Systems
    - Security lighting

- Corrosion Protection Systems
    - Cathodic protection for bridges
    - Pipeline protection

- Space Power Systems

- Other applications
  - Ventilation systems
  - Calculators
  - Path lights
  - Battery charging
  - Boat power

1.10 The future of photovoltaics

There are currently various applied, theoretical research and development projects underway around the world. Researchers are experimenting with new materials and new production techniques to reduce cost and increase efficiency. Semiconductor materials such as gallium arsenide, copper indium diselenide, cadmium teluride and amorphous silicon hold particular promise. Refinements in wafer and ribbon manufacturing and wholly new approaches such as thin film deposits represent potential cost breakthroughs.

More work is needed in areas that are "down line" from the cell. Batteries and inverters are the twos areas which are the subject of more development work. Integration of components and modular designs are simplifying system design and lowering costs.

As PV technology is developing, we are likely to see many more common applications powered by PV cells. Those who elect to place solar cells on their roofs will be able to sell electricity to their local utility during the day when the sun is shining and buy it back at night when it is not. These changes should have a significant impact on reducing the emission of greenhouse gases and other pollutants, and will take us one step closer to a cleaner energy future.

Probably the most significant breakthroughs in PV technology will come from work being done in the emerging nations. The largest markets at current prices exist in the Third World with its 2 billion people who do not have utility power, and will probably never get it. As the poorest people in the world purchase greater quantities of solar power, mass production will lower prices until finally even the richest will be able to afford this technology.

2 The solar radiation

2.1 Solar constant

The amount of solar power received directly outside the earth's atmosphere is continuous at a rate of 1377 watts per square metre. Minor declinations occur because of sunspots and change in the distances of the earth from the sun owing to a small ellipticity in the earth's orbit. More specifically a 1-m^2 area perpendicular to the sun's rays and located about 55 km above the earth's surface would receive energy at a rate of 1377 W/m^2 [14]. This insolation figure is stable enough to be called the solar constant.

On earth however, the amount of solar power available is not constant and it depends on the earth's rotation around its axis and around the sun. The peak solar power experienced on a horizontal surface near sea level is about 1000 watts per square metre when the sun is at its apex in the sky on a sunny day. This figure is often called one 'sun' and is the power level at which solar cells are usually rated. In addition to the regular daily and yearly variation due to the apparent motion of the sun, irregular variations are caused by the climatic conditions (cloud cover), as well as by general composition of the atmosphere. For this reason, the design of a photovoltaic system relies on the input of measured data close to the site of the installation.

A concept, which characterizes the effect of a clear atmosphere on sunlight, is the air mass, equal to the relative length of the direct beam path through the atmosphere (see figure 2-1).

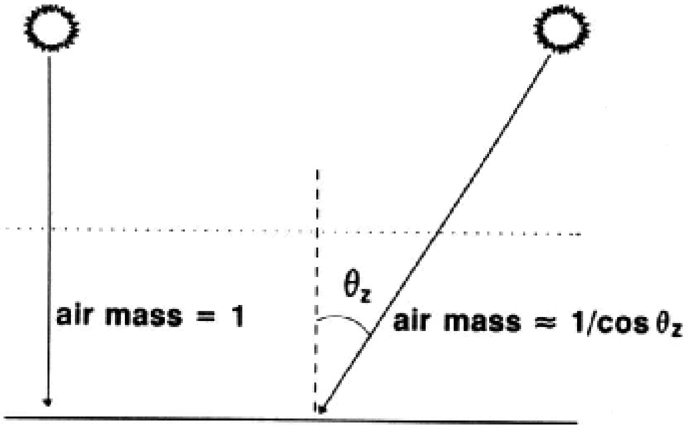


Figure 2-1 Air mass

On a clear summer day at sea level, the radiation from the sun when it is directly overhead corresponds to air mass 1 (AM1). At other times, the air mass is approximately equal to $1/\cos \Theta_Z$, where Θ_Z is the zenith angle, which will be discussed later. The effect of the atmosphere (as expressed by the air mass) on the solar spectrum is shown in figure 2-2. The extraterrestrial spectrum, denoted by AM0, is important for satellite applications of solar cells. AM1.5 is a typical solar spectrum on the earth's surface on a clear day [15].

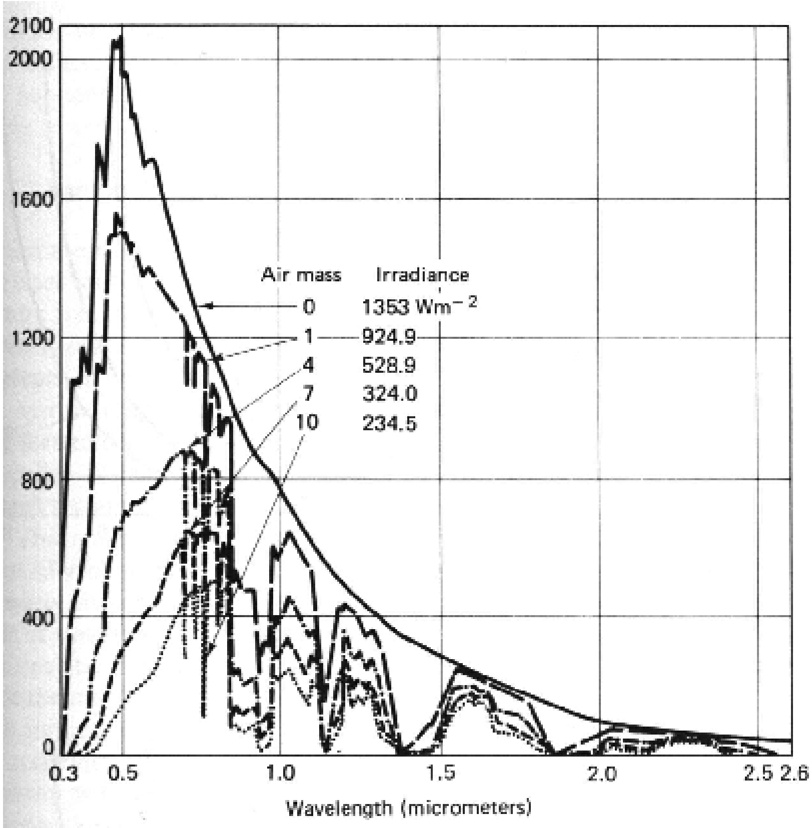


Figure 2-2 Spectral irradiance as a function of air mass

The sunlight received by a surface on earth can be divided in three different types: direct, diffuse and reflected (figure 2-3). Diffuse sunlight approaches a surface from all unobstructed angles, while direct beam rays strike the surface from only one angle. The proportions of direct, diffuse and reflected sunlight that a particular surface will receive depend on variables that are in continuous flux.

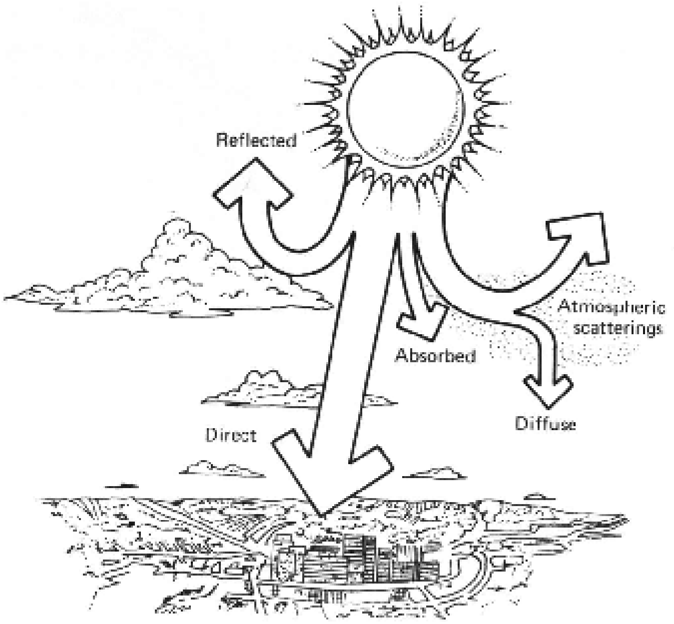


Figure 2-3 Sunlight and the earth's atmosphere

On a cloudy day, all radiation is diffuse. On a sunny winter day at low elevation, humid climate site, the ratio of diffuse to total radiation could be as high as 0.7. In contrast, on a sunny summer day at a high altitude arid climate site, the ratio might be as low as 0.2. More light is reflected by pale than by dark colours. Light reflection often increases in winter when there is snow on the ground and decreases in the summer when the ground is earth or grass coloured. Snow reflects about 70% to 80% of the light it receives, while a grass field reflects only about 15% to 20% [16].

2.2 Sun - Earth Geometric relations

The geometric relationships between the sun and the earth are described in many texts, for example Solar Electricity by T. Markvart.

The Earth revolves around the Sun in an elliptical orbit (very close to a circle) with the Sun as one of the foci. The plane of this orbit is called the ecliptic. The time taken for the Earth to complete this orbit defines a year. The relative position of the Sun and Earth is conveniently represented by means of the celestial sphere around the Earth (figure 2-4). The equatorial plane intersects the celestial sphere in the celestial equator, and the polar axis in the celestial poles. The motion of the Earth round the Sun is then pictured by apparent motion of the Sun in the ecliptic, which is tilted at 23.45° to the celestial equator. The angle between the line joining the centres of the Sun and the Earth and the equatorial plane is called the solar declination and denoted by δ. This angle is zero at the vernal (20/21 March) and autumnal (22/23 September) equinoxes. On these days, the sun rises exactly in the east and sets exactly in the west. At the summer solstice (21/22 June), δ = 23.45° and at the winter solstice (21/23 December), δ = - 23.45°.

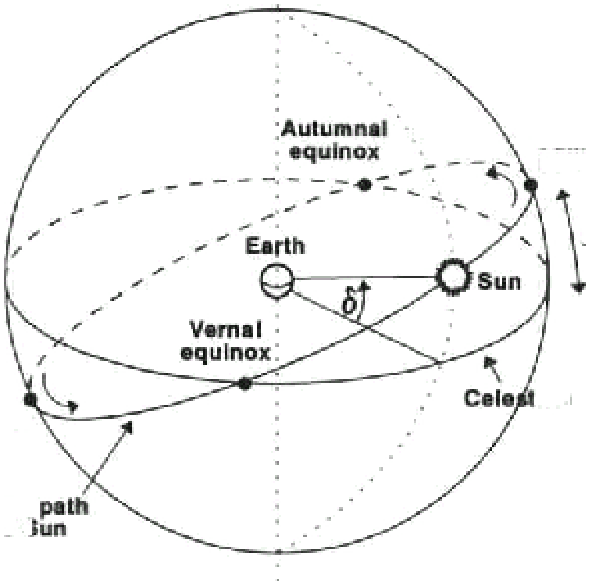


Figure 2-4 The celestial sphere with the apparent yearly motion of the sun

The Earth itself rotates, at the rate of one revolution per day, about the polar axis. The daily rotation of the Earth is depicted by the rotation of the celestial sphere about the polar axis, and the instantaneous position of the sun is described by the hour angle ω, the angle between the meridian passing through the sun and the meridian of the site. The hour angle is zero at solar noon and increases towards the east (Figure 2-5). For an observer on the Earth's surface at a location with geographical latitude Φ, a vertical line at the site, which intersects the celestial sphere in two points, the zenith and the nadir, and subtends the angle Φ with the polar axis, defines a convenient coordinate system. The great circle perpendicular to the vertical axis is the horizon. The angle between the sun's direction and the horizon is the elevation a, whose complement to 90° is the zenith angle Θ_Z. The other coordinate in this system is the azimuth ψ, which is zero at solar noon and increases towards the east. During the daily motion, the solar declination δ can usually be assumed constant and equal to its value at midday.

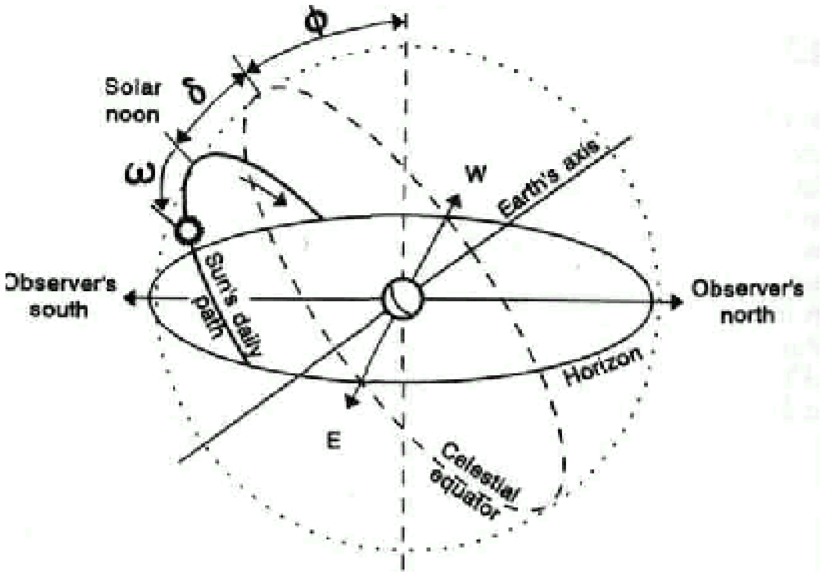


Figure 2-5 The local zenith nadir coordinate system showing the apparent daily motion of the sun.

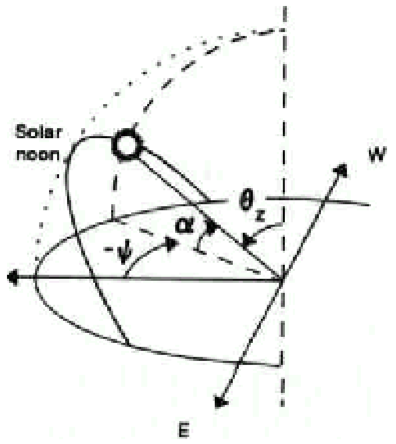


Figure 2-6 Definition of the azimuth, solar elevation and the zenith angle

The sun's azimuth and altitude are calculated from the latitude and hour angle of a place using Equations 2-1 and 2-2 [17]. The following relationships will be used to calculate the amount of solar radiation falling on a sloped surface.

$$\sin\alpha = \sin\delta \sin\Phi + \cos\delta \cos\Phi \cos\omega = \cos\Theta_Z \qquad (2\text{-}1)$$

$$\cos\psi = \frac{(\sin\alpha \sin\Phi - \sin\delta)}{\cos\alpha \cos\Phi} \qquad (2\text{-}2)$$

These equations can be used to determine the sunrise hour angle ω_S.

$$\omega_S = \cos^{-1}(-\tan\Phi \tan\delta) \qquad (2\text{-}3)$$

2.3 Radiation on a sloped surface

Most of the daily solar radiation data, when available, are measured and given on a horizontal surface. The orientation of a surface that maximizes the energy (tilt and azimuth angle) is not considered in the data. The optimal tilt angle for an entire year depends on the latitude of the site and can vary considerably. The horizontal energy data must be adjusted to energy expected on a tilted surface, and a series of equations are used for this procedure.

The conversion of average daily energy per square meter on a horizontal surface depends on the declination (time of year), the latitude of the site and the tilt angle of a south facing slopping surface. It is also necessary to know the relative proportions of direct, diffuse and reflected light that the sloped surface will experience. The first step in the conversion process is to determine the ratio between radiation on tilted and horizontal surfaces. The final stage is to multiply this ratio by the average daily horizontal energy. The procedure is presented below. The derivation of the equation follows [18].

The relative proportion of diffuse to total radiation (assuming light reflection is zero) is calculated from the clarity coefficient or clearness index K_T using the empirical formula in equation

$$\frac{\overline{H}_d}{H} = 1.39 - 4.03K_T + 5.53K_T^2 - 3.11K_T^3 \qquad (2\text{-}4)$$

The clarity coefficient is the ratio between the insolation experienced at the site and the insolation that would be experienced if the earth had no atmosphere. This coefficient is based on measured data for different sites and months of the year. Since light reflection is assumed to be zero, the ratio of direct beam to total insolation must be 1 minus the ratio of diffuse to total insolation.

The ratio of direct beam insolation on a tilted surface to direct beam insolation on the horizontal can be estimated by ignoring the effects of the atmosphere on sunlight and using equation 2-5 [19]. All angles are given in degrees.

$$\overline{R}_b = \frac{\cos(\Phi-\beta)\cos(\delta)\sin(\omega_S') + \left(\pi/180\right)\omega_S' \sin(\Phi-\beta)\sin\delta}{\cos\Phi\cos(\delta)\sin(\omega_S) + \left(\pi/180\right)\omega_S \sin\Phi\sin\delta} \qquad (2\text{-}5)$$

The variables in this equation are the latitude, declination of the sun, surface tilt angle and sunset hour angle of the horizontal and tilted surface. The declination for any day can be found by using equation 2-6.

$$\delta = 23.45\sin\left(360\frac{284+n}{365}\right) \qquad (2\text{-}6)$$

The sunset hour angles for the horizontal and for the tilted surface are computed using equations 2-7 and 2-8. During the summer months, the sun may set on the tilted surface, before it sets on the horizon (at these times the sun also would rise first on the horizon and then on the tilted surface). Consequently, equation 2-8 requires that we take the minimum of two calculations.

$$\omega_S = \cos^{-1}(-\tan\Phi\tan\delta) \tag{2-7}$$

$$\omega'_S = \min\begin{bmatrix}\cos^{-1}(-\tan\Phi\tan\delta) \\ \cos^{-1}(-\tan(\Phi-\beta)\tan\delta)\end{bmatrix} \tag{2-8}$$

The amount of light that is reflected off the ground is estimated by using a factor that ranges from 0 to 1. Common reflection coefficients for different materials are listed in table 2-1 [20].

Table 2-1 Ground reflectance for various surfaces

Surface	*Ground Reflectance*
Ocean	0.05
Bituminous Concrete	0.07
Wheat Field	0.07
Dark Soil	0.08
Green Field	0.12 to 0.25
Grass, Dry	0.20
Concrete, old	0.24
Concrete, light colored	0.30
Paved asphalt	0.18
Concrete, new	0.32
Snow, fresh	0.87
Snow, old	0.50

The ratio of average daily energy on the tilted surface to that on the horizontal surface is calculated using the following equation

Equation

$$R = \frac{\overline{H}_T}{H} = \left(1 - \frac{\overline{H}_d}{H}\right)\overline{R}_b + \frac{\overline{H}_d}{H}\left(\frac{1+\cos\beta}{2}\right) + \rho\left(\frac{1-\cos\beta}{2}\right) \qquad (2\text{-}9)$$

Notice how this equation how the equation is the sum of three different factors that indicate the relative proportions of direct beam, diffuse and reflected light. Multiplying the daily horizontal energy for the location and month under consideration by the ratio computed above will provide us with the daily energy per square meter on a tilted surface. We can get the average horizontal insolation from figure (2-7) or compute it from the following equation (2-10)

$$H = K_T \times S_{OH} \qquad \textbf{(2-10)}$$

where S_{OH} is the extraterrestrial insolation on a horizontal surface and is found from equation 2-11 [21].

$$S_{OH} = S_O \frac{24}{\pi}\left(\cos\Phi\cos\delta\cos\omega_S + \frac{\omega_S}{180}\sin\Phi\sin\delta\right) \qquad (2\text{-}11)$$

$$S_O = 1.356\left(1 + 0.0167\cos\left(\frac{day}{365}\times 360\right)\right)^2 \qquad (2\text{-}12)$$

The solar radiation on an inclined surface is therefore:

$$H_T = R \times H \qquad (2\text{-}13)$$

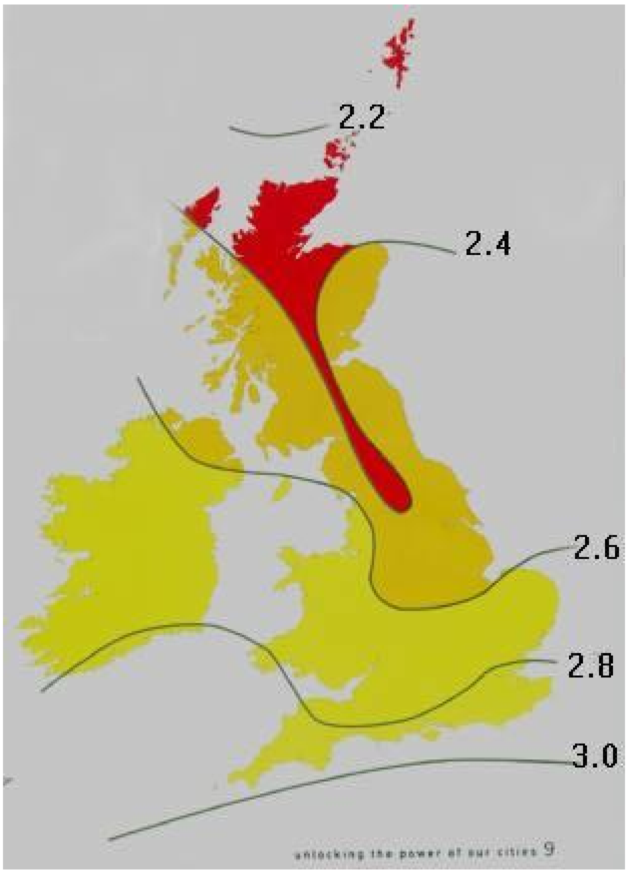


Figure 2-7 UK Solar energy resource map- annual average solar energy in kWh/m^2 day (DTI 1994)

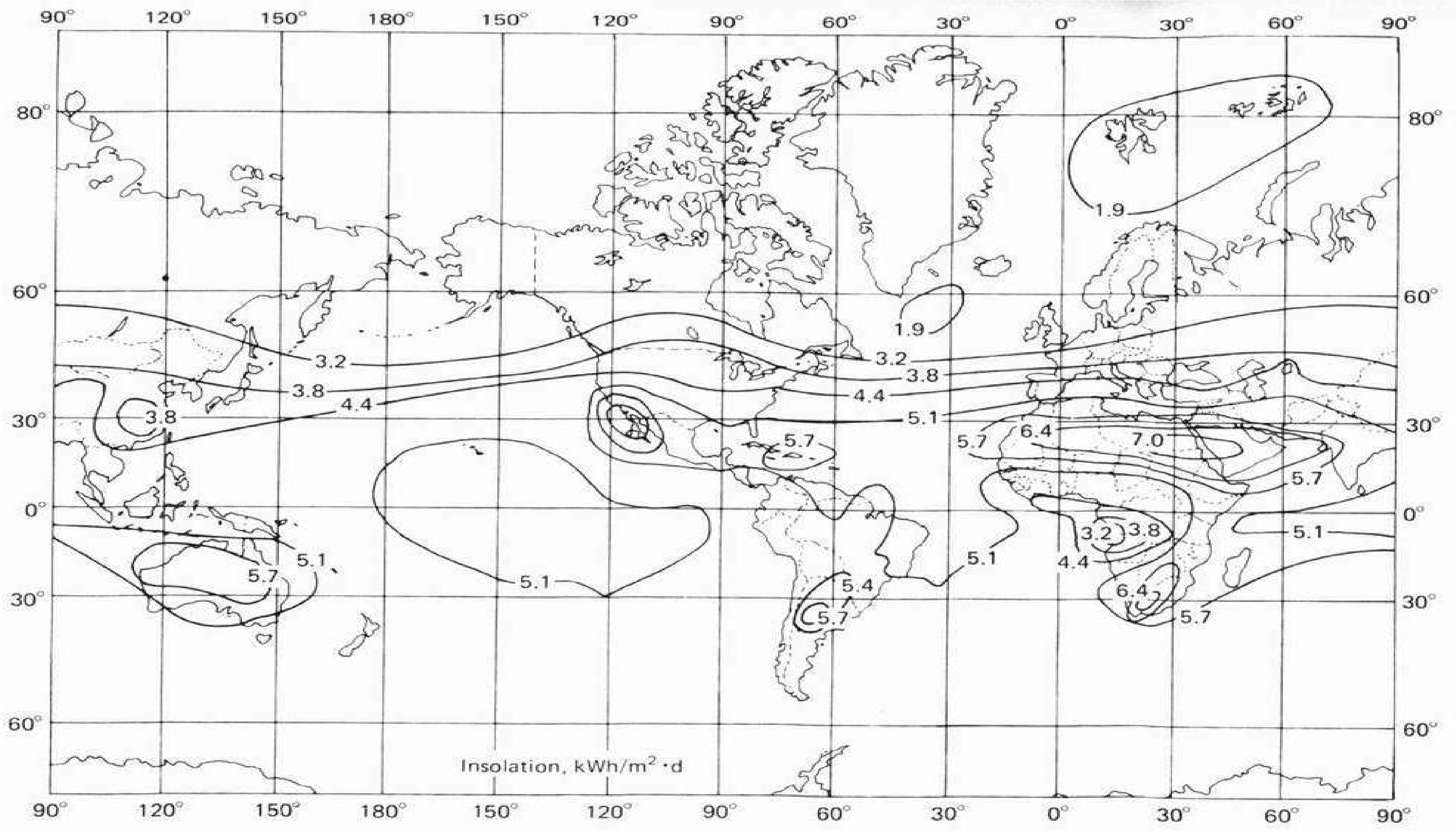


Figure 2-8 World annual average insolation on a horizontal surface kWh/

Table 2-2 Notation and units

Symbol		SI unit
H	Monthly average daily total radiation on a horizontal surface	kWh/m^2
$\overline{H}_d$	Monthly average daily diffuse radiation on a horizontal surface	kWh/m^2
$\overline{H}_T$	Monthly average daily total radiation on a south-facing tilted surface	kWh/m^2
K_T	Clearness index or Clarity coefficient	
R	Ratio of monthly average daily total radiation on a tilted surface to that on a horizontal surface	
$\overline{R}_b$	Ratio of monthly daily direct beam radiation on a tilted surface to that on a horizontal surface	
S_0	Extraterrestrial radiation on a plate normal to the sun's rays	kW/m^2
S_{0H}	Daily extraterrestrial insolation on a horizontal surface	kWh/m^2
N	Day of the year	
A	Solar elevation	
B	Panel inclination to horizontal surface	
Δ	Solar declination	
$Θ_Z$	Zenith angle	
P	Ground reflectivity	
Φ	Geographical altitude	
Ψ	Azimuth	
Ω	Sunset hour angle on horizontal surface	
$ω_S$	Sunset hour angle on a tilted surface	

CHAPTER 3

3 Solar cell technology

3.1 Introduction to photovoltaic technologies

Solar cells represent the heart of the photovoltaic system. They are made from semiconductors, and have much in common with other electronic devices, such as diodes, transistors and integrated circuits. For practical operation, solar cells are usually assembled into modules. A conventional solar cell consists of a wafer of silicon that is about 0.25mm thick. Typical cells that are 100mm in diameter produce about one watt of power, and are grouped into modules of dozens of cells.

Many different solar cells are now available on the market, and yet more are under development. The range of solar cells spans different materials and different structures in the quest to extract maximum power from the device while keeping the cost to a minimum. Devices with efficiency exceeding 30% have been demonstrated in the laboratory. The efficiency of commercial devices, however, is usually less than half this value.

Crystalline silicon cells hold the largest part of the market. To reduce the cost, these cells are now often made from polycrystalline material, rather than from the more expensive single crystals. Crystalline silicon cell technology is well established. The modules have long lifetime (20 years or more) and their best production efficiency is approaching 18%.

3.2 Some semiconductor physics

The operation of solar cells is based on the ability of semiconductors to convert sunlight directly into electricity by exploiting the Photovoltaic Effect. In the conversion process, the incident energy of light creates mobile charged particles in the semiconductor, which are then separated by the device structure and produce electrical current.

To help us understand how solar cells work, we shall first examine the following elements of semiconductor physics:

- The characteristic distribution of electron energies within the semiconductor
- How the electrical properties of semiconductors can be controlled by the addition of impurities
- How illumination creates mobile charged particles called electrons and holes at the semiconductor junction

3.2.1 Band structure and Doping

Many of the electronic properties of semiconductors, can be explained with a simple model. Figure 3-1 shows the arrangement of silicon atoms in the silicon crystal. Each silicon atom in the crystal has four valence (outer orbit) electrons, which it shares with four neighboring atoms. This tetrahedral (4 point) bonding is very stable. This crystal form is called *diamond lattice*. Each of the four bonds contains two electrons, and you can easily see that the bonds take up all the valence electrons.

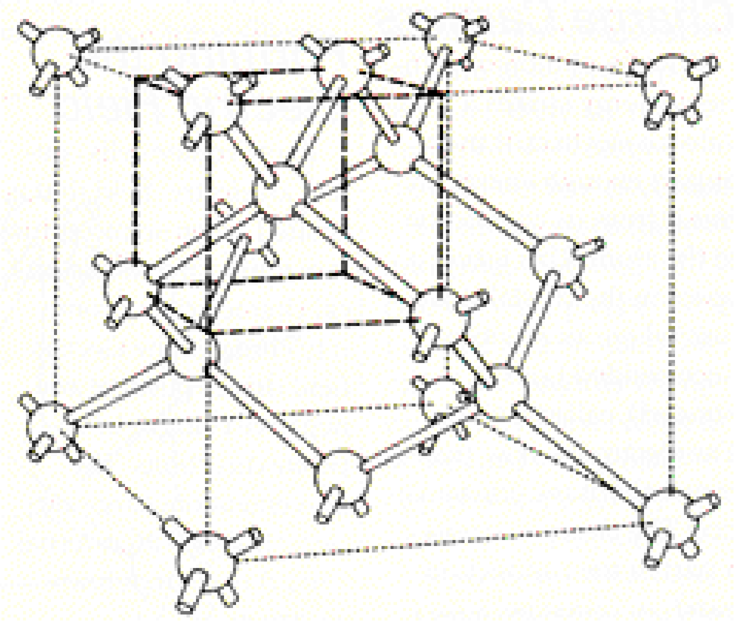


Figure 3-1 The diamond lattice.

It takes 1.12 eV of energy known as the *bandgap* energy of silicon, to separate an electron from the nucleous and create a free *conduction* electron. This table gives the bandgaps of the most important semiconductors for solar-cell applications.

Table 3-1 Bandgap values for different materials

Material	Energy gap (eV)	Type of gap
Crystalline Si	1.12	Indirect
Amorphous Si	1.75	Direct
$CuInSe_2$	1.05	Direct
CdTe	1.45	Direct
GaAs	1.42	Direct
InP	1.34	Direct

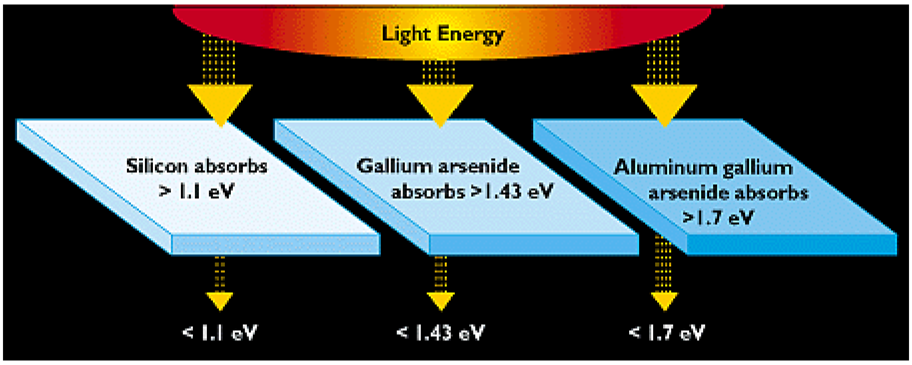
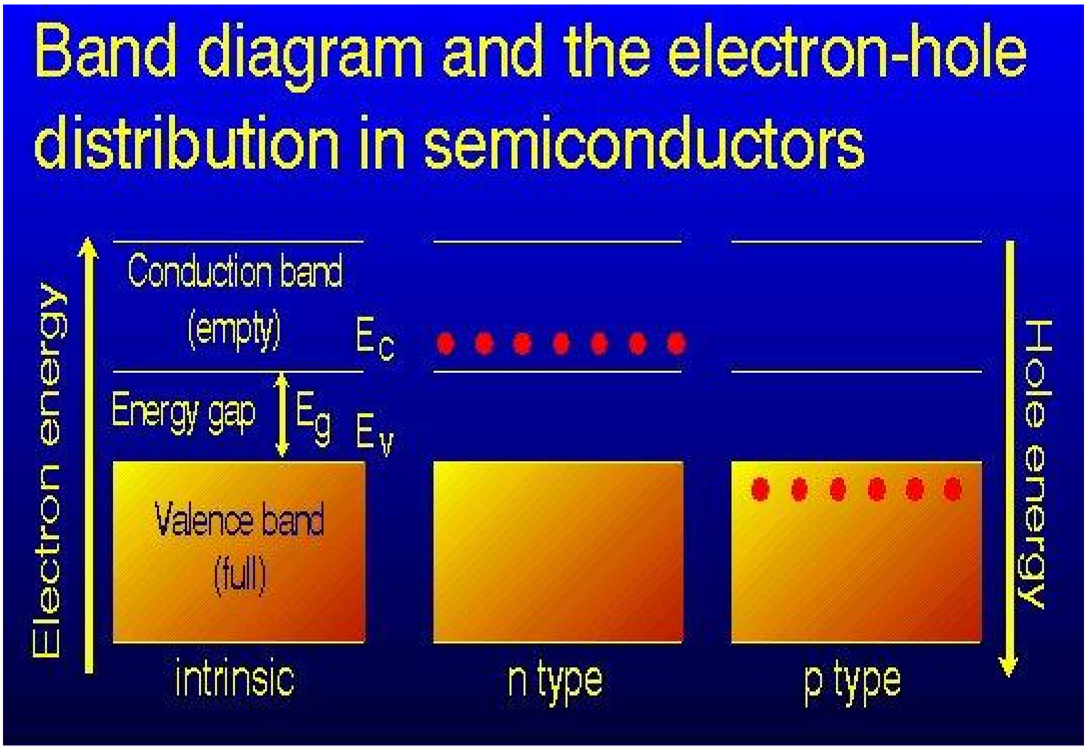


Figure 3-2-Different PV materials have different characteristic energy band gaps. [21]

A pure semiconductor (which is called *intrinsic*) contains just the right number of electrons to fill the valence band, and the conduction band is therefore empty. Electrons in the full valence band cannot move - just as, for example, marbles in a full box with a lid on top. For practical purposes, a pure semiconductor is therefore an insulator.



Band diagram and the electron-hole distribution in semiconductors

Figure 3-3 Band diagram and electron hole distribution in semiconductors. Source http://www.soton.ac.uk/~solar/

Semiconductors can only conduct electricity if carriers are introduced into the conduction band or removed from the valence band. One way of doing this is by alloying the semiconductor with an impurity. This process is called *doping*.

Suppose that some group 5 impurity atoms (for example, phosphorus) are added to the silicon melt from which the crystal is grown. Four of the five outer electrons are used to fill the valence band and the one extra electron from each impurity atom is therefore promoted to the conduction band. For this reason, these impurity atoms are called *donors*. The electrons in the conduction band are mobile, and the crystal becomes a conductor. Since negatively charged electrons carry the current, this type of semiconductor is called *n type*.

A similar situation occurs when silicon is doped with group 3 impurity atoms (for example, boron), which are called *acceptors*. Since four electrons per atoms are needed to fill the valence band completely, this doping creates electron deficiency in this band. The missing electrons - called *holes* - behave as positively charged particles, which are mobile, and carry current. A semiconductor where the electric current is carried predominantly by holes is called *p-type*

3.2.2 Semiconductor junctions

The operation of solar cells is based on the formation of a *junction* between a p-type and a n-type semiconductor or p-n junction. The important feature of all junctions is that they contain a strong electric field. In separation, there is electron surplus in the n-type material and hole surplus in the p-type. Due to differences in electron and hole concentration on the two sides, there is a strong tendency for electrons to diffuse from the n side to the p side and for the holes to diffuse in the opposite direction. Such diffusions would cause positive charges to appear on the n side and negative charges to appear on the p side.

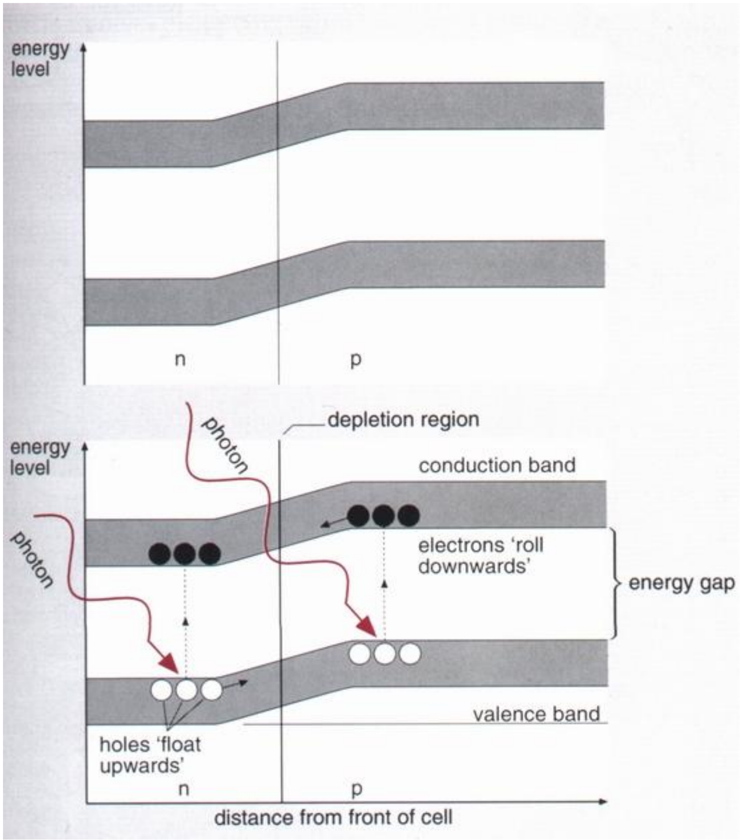


Figure 3-4 Band structure of a p-n junction

The resulting junction region then contains practically no mobile charge carriers, and the fixed charges of the dopant atoms create a potential barrier acting against a further flow of electrons and holes. Note that the electric field in the junction pulls the electrons and holes in opposite directions.

The potential barrier of a junction permits the flow of electric current in only one direction - the junction acts as a rectifier, or diode. This can be seen in our example where electrons can only flow from the p region to the n region, and holes can only flow in the opposite direction. Electric current, which is the sum of the two, can therefore flow only from the p-side to the n-side of the junction (remember that it is defined as the direction of flow of the positive carriers!). The *I-V* characteristic of a diode is shown in figure 3-5.

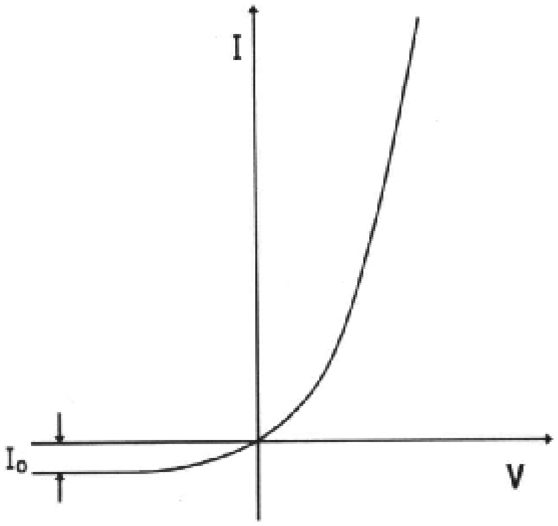


Figure 3-5 The diode I-V characteristic

To see how a diode under illumination becomes a solar cell, we must first consider how light is absorbed by a semiconductor.

3.2.3 Generation caused by light absorption

Photovoltaic energy conversion relies on the quantum nature of light whereby we perceive light as a flux of particles called photons. On a clear day, about 4.4 x 10^{17} photons strike a square centimeter of the Earth's surface every second.

Only some of these photons - those with energy in excess of the bandgap - can be converted into electricity by the solar cell. When such photon enters the semiconductor, it may be absorbed and promote an electron from the valence to the conduction band (figure 3-6). Since a hole is left behind in the valence band, the absorption process generates *electron-hole pairs*.

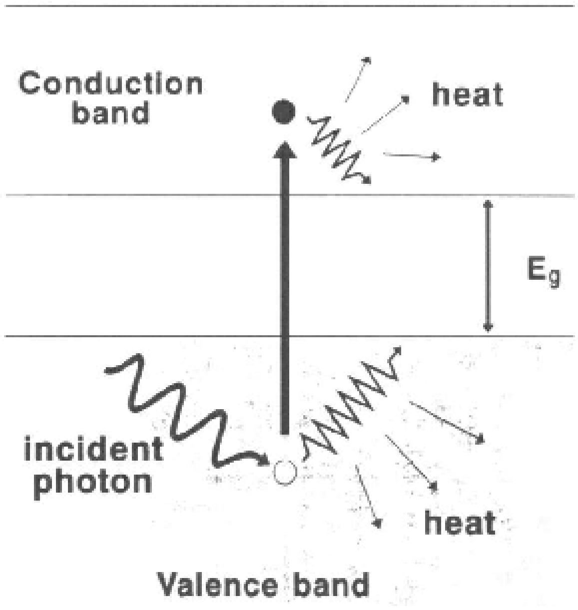


Figure 3-6 The generation of electron hole pairs by light

Each semiconductor is restricted to converting only a part of the solar spectrum (figure 3-7). The spectrum is plotted here in terms of the incident photon flux as a function of photon energy. The shaded area represents the photon flux that can be converted by silicon cell - about two-thirds of the total flux. The nature of the absorption process also indicates how a part of the incident photon energy is lost in the event. Indeed, it is seen that practically all electron-hole pairs by photons with energy in excess of the bandgap. Immediately after their creation, the electron and hole decay to states near the edges of their respective bands. The excess energy is lost as heat and cannot be converted into useful power. This represents one of the fundamental loss mechanisms in a solar cell. A solar cell is a device that transforms this electron traffic across the bandgap into electric current.

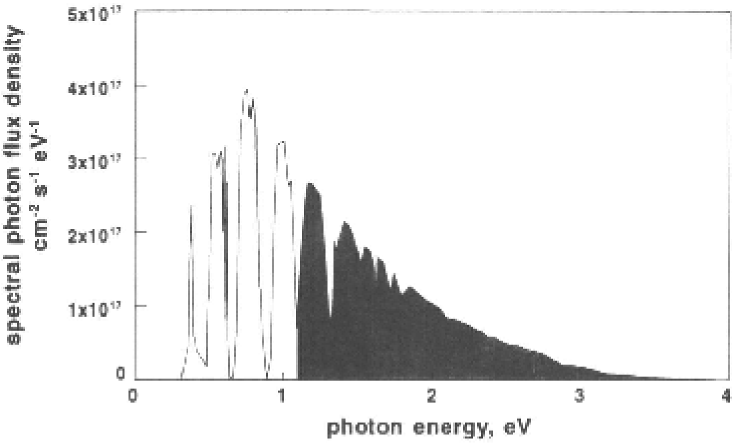


Figure 3-7 Photon flux utilized by solar cell

3.3 How solar cells work

This diagram shows a typical crystalline silicon solar cell. The electrical current generated in the semiconductor is extracted by contacts to the front and rear of the cell. The top contact structure, which must allow light to pass through is made in the form of widely spaced thin metal strips (usually called *fingers*) that supply current to a larger bus bar. The cell is covered with

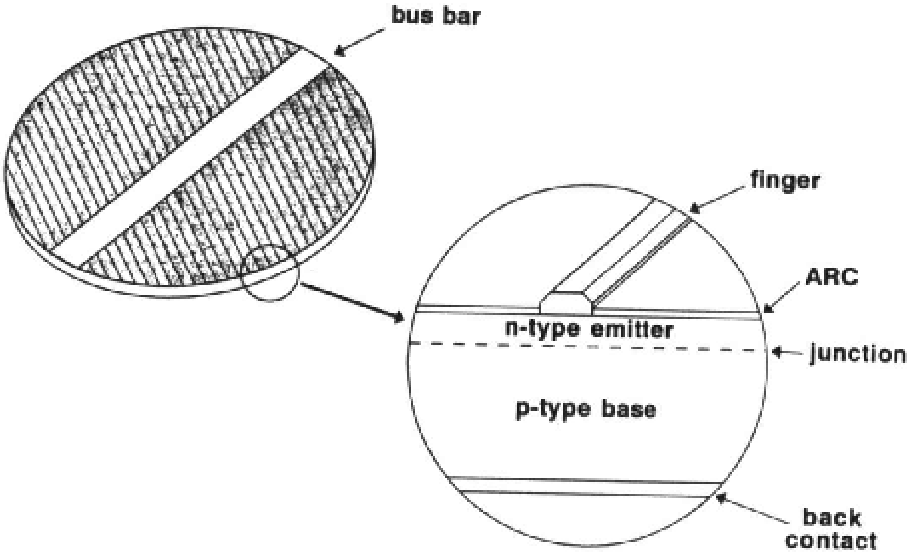


Figure 3-8 The silicon solar cell

a thin layer of dielectric material - the *anti-reflection coating*, ARC - to minimize light reflection from the top surface.

Solar cells are essentially semiconductor junctions under illumination. Light generates electron-hole pairs on both sides of the junction, in the n-type emitter and in the p-type base. The generated electrons (from the base) and holes (from the emitter) then diffuse to the junction and are swept away by the electric field, thus producing electric current across the device. Note how the electric currents of the electrons and holes reinforce each other since these particles carry opposite charges. The p-n junction therefore separates the carriers with opposite charge, and transforms the generation current between the bands into an electric current across the p-n junction.

A more detailed consideration makes it possible to draw an equivalent circuit of a solar cell in terms of a current generator and a diode. This equivalent circuit has a current-voltage relationship.

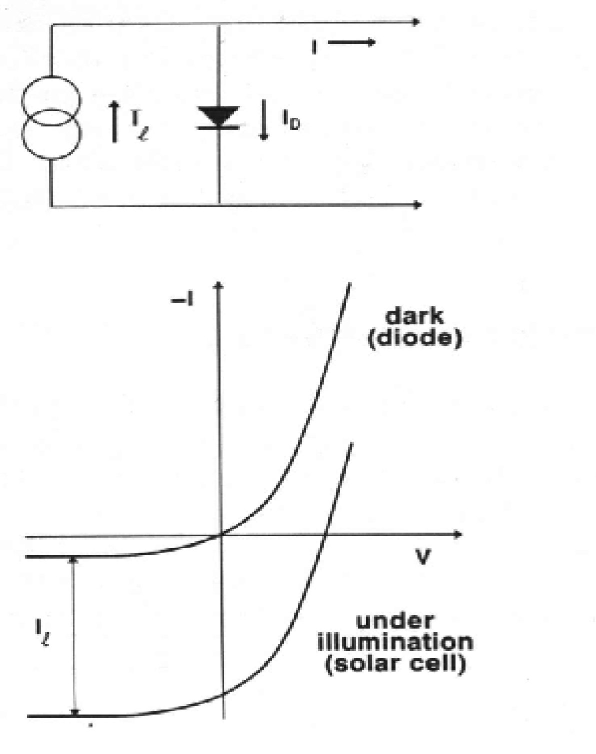


Figure 3-9 Equivalent circuit and I-V characteristic of a solar cell compared to a diode

In solar cell applications this characteristic is usually drawn inverted about the voltage axis, as shown below. The cell generates no power in short-circuit (when current I_{sc} is produced) or open-circuit (when cell generates voltage V_{oc}). The cell delivers maximum power P_{max} when operating at a point on the characteristic where the product IV is maximum.

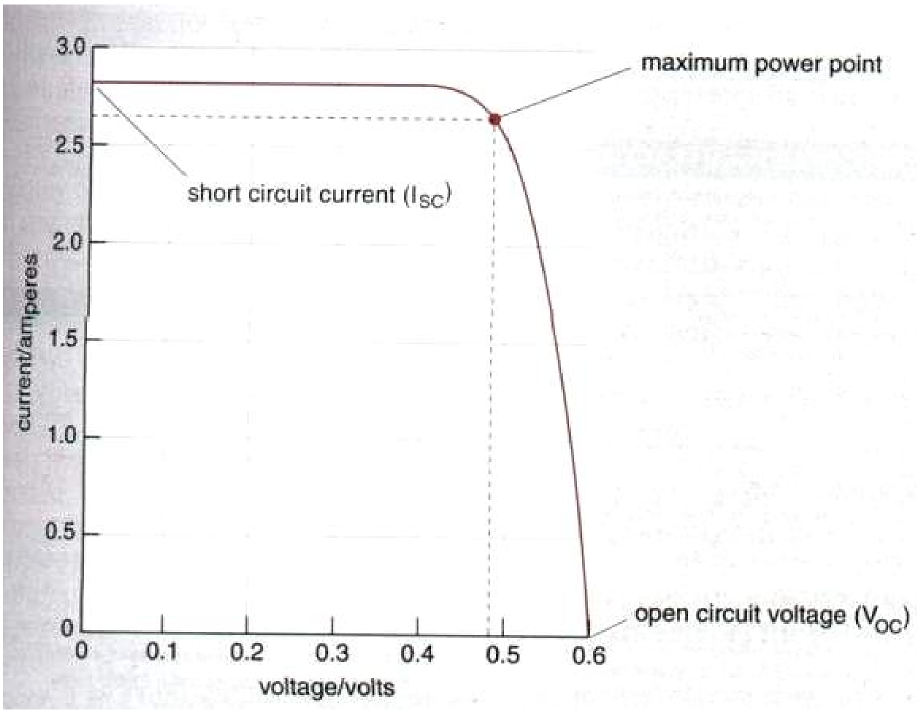


Figure 3-10 The I-V characteristic of a solar cell

Above is shown graphically where the position of the maximum power point represents the largest area of the rectangle shown.

The efficiency of a solar cell is defined as the power P_{max} supplied by the cell at the maximum power point under standard test conditions, divided by the power of the radiation incident upon it. Most frequent conditions are: irradiance 1 kW/m^2, standard reference spectrum AM1.5, and ambient temperature 25 ^{0} C. The use of this standard irradiance value is particularly convenient since the cell efficiency in percent is then numerically equal to the power output from the cell in kW/m^2.

3.4 Factors affecting the electrical characteristics

3.4.1 The temperature and irradiance effects

In practical applications, solar cells do not operate under standard conditions. The two most important effects we must examine are the temperature and the irradiance.

So temperature influences the solar cell during its operation. Cells perform more efficiently when working under low temperatures. As the temperature of the cell increases, its operating efficiency will decrease slightly. The figure 3-9 shows the I-V curves for a cell under various temperature conditions. The cell current will increase as the temperature is rising at a rate of 0.5 mA per ^{0}C. The voltage on the other hand, will decrease 2.3 mV per ^{0}C. The above combined effect will result a decrease in the power output of the cell at a rate of 0.3 to 0.5 percent for every degree Celsius. The result is that in hotter regions solar cells will be less efficient than in colder climates [22].

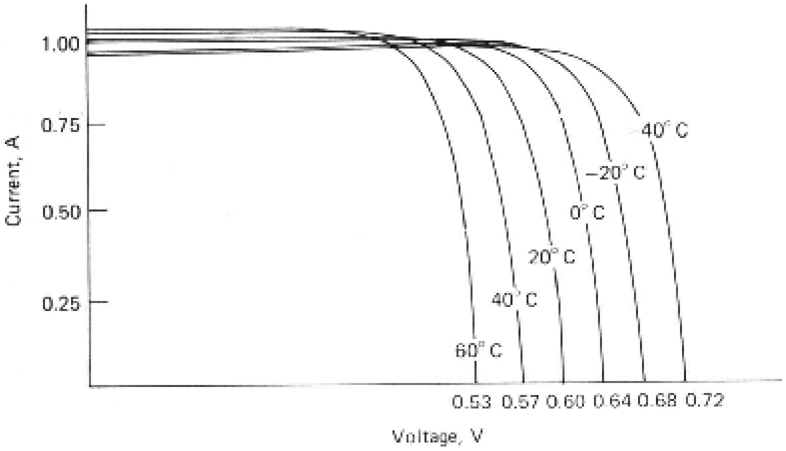


Figure 3-11 Changing voltage with changing temperature

The solar cell characteristics, under different levels of illumination are shown in figure 3-10. The maximum value for unconcentrated sunlight reaching the earth is 1kW/m^2. As the intensity of the sunlight decreases, the shape of the curve remains almost the same. We also notice that the current

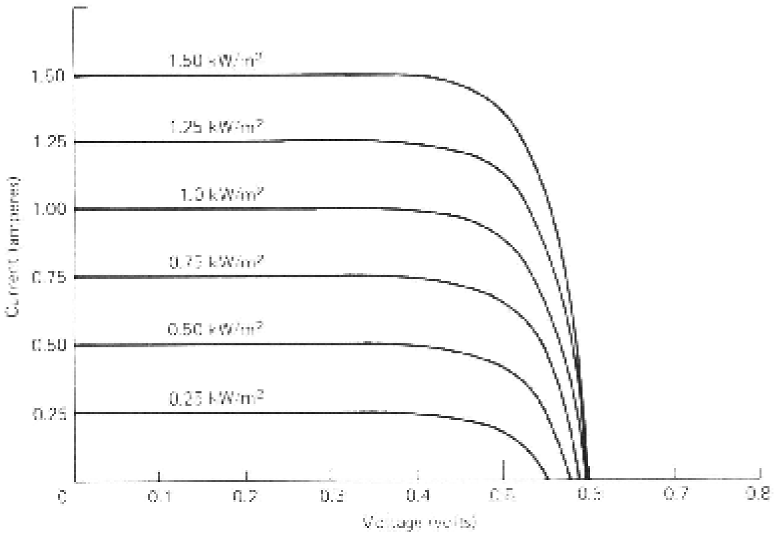


Figure 3-12 Changing current with changing insolation

is greatly decreasing with the illumination and this is because the light-generated current is proportional with the flux of photons with above-bandgap energy. As the irradiance decreases, the photon flux generates a proportional lower current. In all cases, maximum power is achieved at the knee of the curve, regardless the sun intensity. The voltage of the cell does not change very much under varying irradiation and usually is neglected in practical applications.

3.4.2 Effect of the number of cells in a module

The number of cells in a module usually affects the voltage. Each cell produces a voltage of about 0.5V [23]. As each cell is added in the series of a module, it increases the V_{OC} of the module by about 0.5V, without affecting the current. In figure 3-11 we have the I-V curves, for various numbers of cells in a module. There appears to be no advantage in having more than 33 cells, unless high voltage is needed. Modules with more cells are needed for sites in hot climates. The extra cells compensate for the drop in voltage caused by the cells having to operate in higher temperatures.

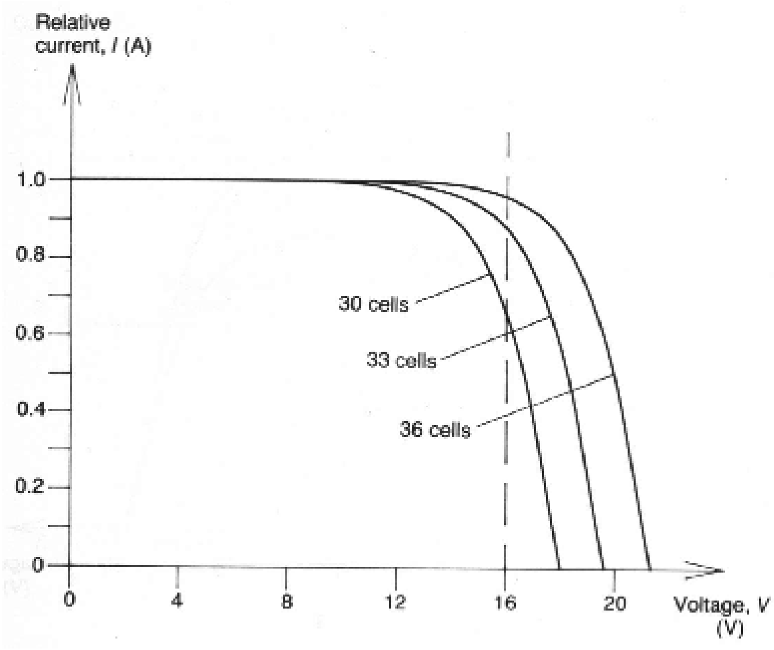


Figure 3-13 The effect of number of cells in the I-V curve for the solar module

3.5 Solar cell materials

The most important parts of a solar cell are the semiconductor layers, because this is where the electron current is created. There are a number of different materials suitable for making these semi-conducting layers, and each has benefits and drawbacks. Unfortunately, there is no one ideal material for all types of cells and applications.

In addition to the semi conducting materials, solar cells consist of a top metallic grid or other electrical contact to collect electrons from the semiconductor and transfer them to the external load, and a back contact layer to complete the electrical circuit. Then, on top of the complete cell is typically a glass cover or other type of transparent encapsulant to seal the cell and keep weather out, and an antireflective coating to keep the cell from reflecting the light back away from the cell. In general, PV materials are categorized as either thick crystalline (sliced from boules or casting) or thin film (deposited in thin layers on a substrate) polycrystalline or amorphous.

3.5.1 Thick Crystalline Materials

3.5.1.1 Silicon

The use of crystalline silicon for PV production is one of the best known of the PV technologies, and the European PV market has been essentially based on crystalline silicon, which is likely to be the case for the forthcoming decade. The prime advantages for crystalline silicon PV systems that make the technology attractive to industry for production are:

- The raw material is widely available;
- It contains uniform electrical, mechanical and chemical qualities due to its crystalline structure;
- Silicon is non-toxic and environmentally benign.
- The process of the PV cell manufacture is relatively simple. Hence production is capable of being automated;
- PV modules have a long life span, easily achieving 30 years.

The production process for silicon crystals has some disadvantages that have large financial implications. These disadvantages are associated with:

- The thickly cut material from high quality, expensive silicon ingots or cast blocks;
- Cells have to be restricted to certain sizes, which require the addition of tabbing or interconnections;
- The process of manufacture is intensive in energy and other resources, requiring a substantial investment for production equipment and facilities.

Mono-crystalline silicon produces the most efficient cells but is more costly. It is produced by the extraction of a slow cooling ingot from molten silicon at a rate such that the crystals, or grains, within the cells are large. The aim is to reduce the number of grain boundaries by growing the crystals as large as possible, as inter crystal discontinuities have a detrimental effect on the conversion efficiency. Multi-crystalline silicon is of lesser quality but more cost effective in production. It is basically produced by the cooling of molten silicon at a controlled rate within an impurity free environment. With current production techniques, crystalline silicon cells the conversion efficiencies are around 15%, noting that the theoretical maximum for silicon is 30%.

3.5.1.2 Gallium Arsenide

Gallium arsenide (GaAs) is a compound semiconductor: a mixture of two elements, gallium (Ga) and arsenic (As). Gallium is a by-product of the smelting of other metals, notably aluminium and zinc, and it is more rare than gold. Arsenic is not rare, but it is poisonous. The properties of Gallium Arsenide make it a very suitable raw material for solar cells. It has a band gap of 1.4 eV and much higher solar radiation absorption than silicon. Because of this it can have a thickness of 2 micrometers compared to 100 micrometers of silicon [24]. Research cells give efficiencies greater than 25 percent under 1-sun conditions, and nearly 28 percent under concentrated sunlight [25].

3.5.2 Thin-Film Materials

There are a variety of technologies that are available for the production of thin-film PV cells. The use of thin-film technology is ideally aimed at building integration such as replacement of glass panelling on buildings, and replacement of roofing tiles etc. A major advantage of this form of PV technology is the ability to produce panels in arbitrary shapes making them ideal for the building integration on any designed structure. The types of materials used in common thin-film technologies are amorphous silicon (a-Si), Cadmium Telluride (CdTe) and Copper Indium Diselenide (CIS). CdTe and CIS have high efficiency conversion rates for thin-film technologies. However, there are toxic waste problems associated with both the production and eventual disposal of these materials. Amorphous silicon is the best known of the thin-film technologies. Unlike crystalline materials, amorphous silicon holds no crystalline structure; i.e. the position and angle of the silicon atoms form no correlating pattern. To date, the use of amorphous cells have been limited to small consumer products such as calculators. Amorphous PV units are currently beginning to penetrate the consumer power market, such as battery chargers and street lamps (products up to 50W).

The advantages of amorphous silicon can be summed up as:

- Low material cost during production. Large area thin-film technology is the promise to reduce costs even more
- Low toxicity of PV materials, i.e. no disposal hazards;
- Low energy requirements for production;
- Can be produced in arbitrary shapes and sizes making it ideal for building integration etc.

The disadvantages associated with amorphous technology include:

- The complexity of the technology (vacuum and batch processing etc) results in high initial investment costs.
- Amorphous silicon is unstable and the conversion efficiency degrades (to a stabilised value) after a period of time.
- The stabilized conversion efficiency is relatively low.

3.5.2.1 . Amorphous silicon

Amorphous silicon, like common glass, is material in which the atoms are not arranged in any particular order. They do not form crystalline structures at all, and they contain large numbers of structural and bonding defects. Amorphous silicon absorbs solar radiation 40 times more efficiently than does single-crystal silicon, so a film only about 1 micron (10^{-6}m) thick can absorb 90% of the usable solar energy [26]. This is one of the most important factors affecting its potential for low cost. Other principal economic advantages are that amorphous silicon can be produced at a lower temperature and can be deposited on low-cost substrates. These characteristics make amorphous silicon the leading thin-film PV material. In 1996, amorphous silicon constituted more than 15% of the worldwide PV production. Small experimental a-Si modules have exceeded 10-percent efficiency, with commercial modules in the 5% - 7% range [27]. Used mostly in consumer products, a-Si technology holds great promise in building-integrated systems, replacing tinted glass with semi-transparent modules.

The versatility of amorphous silicon is shown in figure flexible roof-shingle module developed under a DOE project called Photovoltaics Building Opportunities in the United States. The tile can be built right into new homes where planning restrictions would prohibit more conventional PV modules.

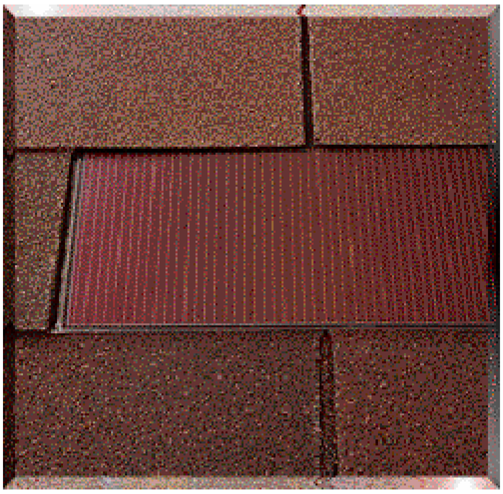


Figure 3-14 Tile integrated in rooftop

3.5.2.2 Cadmium Telluride (CdTe)

This is a thin-film polycrystalline material, deposited by electro deposition, spraying, and high-rate evaporation and holds the promise of low-cost production. Small laboratory devices approach 16-percent efficiency, with commercial-sized modules (7200-cm^2) measured at 8.34-percent efficiency and production modules at approximately 7 percent [28].

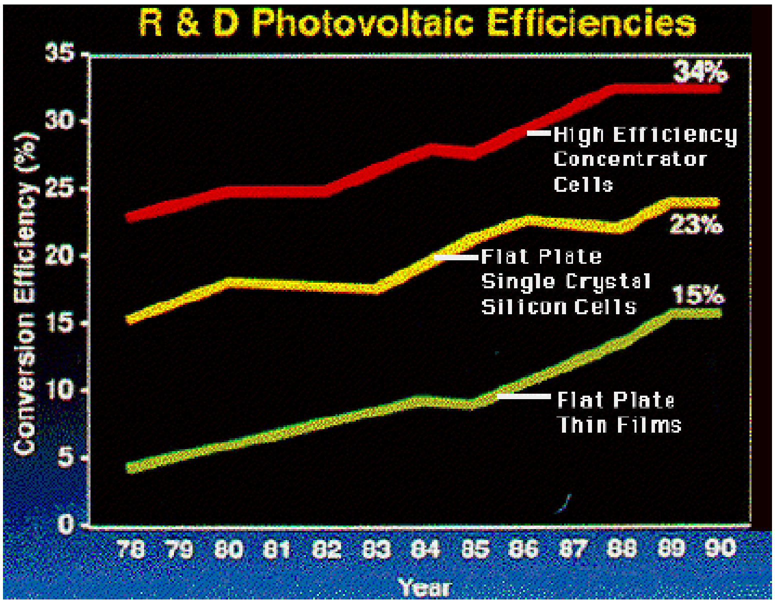


Figure 3-15 Efficiencies for different types of solar cells

4 The photovoltaic system

4.1 Introduction

A complete photovoltaic power system does not end with the solar module, but requires several additional components for efficient operation. One of the major strengths of photovoltaic systems is modularity. As needs grow, components can be replaced or added to increase capacity. Although the selected components will vary depending on the applications, PV systems generally conform to the schematic shown below. The four primary components of a typical solar power electrical system that produces common 110/220-volt power for daily use are:

- The PV generator with a mechanical support and possibly a sun tracking system (PV panels).
- The storage subsystem (Batteries).
- Power conditioning and control equipment (Inverters, Regulators etc)
- Backup generator

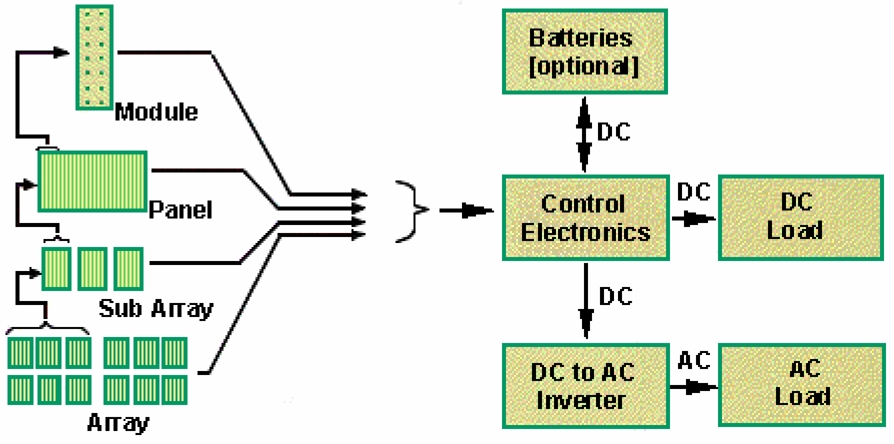


Figure 4-1 Basic photovoltaic system

Solar panels charge the battery. The charge regulator ensures proper charging of the battery. The battery provides DC voltage to the inverter, and the inverter converts the DC voltage to normal AC voltage. The backup generator provides additional energy when the PV system cannot meet the required demand load. All these components have to be properly interconnected, sized and specified for PV operation. The size of the system can vary depending on the application for the system is intended and its geographical location.

There are two main categories of systems, *stand-alone* and *grid connected* (figure 4-2). The stand-alone system uses battery storage to provide dependable DC electricity day and night. For a home connected to the utility grid, PV can produce electricity during the day (converted to AC through a power conditioner). This configuration is desirable because extra electricity can be sold to the utility during the day, and the utility can in turn provide electricity at night or during poor weather.

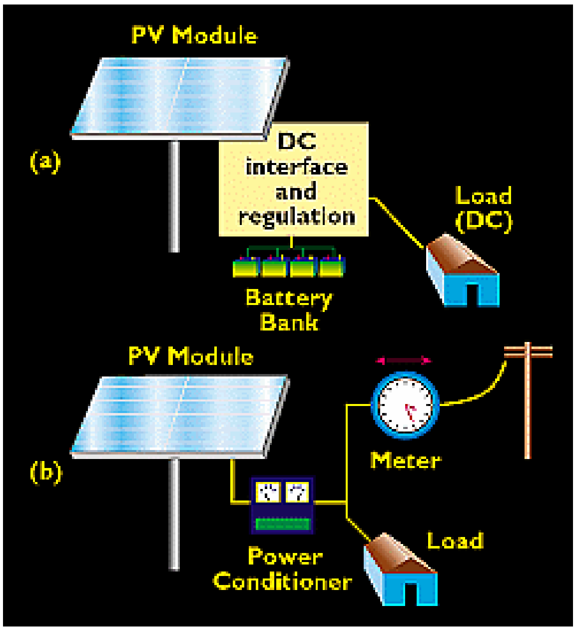


Figure 4-2 Stand alone and grid connected systems

In this chapter, we will look at various types of PV systems, examine the structure of a system, how the various components work together, and analyse each subsystem in detail.

4.2 The PV generator

4.2.1 PV modules

The PV module represents the basic unit of the generator. The modules are interconnected together, in order to form a power-producing unit. These units along with their mounting structures are usually called an *array*.

Each cell provides between 1-1.5 W (under standard conditions) at a voltage of 0.5V. Since very few appliances operate at this voltage, the common practice is to connect cells in series to make up the required voltage.

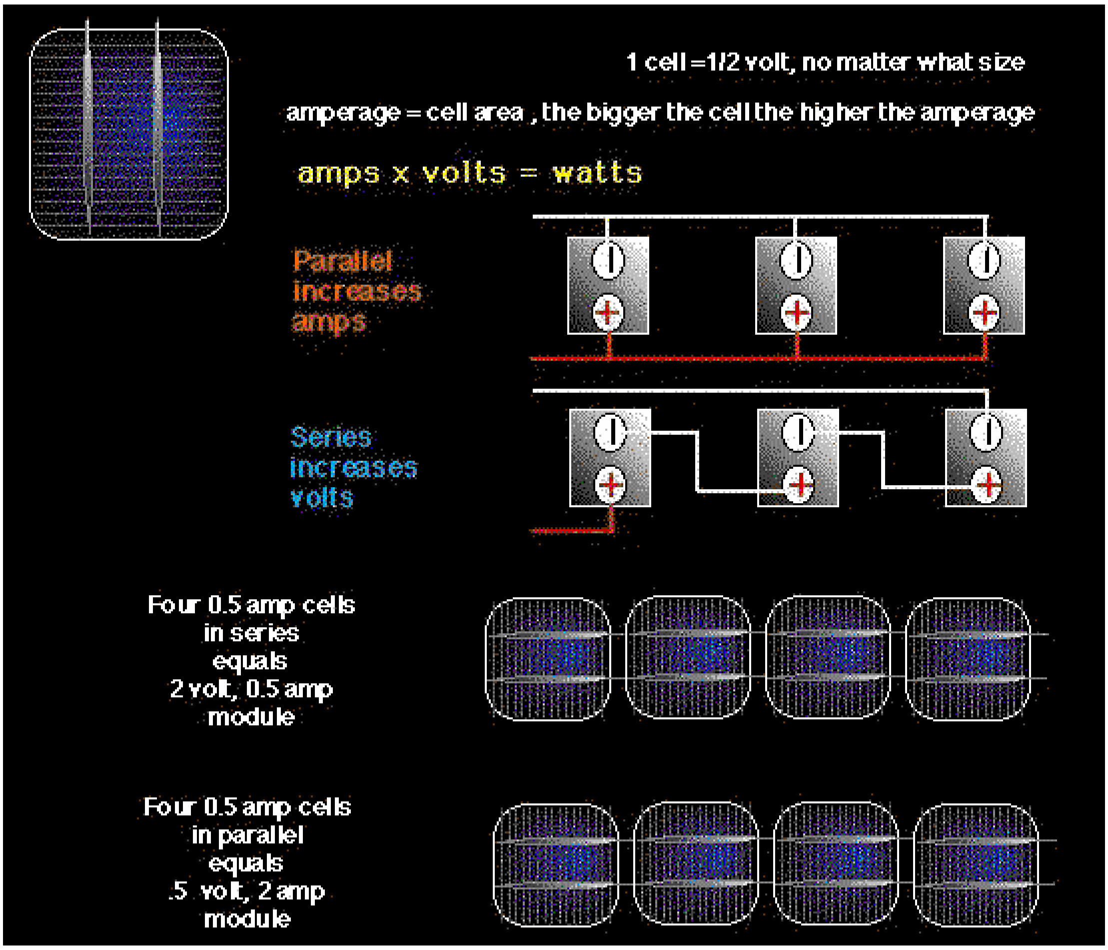


Figure 4-3 Solar cell interconnection

The nominal operating voltage of the system has to be matched with the operating voltage of the storage subsystem. PV manufacturers provide modules that can work with 12V batteries, typically with 33 to 36 cells in series. The module parameters are specified by the manufacturers under the following standard conditions, that are the same used for solar cells.

Irradiance	1kW/m^2
Spectral Distribution	AM 1.5
Cell Temperature	25^{0}C

The nominal power is peak power of the module and is expressed in peak watts (Wp). The three most important electrical characteristics of a module are the short circuit current, open circuit voltage and the maximum power point.

4.2.2 Mounting and tracking structures

Photovoltaic arrays have to be mounted on some sort of stable, durable structure that can support the array and withstand wind, rain, hail, and other adverse conditions. Sometimes, the mounting structure is designed to track the sun. Stationary structures are usually used with flat-plate systems and generally tilt the PV array at a fixed angle that is determined by the latitude of the site, the requirements of the load, and the availability of the sunshine.

There are two general kinds of tracking structures: one-axis and two-axis. Single-axis trackers are typically designed to track the sun from east to west on its daily route. They are used with flat-plate systems and some concentrator systems. By mounting the array on a tracking mechanism, up to 40% more of the solar energy can be collected over the year as compared with a fixed mounting. However this increases complexity and result in lower reliability and higher maintenance costs.

4.3 Storage subsystem

As mentioned above, there are two ways of storing the excess energy produced by the PV system: the batteries and the utility grid. The battery stores electricity in a chemical state, while the utility grid act as a bank for surplus energy that will be withdrawn at a later time. Since this project is concerned primarily with stand-alone systems, the batteries will be examined as a storage medium.

Batteries are common storage devices that convert chemical energy to electrical energy through chemical reactions. A storage battery can be used to store energy on a short-term basis and is rarely used to store energy longer than a few months.

4.3.1 Advantages and disadvantages of batteries in PV systems

Batteries give the following advantages to PV systems

- Capability to provide energy for sunless periods.
- Capability to meet momentary peak power demands.
- A stable voltage for the system.
- Capability to store excess energy produced by the array in excess of the instantaneous demand and thereby reduces energy loss.

Because batteries and the associated charge regulator add to the number of parts in the system, there are certain disadvantages. Batteries decrease the efficiency of the PV system, because only about 80% of the energy channelled into them can be reclaimed. They also add to the expense of the overall system and must be replaced every five to ten years. They take up considerable floor space, pose some safety concerns, and require periodic maintenance.

4.3.2 Lead Acid Battery

The lead acid battery is the most commonly used photovoltaic storage system. A lead acid battery contains plates of lead dioxide (the positive electrode – anode) and lead in a sponge type matrix (the negative electrode – cathode) in an electrolyte solution. Both are converted to lead sulphate in the discharge process. During the charging process, lead oxide is formed at the anode, pure lead is formed at the cathode, and sulphuric acid is liberated in the electrolyte. These lead-acid cells produce a voltage of 2V and are connected in series to produce a battery of the required voltage (typically 6V or 12V). By wiring batteries in series, system voltage can be increased beyond a single battery's voltage characteristics.

Table 4-1 Characteristics for various battery types

Battery Type	Electrolyte	Cycling	Comments
Lead Acid	Liquid, flooded Can add water	Shallow	Starting
		Deep	Forklift, golfcart, floor waxer
	Liquid, flooded Cannot add water	Shallow	Starting
	Gelled	Medium	Sealed, sensitive to temperature
	Absorbed	Medium	
Ni-cad	Liquid, pocket plate	Deep	Very expensive, very tough
	Liquid, sintered plate	Deep	Small, memory effect

4.3.3 Battery operation

Batteries are rated by their amp hour storage capability and their cycle life. The battery's amp hour (or watt hour) storage simply indicates the amount of current it can deliver over what period of time. In theory, a 100-amp hour battery, for instance, can provide 1 amp for 100 hours or 5 amps for 20 hours. In practice, though, the more quickly the battery is discharged, the less charge is delivered. Batteries must not be discharged completely, nor recharged too quickly. The charge/discharge cycle plays an important role in the life of the battery. The *depth* of discharge in one cycle depends on what the cell is being used for. A shallow cycle is when a cell is discharged by only a few percent before being charged back up. "Deep cycling" of a battery can cause lead sulphate to be deposited and crystallize on the plates, degrading the performance of the battery. The addition of antimony to the battery plates will improve deep cycling characteristics, allowing up to 1000 or more such cycles. This type of battery is used for heavy-duty applications such as marine trolling, golf cart, floor sweeper, etc.

4.4 Power Conditioning

Power conditioners process the electricity produced by a PV system to make it suitable for meeting the specific demands of the load. Although most of this equipment is standard stock, it is extremely important to match the specifications of these devices with the characteristics of the load. Power conditioners may have to perform these functions:

- Limit current and voltage to maximize power output
- Convert DC power to AC power

The requirements of power conditioners generally depend on the type of system they are integrated with and the applications of that system. For DC applications, power conditioning is often accomplished with regulators, which control output at some constant voltage and current to maximize output. For AC loads, power conditioning must include an inverter that converts the direct current generated by the PV array into alternating current.

4.4.1 Self regulating systems

The simplest type of photovoltaic power system will be a self-regulated system, which incorporates an array, a blocking diode battery storage and a DC load. A blocking diode is a device, which allows electricity to flow out of the array but prevents it from flowing back to the array from the batteries, which could harm the system. There is a direct connection of the array to the battery through the blocking diode (figure 4-5). When the battery reaches full charge, the charging current is automatically reduced to a trickle.

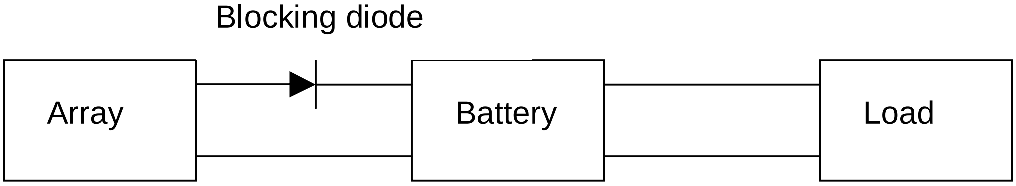


Figure 4-4 A self regulating system

4.4.2 Charge regulators

Two disadvantages of self-regulating systems are that the batteries are not charged as quickly as possibly and the charging current is low in cloudy weather. The voltage variations that occur can be compensated by means of charge regulators. In small applications, a *shunt regulator* is used to disperse any unwanted power from the generator. A common practice is to use a transistor in parallel with the generator, which is set to conduct and divert current from the battery at a certain threshold voltage value. In larger applications, it is recommended to disconnect the battery from the generator by means of a *series regulator*.

The battery may be protected against excessive discharge by a charge limiter. This device is introduced between the load and the battery and acts as a switch, which opens when the battery charge reaches a minimum acceptable level.

4.4.3 Converting DC to AC (Inverter)

In most cases, electric appliances such as refrigerators are used with AC electricity. In these cases, an AC/DC inverter can be used to convert DC power to utility grade AC power. The efficiency of the inverters usually depends on the load current being a maximum at the nominal output power. It can be as high as 95%, but will be lower if the inverter runs under part load. Even though there is a loss of electricity, it is easier to convert the PV energy to AC rather than converting all appliances to DC.

5 Sizing a PV system

5.1 Introduction

Sizing a photovoltaic system is an important task, in the system's design. In sizing a solar power electric system the first two factors we consider are the sunlight levels (insolation values) from the selected area and the daily power consumption of the electrical loads. If the system is oversized it will have a big impact in the final cost and the price of the generated power. If on the other hand the system is undersized problems might occur in meeting the power demand. The sizing should be carefully planned in order to have a cost efficient system. Two sizing procedures will be discussed in this chapter.

5.1.1 Solar radiation data

The amount of sunshine available at a given location is called the 'solar resource' or insolation. The amount of electrical energy produced by a PV array depends on the insolation at a given location and time of. Data are usually given in the form of global radiation over a horizontal surface. The procedure of calculating the solar radiation on a sloped surface has been discussed in chapter 2.

5.1.2 Load Data

From the load data, we get information about the appliances to be powered by the system. These appliances could be domestic appliances like TV sets, lights etc. Determining the total daily energy use requires the following steps: Identifying all the electrical devices that will rely on the system for power; Determining each device's power usage (in watts); Making an estimate of the average daily use of each device in hours per day; Multiplying each device's wattage by the hours of daily use to get watt-hours per day; Adding together the watt-hours for all devices to get the total daily energy requirement. An example of such a load profile is shown below.

Table 5-1 Example of an energy profile

Appliance	*No.*	*Watts*	*Hrs/Day*	*W-hrs/day*
Cooker	1	3000	1	3000
Clothes Dryer	1	2000	0.25	500
Lights	5	80	6	2400
TV	1	100	4	400
			SUM	6300

An example of a simplified energy profile for a household is shown in the table, the daily energy requirement would equal the sum of the calculated values in kWh per day. If the energy requirement varies from season to season, it must be calculated for each season to determine the largest requirement. Residences tend to use more energy in winter when the days are shorter, since lights and other appliances such as televisions are on longer.

5.1.3 Sizing Procedure

The system design will be based on the yearly energy balance between the solar radiation and the load. A block diagram of the sizing procedure is shown in the next page.

5.1.3.1 Input data for sizing procedure

The available solar energy falling on the panels for a typical day of each month and for different panel declinations can be determined from blocks 1-3.

The load specifications are used in order to calculate the average daily load power demand for a typical day each season (blocks 4-5).

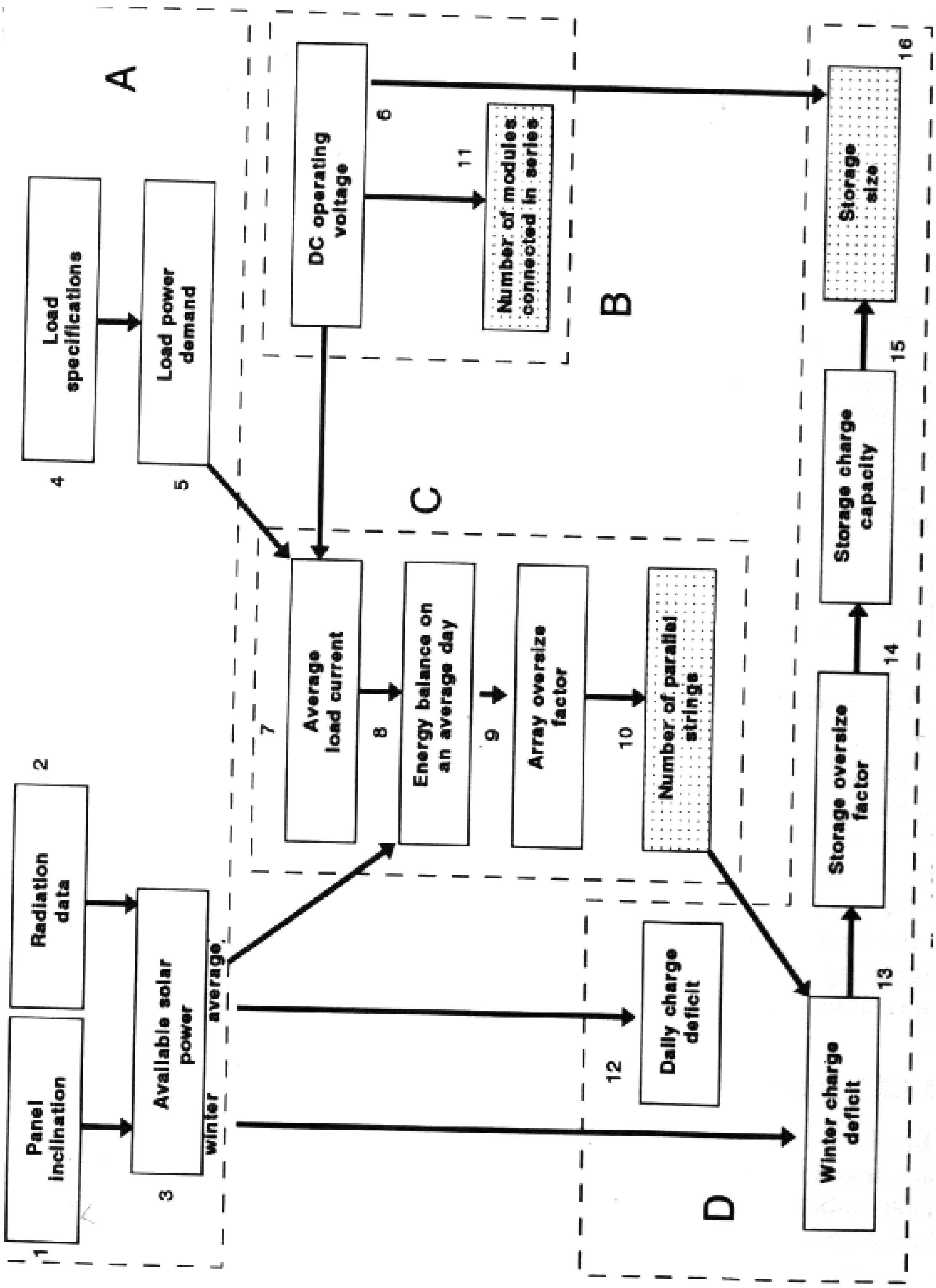


Figure 5-1 Sizing procedure based on energy balance

5.1.3.2 Number of series connected modules

In order to calculate the number of modules that need to be connected in series, first the DC operating bus bar voltage must be specified. The number of connected modules in series N_S is given by the equation 5-1

$$N_S = \frac{V_{DC}}{V_m} \tag{5-1}$$

where V_m is the operating voltage of one module.

5.1.3.3 Number of parallel connected strings

The number is related to the load and its required current. Block 7 is the current needed by the load and is given by the following equation, where E_L is the average power required by the load.

$$I_L = \frac{E_L}{24V_{DC}} \tag{5-2}$$

The nominal current I_P that the system generates when working at its maximum power is needed for the calculations. The energy required by the load should be equal to the energy generated from the PV modules. This can be written as:

$$E_L(\mathrm{Wh/day}) = \mathrm{PSH} \times I_P \times V_{DC} \tag{5-3}$$

where PSH is numerically equal to the irradiation in $\mathrm{kWh/m^2}$. Substituting equation 5-2 to 5-3 and solving for I_P yields:

$$I_P = \frac{24I_L}{\mathrm{PSH}} \tag{5-4}$$

Equation 5-4 displays that the average daily load current multiplied by the number of hours, should be numerically equal to the current that the system produces multiplied by the number of peak solar hours.

The number of modules connected in parallel (blocks 9-10) is given by the following equation where SF is the safety factor, introduced to oversize the current produced from the array to cover for any loses and I_m is the current generated from one module.

$$N_P = SF\frac{I_P}{I_m} \tag{5-5}$$

The total number of modules needed is

$$N = N_P \times N_S \tag{5-6}$$

5.1.3.4 Sizing of the storage subsystem

The daily and seasonal deficit is calculated in block 12. Night and periods with very little sunshine must be covered satisfactory. Also excess (unused) energy must be store in order to be used later. The analysis determines the daily charge/discharge of the battery that cannot exceed a certain value.

The charge deficit (block 13) is a value –usually given in Ah- that is related to the energy balance of the year. Excess energy during summer period has to be stored in order to cover the energy deficit during the winter. The charge deficit is given by the following equation and ΔE is the winter energy deficit.

$$Q_{Yd} = \frac{\Delta E}{V_{DC}} \tag{5-7}$$

Another charge deficit (block 14) is used to allow a certain number days of operation with no energy input (no sunshine, system maintenance etc). This number is determined from experience and depends on the system's use. It is given by equation 5-8 where n is the number of days with no energy input.

$$Q_{los} = I_L \times 24 \times n \tag{5-8}$$

The nominal capacity of the battery will be given by equation 5-9 (block15) where Φ is the battery's maximum discharge depth.

$$Q_B = (Q_{Yd} + Q_{los})(1/\Phi) \tag{5-9}$$

From the operating voltage and capacity of one battery, the total number of batteries can be calculated (block 16) the same way it was calculated for the number of panels. The number of batteries in series is given by equation 5-10 below, where V_B is the nominal operating voltage of the battery.

$$N_{BS} = \frac{V_{DC}}{V_B} \tag{5-10}$$

The number of batteries in parallel is given by equation 5-11 where Q_C is the nominal capacity of a single battery.

$$N_{BP} = \frac{Q_B}{Q_C} \tag{5-11}$$

The total number of batteries is then

$$N_B = N_{BP} \times N_{BS} \tag{5-12}$$

Table 5-2 Notation and units

Symbol		SI unit
E_L	Daily load energy requirement	Wh
I_L	Average load current	A
I_m	Module current at maximum power point	A
I_P	Current generated from PV at maximum power point under standard conditions	A
N_S	Number of series connected modules	
N_P	Number of parallel strings	
N_{BS}	Number of series connected batteries	
N_{BP}	Number of batteries connected in parallel	
PSH	Peak solar hours	h
Q_{Yd}	Yearly charge deficit	C (Ah)
Q_{lod}	Charge deficit to compensate for loss of sunshine	C (Ah)
Q_B	Nominal battery capacity	C (Ah)
Q_C	Single battery capacity	C (Ah)
SF	Array oversize factor	
V_{DC}	DC bus bar voltage	V
ΔE	Yearly energy deficit	Wh
Φ	Lowest permitted state of charge of the battery	

6 Case study

6.1 Introduction

In this chapter, an application of the previous method will be used in order to size a system in two different locations. The first step will be to determine the available average daily insolation for each site, the average power consumption and then finally size the system in order to cover the desired load.

6.2 Average daily solar radiation

6.2.1 Sifnos-Greece

The available solar energy to the panels will be computed according to the procedure described in chapter 2. Some of the parameters that are needed are the site's latitude and the Clarity coefficient or Clearness index. These parameters are shown in Appendix 1 along with the complete calculations for Sifnos-Greece. The average daily radiation on an inclined surface is shown in table 6-1.

Table 6-1 Daily irradiation in Sifnos (in kWh/m^2 –day) for a typical day every month as a function of the panel inclination in degrees.

Panel Tilt	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Annual**
0	2.20	3.36	3.96	5.39	6.03	6.46	6.63	5.77	4.58	3.20	2.20	1.98	4.31
5	2.43	3.63	4.13	5.50	6.04	6.42	6.61	5.84	4.74	3.40	2.40	2.21	4.44
10	2.64	3.87	4.28	5.57	6.02	6.36	6.56	5.88	4.87	3.58	2.58	2.42	4.55
15	2.85	4.10	4.41	5.62	5.97	6.26	6.48	5.88	4.98	3.73	2.75	2.61	4.64
20	3.03	4.30	4.51	5.63	5.89	6.14	6.37	5.86	5.05	3.87	2.90	2.79	4.70
25	3.20	4.47	4.59	5.61	5.79	5.98	6.23	5.80	5.10	3.99	3.04	2.96	4.73
30	3.35	4.61	4.64	5.57	5.65	5.80	6.06	5.71	5.12	4.08	3.16	3.10	4.74
35	3.47	4.73	4.66	5.49	5.49	5.60	5.86	5.60	5.11	4.15	3.26	3.23	4.72
40	3.58	4.82	4.65	5.38	5.30	5.37	5.63	5.45	5.06	4.19	3.34	3.34	4.68
45	3.66	4.88	4.62	5.24	5.09	5.11	5.38	5.27	4.99	4.21	3.40	3.43	4.61

50	3.72	4.90	4.57	5.07	4.85	4.84	5.10	5.07	4.89	4.21	3.44	3.49	4.51
55	3.76	4.90	4.48	4.88	4.59	4.54	4.80	4.84	4.77	4.18	3.46	3.53	4.39
60	3.78	4.87	4.37	4.66	4.31	4.23	4.49	4.59	4.61	4.12	3.45	3.55	4.25
65	3.77	4.80	4.24	4.42	4.02	3.91	4.15	4.32	4.44	4.04	3.43	3.55	4.09
70	3.73	4.71	4.08	4.16	3.71	3.58	3.81	4.03	4.23	3.94	3.39	3.53	3.91
75	3.68	4.59	3.90	3.87	3.39	3.24	3.45	3.72	4.01	3.81	3.32	3.48	3.71
80	3.60	4.44	3.70	3.57	3.06	2.90	3.09	3.40	3.76	3.66	3.24	3.41	3.49
85	3.49	4.26	3.48	3.26	2.74	2.56	2.74	3.07	3.49	3.50	3.13	3.32	3.25
90	3.37	4.06	3.24	2.93	2.41	2.24	2.39	2.73	3.21	3.31	3.01	3.21	3.01

Figure 6-1 shows the average daily radiation for different panel declinations, in Sifnos.

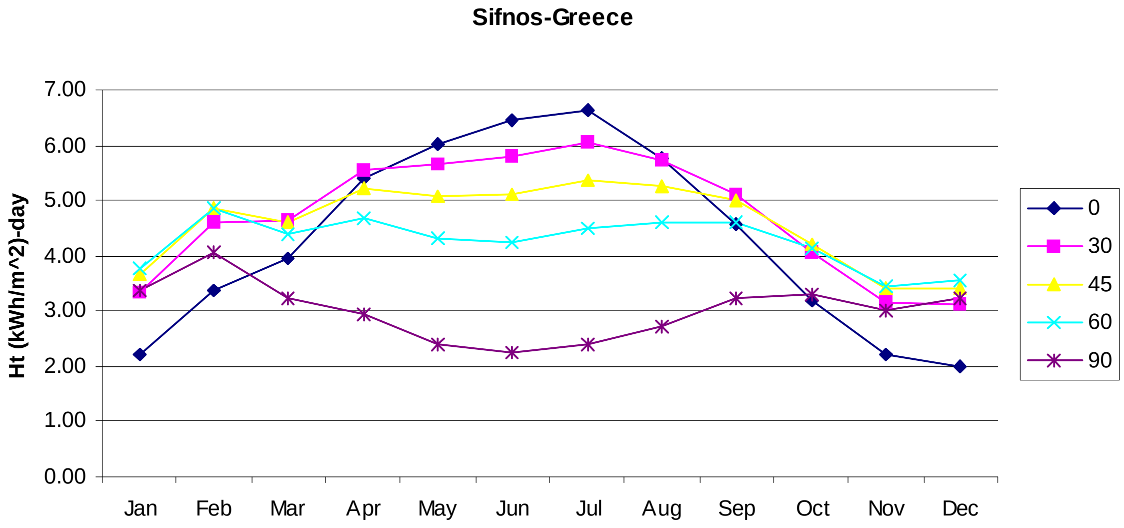


Figure 6-1 Average daily radiation for different declination angles in Sifnos

6.2.2 Glasgow-Scotland

Using the same procedure data for Glasgow are presented in the Appendix. The average daily solar radiation falling on an inclined surface is shown in table 6-2.

Table 6-2 Daily irradiation in Glasgow (in kWh/m^2 –day) for a typical day every month as a function of the panel inclination in degrees.

Panel Tilt	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
0	0.65	0.93	1.91	3.33	4.48	4.22	4.12	3.30	2.45	1.33	0.55	0.34	2.30
5	0.82	1.03	2.04	3.44	4.54	4.23	4.14	3.38	2.58	1.47	0.63	0.41	2.39
10	0.98	1.12	2.16	3.54	4.58	4.23	4.16	3.44	2.71	1.60	0.70	0.47	2.48
15	1.14	1.21	2.27	3.63	4.61	4.22	4.16	3.48	2.81	1.72	0.78	0.54	2.55
20	1.29	1.29	2.36	3.69	4.61	4.20	4.15	3.51	2.90	1.83	0.84	0.60	2.61
25	1.44	1.37	2.45	3.74	4.60	4.15	4.12	3.53	2.98	1.93	0.91	0.65	2.66
30	1.57	1.43	2.52	3.77	4.56	4.10	4.07	3.52	3.04	2.02	0.97	0.71	2.69
35	1.70	1.49	2.57	3.77	4.51	4.02	4.00	3.50	3.08	2.10	1.02	0.75	2.71
40	1.81	1.54	2.61	3.76	4.43	3.93	3.92	3.47	3.11	2.17	1.07	0.80	2.72
45	1.91	1.58	2.64	3.73	4.33	3.82	3.82	3.41	3.12	2.22	1.11	0.84	2.71
50	2.00	1.62	2.65	3.68	4.22	3.70	3.71	3.34	3.11	2.26	1.14	0.87	2.69
55	2.07	1.64	2.65	3.61	4.08	3.56	3.58	3.25	3.08	2.29	1.17	0.90	2.66
60	2.13	1.65	2.63	3.52	3.92	3.41	3.43	3.15	3.04	2.30	1.19	0.92	2.61
65	2.18	1.65	2.60	3.41	3.75	3.24	3.27	3.04	2.98	2.30	1.20	0.94	2.55
70	2.21	1.65	2.55	3.28	3.56	3.07	3.10	2.91	2.91	2.28	1.21	0.95	2.47
75	2.23	1.63	2.49	3.14	3.36	2.89	2.92	2.77	2.81	2.25	1.21	0.95	2.39
80	2.23	1.61	2.41	2.98	3.15	2.69	2.73	2.61	2.71	2.21	1.20	0.95	2.29
85	2.21	1.57	2.32	2.81	2.92	2.49	2.54	2.45	2.59	2.16	1.18	0.94	2.18
90	2.18	1.53	2.22	2.63	2.69	2.29	2.33	2.28	2.45	2.09	1.15	0.93	2.06

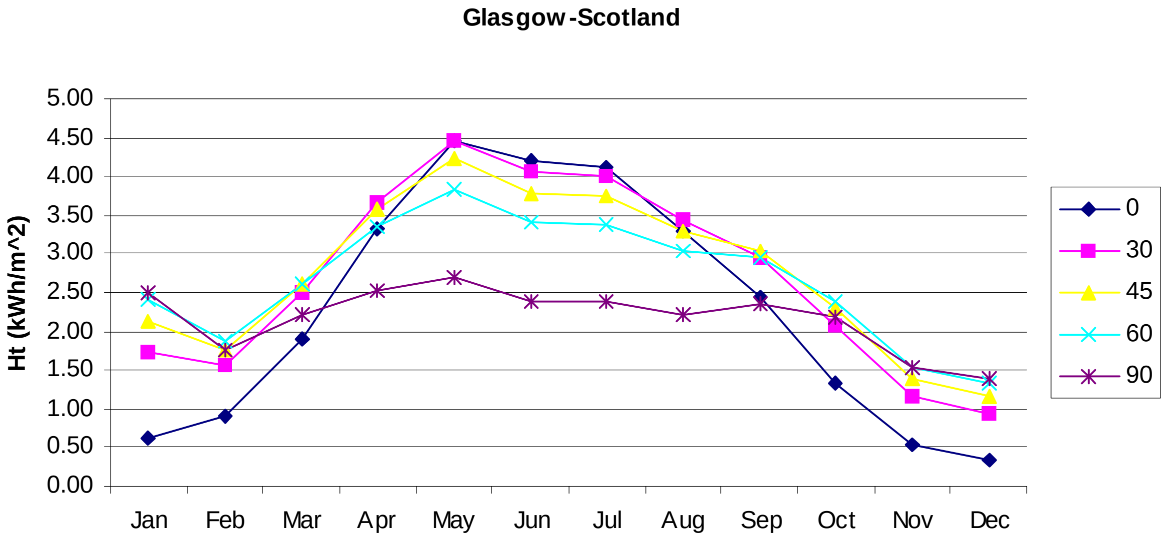


Figure 6-2 Average daily radiation for different declination angles in Glasgow

6.3 Load demand

A table showing the most common appliances used in a household is found in the next page. They are described by their nominal power the time they are used during the day. These numbers are then multiplied to find the total energy (in Wh-day) consumed during a typical day. Four seasons are included in the profile, with different utilization times for the appliances. The values found for each season are used to find the average daily annual consumption. These values are just estimates, and they can vary according to the place, time of season or resident.

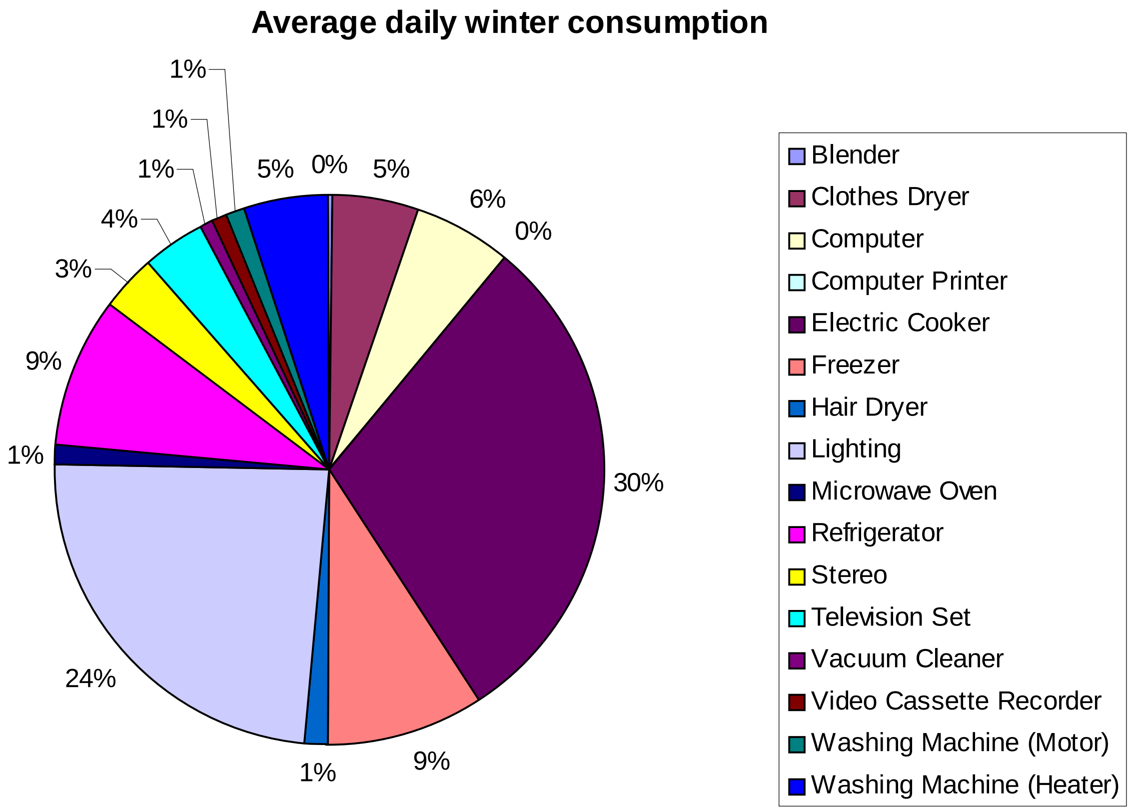


Figure 6-3

			Winter		*Spring*		*Summer*		*Autumn*	
Appliance Power Requirements	No.	Watts	hrs/Day	W-hrs/day	hrs/Day	W-hrs/day	hrs/Day	W-hrs/day	hrs/Day	W-hrs/day
Blender	1	350	0.05	18	0.05	18	0.05	18	0.05	18
Clothes Dryer	1	2000	0.25	500	0.25	500	0.25	500	0.25	500
Computer	1	100	6	600	6	600	6	600	6	600
Computer Printer	1	20	0.25	5	0.25	5	0.25	5	0.25	5
Electric Cooker	1	3000	1	3000	1	3000	1	3000	1	3000
Freezer	1	150	6	900	6	900	6	900	6	900
Hair Dryer	1	750	0.2	150	0.2	150	0.2	150	0.2	150
Lighting	6	80	5	2400	4	1920	4	1920	5	2400
Microwave Oven	1	1200	0.1	120	0.1	120	0.1	120	0.1	120
Refrigerator	1	150	6	900	6	900	6	900	6	900
Stereo	1	80	4	320	4	320	4	320	4	320
Television Set	1	75	5	375	5	375	5	375	5	375
Vacuum Cleaner	1	700	0.1	70	0.1	70	0.1	70	0.1	70
Video Cassette Recorder	1	80	1	80	1	80	1	80	1	80
Washing Machine (Heater)	1	2000	0.25	500	0.25	500	0.25	500	0.25	500
	W-hrs Consumed daily			9938		9458		9458		9938
	Average Annual Consumption			9698Wh/day						

6.4 Sizing of the PV system

The optimum tilt angle for both systems must be determined. The operating voltage of the system is set equal to 12V. The voltage of the PV system should be equal to that of the storage subsystem. The panel chosen for the sizing procedure is KC120, which has high conversion efficiency (13%) among the other panel types. Some available panel types that can be used in the sizing of the system are shown in table 6-3 [30]. A different choice of panel can affect the number of modules required, according to its efficiency, power and electrical characteristics.

Table 6-3 Different panel types

Module Name	*Peak Power (W)*	*Voltage (V)*	*Current (I)*	*Length (m)*	*Width (m)*	*Total Area (m^2)*	*Efficiency*	*Price*
MSX120	120	17.7	7	1.12	0.99	1.11	0.12	364
MSX83	83	17.1	4.85	1.12	0.66	0.74	0.11	272
MSX77	77	16.9	4.56	1.12	0.66	0.74	0.10	253
VLX80	80	17.1	4.71	1.12	0.66	0.74	0.11	273
KC120	120	16.9	7.1	1.43	0.65	0.93	0.13	372
KC80	80	16.9	4.73	0.98	0.65	0.64	0.13	248
SR100	100	17	6	1.5	0.6	0.90	0.11	328
SR90	90	17	5.4	1.5	0.6	0.90	0.10	299
SP75	75	17	4.4	1.2	0.53	0.64	0.12	263

The complete calculations for the sizing of the system are presented in detail in Appendix 2. The optimum tilt angle, at which the systems cover the energy needs with the minimum cost, is not the same for both sites. Table 6-5 gives the total number of panels and batteries for different tilt angles. Calculations are made using, the same type of panels and the same load requirements.

6.4.1 Storage subsystem

The energy balance of the system and the assumed days with no energy input, play an important role upon the size of the storage subsystem, since the two charge deficits Q_{Yd} and Q_{los} depend upon these factors. The monthly energy balance of the system will be equal to the energy input from the PV generator minus the energy needed by the load ($E_{PV} - E_L$) for every month.

The complete sizing procedure for the storage subsystem is show in Appendix 2. Again, the same type of battery is used for both calculations (Sifnos and Glasgow) and the same number of days without energy input (5 days). Other available batteries for the sizing of the storage subsystem are shown in table 6-4. As mentioned earlier, the number of batteries for different tilt angles is shown in table 6-5.

Table 6-4 Various types of batteries

Battery Name	Voltage (V)	Capacity (Ah)	Price
6-50A-07	12	180	138
6-50A-09	12	210	163
6-50A-11	12	265	185
6-50A-13	12	320	208
6-50A-15	12	370	230
6-90A-07	12	265	173
6-90A-09	12	350	202
6-90A-11	12	440	238
6-90A-13	12	530	278
3-90A-17	6	700	362
3-90A-19	6	790	392

6.4.2 Optimum tilt angle

Table shows the required number of panels and batteries for different tilt angles. The results are also plotted in two different graphs for Sifnos and Glasgow in figures 6-4 and 6-5.

From these tables and figures it is shown that the best tilt angle for Sifnos is between 40 and 55^0, since there is a balance between the number of panels and batteries. This can also be seen from the total capital cost of the system, plotted in figure 6-6. The fact that a system has low capital cost does not mean that its total lifetime cost will also be low. Maintenance and replacement costs might increase the overall system cost over time. For tilt 15 to 45^0 the required number of panels and batteries remains the same. For Sifnos the tilt angle is chosen to be 55^0.

Examining the results obtained for Glasgow, it is shown that the optimum angle for the system is 75 to 85^0, where the number of batteries and panels is balanced. For lower values of tilt angles the number of panels is decreasing, but the number of batteries is substantially high. This could result very high maintenance and replacement costs (for the batteries). The tilt angle is chosen to be 80^0.

Table 6-5 Number of panels and batteries and capital costs for different tilt angles.

Sifnos				Glasgow			
Tilt	Panels	Batteries	Cost-GBP	Tilt	Panels	Batteries	Cost-GBP
0	27	10	12825	0	51	51	33165
5	26	11	12731	5	49	55	33535
10	26	11	12731	10	47	60	34184
15	25	14	13195	15	46	63	34647
20	25	14	13195	20	45	66	35111
25	25	14	13195	25	44	68	35296
30	25	14	13195	30	43	71	35759
35	25	14	13195	35	43	71	35759
40	25	14	13195	40	43	71	35759
45	26	11	12731	45	43	71	35759
50	26	11	12731	50	43	71	35759
55	27	10	12825	55	44	68	35296

60	28	10	13196	60	45	66	35111
65	29	10	13568	65	46	63	34647
70	31	10	14312	70	47	60	34184
75	32	10	14684	75	49	55	33535
80	34	10	15428	80	51	51	33165
85	37	10	16543	85	53	48	33074
90	40	10	17659	90	56	44	33075

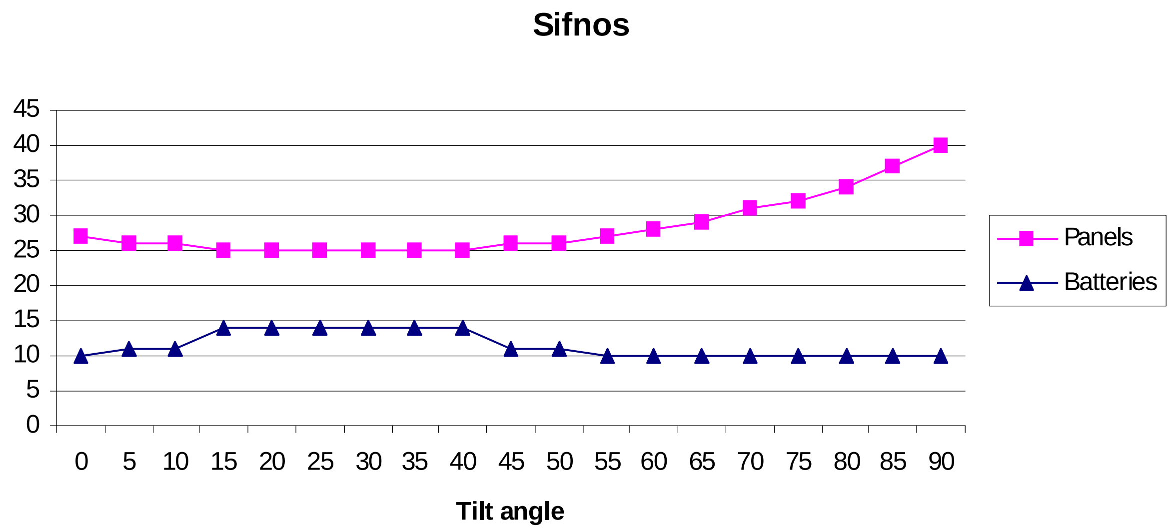


Figure 6-4 Number of panels and batteries for different tilt angles in Sifnos

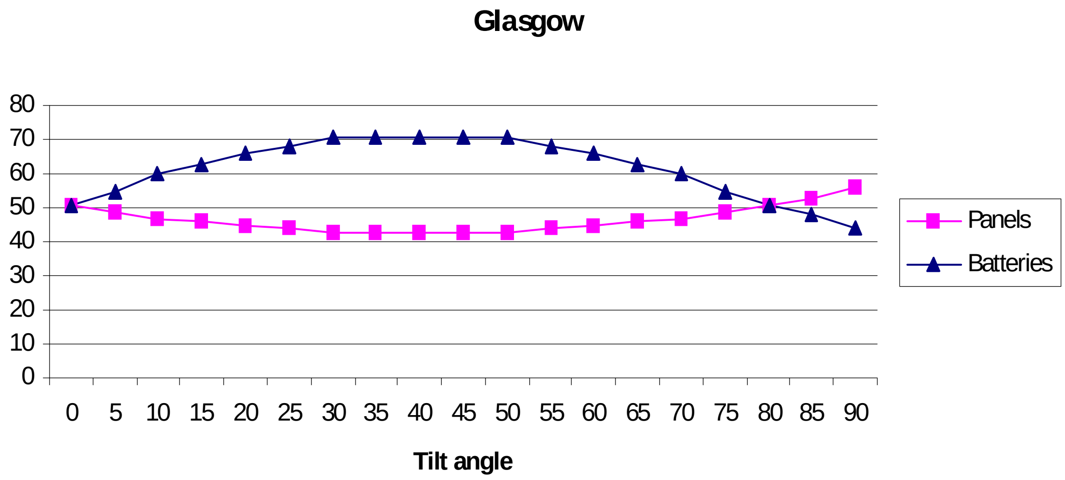


Figure 6-5 Number of panels and batteries for different tilt angles in Glasgow

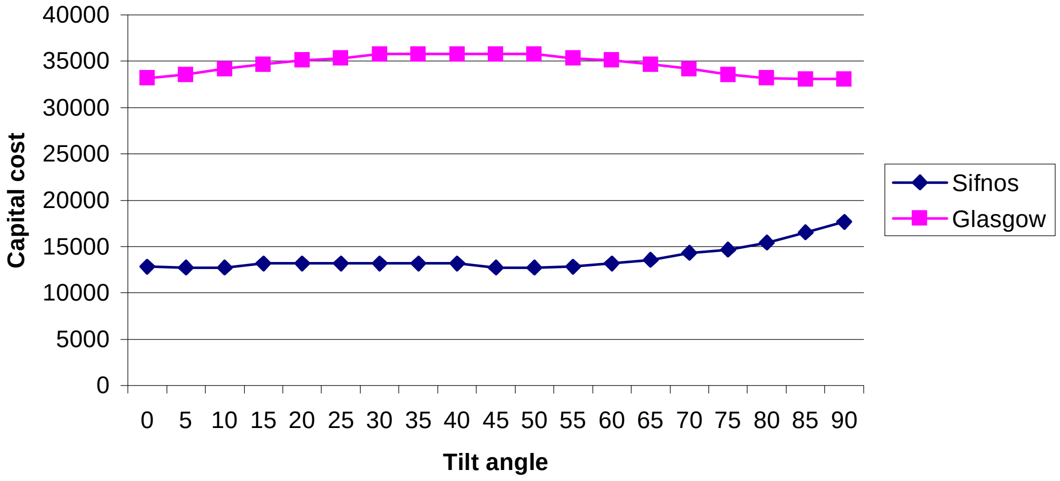


Figure 6-6 Capital cost as a function of tilt angle

Finally the chosen angle, along with the number of panels and batteries is presented in table 6-6.

Table 6-6 Final values for Sifnos and Glasgow

	Tilt	Panels	Batteries
Sifnos	55	27	10
Glasgow	80	51	51

7 Economic evaluation

7.1 Economics of PV energy systems

The price of power generated from PV systems, depends upon two factors; the system’s capital cost and the running cost. As capital cost is considered to be the cost of PV panels, the balance of system cost (BOS) - which includes the power conditioning, the wirings, support structures etc- and finally the cost of the storage subsystem. In this chapter, the economic value for both systems will be calculated, so that it can be compared with other alternative methods of power generation (grid connection, diesel etc).

Even though the capital cost for a PV system is substantially high, the running costs are low compared to other renewable or non-renewable systems, since it consumes no fuel nor has any moving parts (except if a tracking system is included). Maintenance of the system becomes more demanding if battery storage is included. In that case, special attention is needed for the proper maintenance of the batteries. Also the batteries need to be replaced in regular periods of time.

7.2 Life cycle costing

The two systems described in chapter 6, will be evaluated using a life cycle analysis. Doing a life cycle cost analysis (LCC) gives the total cost of your PV system - including all expenses incurred over the life of the system. There are two reasons to do an LCC analysis: 1) to compare different power options, and 2) to determine the most cost-effective system designs. If PV power is the only option, a life-cycle cost (LCC) analysis can be helpful for comparing costs of different designs and/or determining whether a hybrid system would be a cost-effective option. An LCC analysis allows the designer to study the effect of using different components with different reliabilities and lifetimes. Some might want to compare the cost of different power supply options such as photovoltaics, fuelled generators, or extending utility power lines. The initial costs of these options will be different, as will the costs of operation, maintenance, and repair or replacement. A LCC analysis can help compare the power supply options.

The LCC analysis consists of finding the present worth of any expense expected to occur over the reasonable life of the system. In order to make a valid comparison, all future costs have to be discounted to equivalent today values. This is called ‘present worth’ value or PW. To find the PW of a future cost, it must be multiplied by a calculated discount factor.

The parameters that need to be established for the calculations of life cycle cost are the following [32]:

- Period of analysis. The lifetime of the longest lived system under comparison.
- Excess inflation. The rate of price increase of a component above (or below) inflation (usually assumed to be zero).
- Discount rate (d). The rate (relative to general inflation) at which money would increase in value if invested.
- Capital cost. It includes the initial capital expense for equipment, the system design, engineering, and installation. This cost is always considered as a single payment occurring in the initial year of the project.
- Operation and maintenance. The amount spent each year in keeping the system operational.
- Replacement costs. The cost of replacing each component at the end of each lifetime.

7.3 Calculation of present worth

Present worth of a system will be calculated by considering all the expenses (running costs, replacements etc) made in one year of operation as a single payment. The sum of the discounted values (present worth) over the lifetime of the system is the life cycle cost of the system.

The present worth of a single payment is given by equation 7-1.

$$\mathrm{PW} = \mathrm{Cr} \times \mathrm{Pr} \tag{7-1}$$

Factor Pr is given by equation 7-2, where i is the excess inflation, d the discount rate and N the number of year.

$$\mathrm{Pr} = \left(\frac{1+\mathrm{i}}{1+\mathrm{d}}\right)^{\mathrm{N}} \tag{7-2}$$

7.4 Case study

7.4.1 PV systems

The life cycle cost of both systems will be calculated over a lifetime period of 20 years. The systems will be compared with a diesel system and finally, the utility grid. Excess inflation is set to zero.

Table 6-6 gives the total required number of panels and modules. The prices are found in tables 6-3 and 6-4.

Table 7-1

	Panels	Price (GBP)	Batteries	Price (GBP)
Sifnos	27	372	10	278
Glasgow	51	372	51	278

The total capital cost for the systems will include also the BOS costs, which includes (power conditioning, installation, wirings etc). These costs even though represent a considerable part of the total cost, will be neglected for convenience. The running costs are set to be equal to 20 GBP per year, and replacement time for the batteries is set to 7 years, assuming proper maintenance. The complete procedure for the life cycle costing is found in Appendix 3. The results are shown in the next table (7-2).

Table 7-2 Life cycle cost for PV system

Location	Life cycle cost (GBP)

Sifnos	18134
Glasgow	52354

The final cost for the system in Glasgow, seems very high. A way of reducing this cost is by increasing the safety factor of equation 5-5. The result is that more panels are needed as this factor is increased, but at the same time less batteries are required, and hence the replacement costs are less. The next table shows the number of panels and batteries needed for different values of safety factors, along with the LLC.

Table 7-3 LLC for different values of safety factor

Safety factor	Panels	Batteries	LLC
1	51	51	52354
1.1	56	44	49895
1.2	61	36	46818
1.3	66	29	44359
1.4	71	23	42516
1.5	76	19	41908
1.6	81	16	41916
1.7	86	13	41924

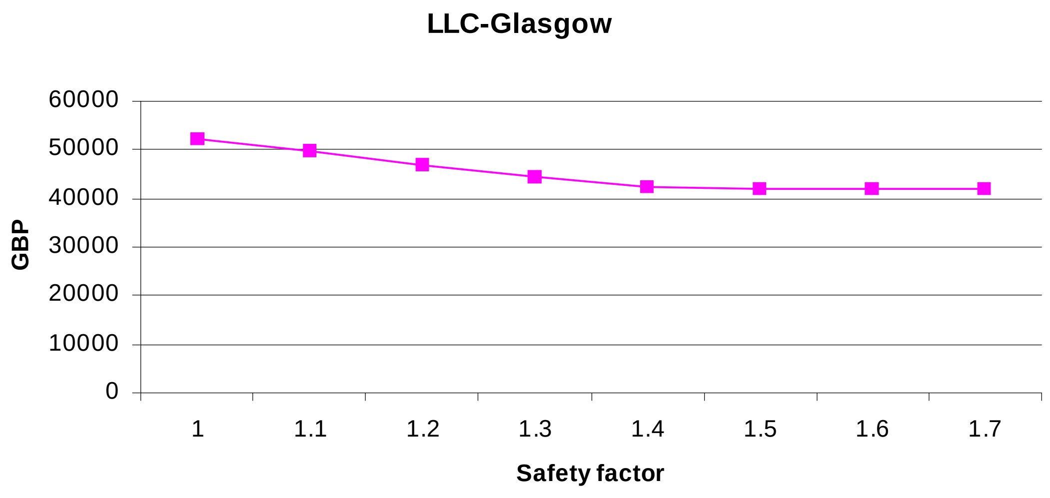


Figure 7-1 LLC as a function of safety factor for Glasgow

Changing safety factor in Sifnos only increases the final LLC, since the number of batteries required is very small. An increase in safety factor, only increase the total number of panels and hence the final system cost.

7.4.2 Diesel Generator

The diesel generator chosen for the comparison is a 12kW generator [33]. The specifications and data needed for the calculation of life cycle costing of the engine are shown below.

Model	HD-295-12kW
Power	12kW
Fuel consumption	0.3 lt per kW per hour
Price	2875 GBP

The average load that the engine needs to cover is nearly 10 kWh per day. The fuel consumption each day will be 10x0.3=3lt. The total fuel consumption for the whole year will be 365x3=1095lt. The price for heating diesel in Greece is roughly; 14p per liter, while in UK the price is 13p per liter [34]. Operation and maintenance costs are set equal to 250 GBP per year. The above are shown in table 7-4.

Table 7-4

	Load	Yearly fuel Consumption	Price per liter	Total fuel cost	O&M
Sifnos	10kW	1095 lt	13p	142 GBP	250
Glasgow	10kW	1095 lt	14p	153 GBP	250

Doing a LLC analysis for both systems –as described in Appendix 3- yields the following results.

Table 7-5 Life cycle cost for diesel generator

Location	Life cycle cost (GBP)
Sifnos	7800
Glasgow	7900

7.4.3 Utility grid

A LLC analysis will be done also for the utility grid, in order to be compared with the PV system. The capital costs in order to be connected to the grid vary according to the distance from the nearest power substation. It is assumed for the analysis that there are no significant costs occurring when connecting to the grid. The energy prices for UK and Greece are 9.23p and 7.80p per kWh respectively [35]. The load demand each day is set to 10kWh. Repeating the analysis described in Appendix 3 for a 20-year period, the LLC for utility generated electricity is shown below.

Table 7-6 LLC for utility generated electricity

Location	LLC
Sifnos	3500 GBP
Glasgow	4124 GBP

7.4.4 Result comparison

The results obtained from the previous analysis, are shown in figures 7-1 and 7-2.

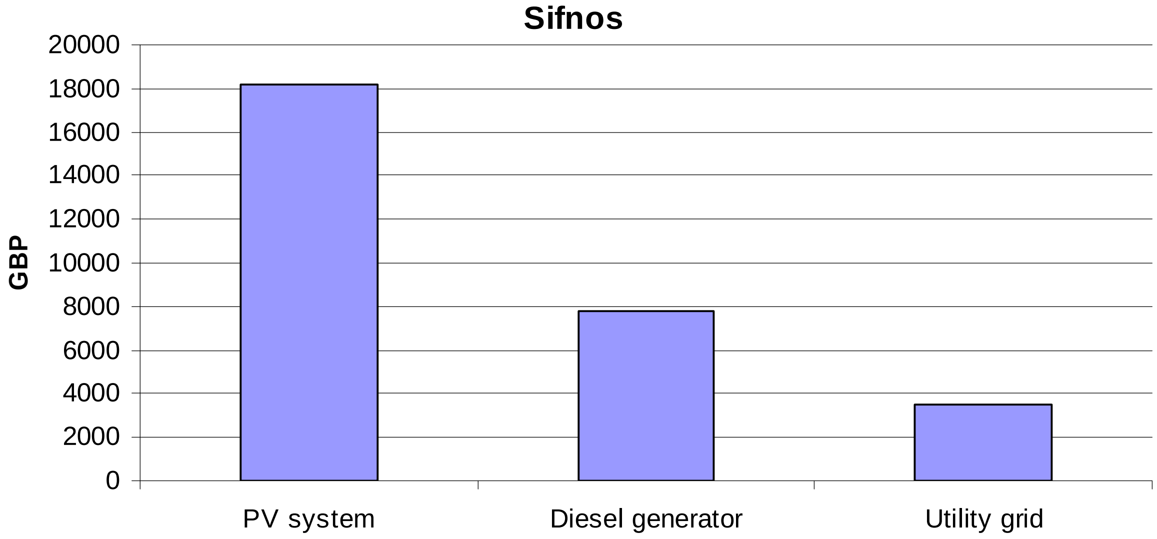


Figure 7-2 Sifnos LLC comparison for different ways of providing electricity

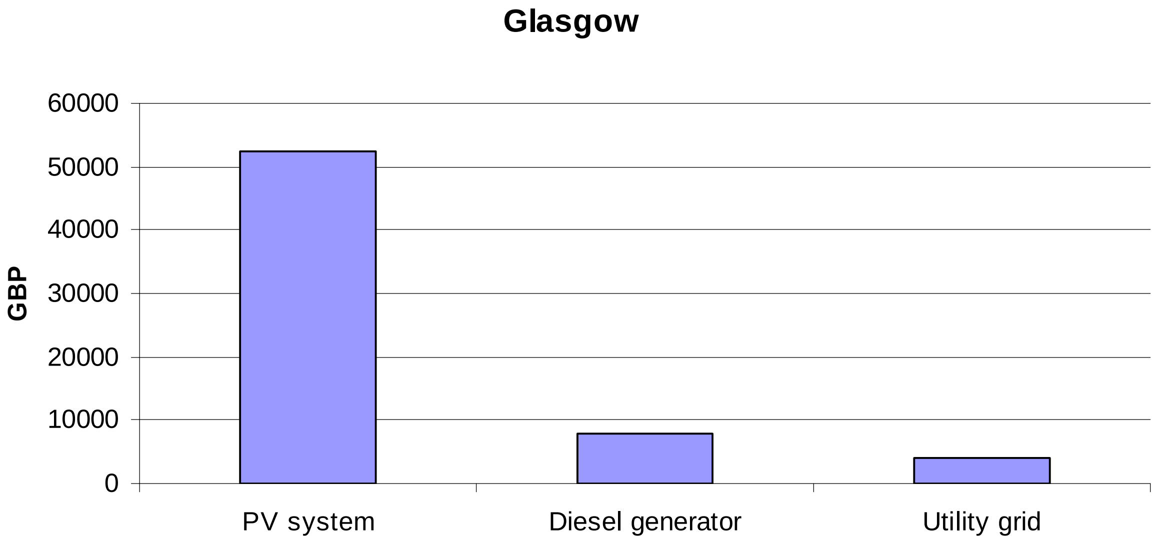


Figure 7-3 Glasgow LLC comparison for different ways of providing electricity

It can be seen from both figures, that the LLC is substantially higher than the other available options. Comparing the two PV systems, Glasgow has a much higher LLC cost than the system located in Sifnos, and both systems don’t seem to have an obvious advantage. Doing various analyses with different kind of panels and batteries in order to find the most economical solution can optimise both systems further. This however, will only improve the system slightly. The disadvantage shown in the above figures will not be changed unless technological or other improvements are made. This will be discussed further in chapter 8.

8 Conclusions

8.1 Evaluation of system design

The basic elements of PV technology have been presented in this project. These include the sun-earth geometric relations, the available solar energy in the earth's surface, the photovoltaic effect, the structure of a PV cell and the PV system. A simple method of sizing a PV system according to specific energy has also been presented, along with an economic evaluation of the system.

The main sources of error and limitations in the system design are associated to the four areas of data collected for the analysis. Weather data, such as clearness index, where take from literature and correspond to measurements from various weather stations near the areas of interest. So the values of incident radiation at the given locations are not accurate.

The load profile used for the calculation assumed that all appliances operate at the same time when in practice energy demand varies according to the time of day. The appliances' specification and daily use was also an approximate and can vary substantially between different locations, season etc.

The calculation for the required number of panels, was made by assuming that current will always be available to satisfy the load. This current generated is dependant on the incident radiation and the number of PSH. The PV system might not always operate at the maximum power point as the above assumption is suggesting and lack of energy might occur.

8.2 Conclusions – final comments

The first conclusion made, is that the system size depends upon its location. The available solar energy in Greece is substantially higher than in Scotland for the same period of time and the energy produced by the PV system is higher. The panels needed to cover the same load in Glasgow are nearly two times the number needed in Sifnos. Also a big number of batteries are needed in Glasgow in order to compensate for the energy deficit in winter (also existing because of very little incident solar energy during winter). This is not the case for Sifnos, where the available solar energy throughout the year is enough for the system to operate without any energy deficit.

Sizing a PV system is not an easy task. There are many considerations; assumptions and forecasts need to be made in order for the system to be efficient. The designer needs to have a detailed knowledge of the climatic data of the location and the intended use of the PV system. Every detail has to be examined carefully so that the system is neither oversized nor undersized.

When the PV systems are compared with other sources of energy, like diesel engines or the utility grid, PV seem to have a big disadvantage over life cycle cost. The capital costs are too high and in the case of Glasgow replacement costs because of the batteries, are extremely elevated, making the system totally uneconomical. The electricity generated by the other mentioned sources is still very cheap and PV cannot be considered as a competitive alternative.

The first step for PV to be competitive should be the reduction of cost per peak watt. It is expected that the manufacturing costs will fall to around 90p per watt by the early years of this century and the selling price for modules in large systems will be 1.2 GBP.

Secondly, the conversion efficiency of the PV arrays needs to increase. The current efficiency of commercial modules is around 10 to 13%. It is also expected that during the early years of the century, modules will achieve annual conversion efficiency of around 20% and peak efficiency around 23% [36].

Thirdly, the balance of system costs (BOS) need to be reduced, since they are roughly equal to module costs. As PV become more popular, manufacturing experience is gained and production is increased, the cost of BOS will fall along with module prices. A target for the overall system cost is about 2.66 GBP by 2005.

Appendix 1

Available solar radiation

SIFNOS-GREECE

- Latitude 36.6^0
- Clearness Index [31]

Table A-1 Values for K_T in Sifnos

	JAN	*FEB*	*MAR*	*APR*	*MAY*	*JUN*	*JUL*	*AUG*	*SEP*	*OCT*	*NOV*	*DEC*
K_T	0.466	0.543	0.496	0.551	0.548	0.563	0.591	0.564	0.532	0.477	0.432	0.453

From table 2-1 the reflectivity of the area is 0.2. The sun's declination angle is given by equation $\delta = 23.45\sin\left(360\frac{284+n}{365}\right)$ where n is the number of a typical day for each month.

Table A-2 Solar declination

	Jan	*Feb*	*Mar*	*Apr*	*May*	*Jun*	*Jul*	*Aug*	*Sep*	*Oct*	*Nov*	*Dec*
Day	15	47	75	105	135	162	198	228	258	288	318	344
δ	-21.3	-13.0	-2.4	9.4	18.8	23.1	21.2	13.5	2.2	-9.6	-18.9	-23.0

The sunset hour angle on a horizontal surface for a typical day of each month is given by the equation $\omega_S = \cos^{-1}(-\tan\Phi\tan\delta)$, where Φ is the site's latitude (36.59)

Table A-3 Sun's hour angle

	Jan	*Feb*	*Mar*	*Apr*	*May*	*Jun*	*Jul*	*Aug*	*Sep*	*Oct*	*Nov*	*Dec*
Day	15	47	75	105	135	162	198	228	258	288	318	344

ω_S	73.2	80.2	88.2	97.1	104.6	108.4	106.7	100.2	91.6	82.8	75.3	71.6

The ratio $\frac{H_D}{H}$ depends on the clearness index K_T.

$$\frac{\overline{H}d}{H} = 1.39 - 4.03K_T + 5.53K_T^2 - 3.11K_T^3$$

Table A-4 Ratio H_d/H

	Jan	*Feb*	*Mar*	*Apr*	*May*	*Jun*	*Jul*	*Aug*	*Sep*	*Oct*	*Nov*	*Dec*
$\frac{H_D}{H}$	0.40	0.33	0.37	0.33	0.33	0.32	0.30	0.32	0.34	0.39	0.43	0.41

In order to find the monthly average daily total radiation on a horizontal surface H, the extraterrestrial insolation (S_{OH}) on a horizontal surface must be calculated first.

$$S_O = 1.356\left(1 + 0.0167\cos\left(\frac{day}{365} \times 360\right)\right)^2$$

$$S_{OH} = S_O \frac{24}{\pi}\left(\cos\Phi\cos\delta\cos\omega_S + \frac{\omega_S}{180}\sin\Phi\sin\delta\right)$$

	Jan	*Feb*	*Mar*	*Apr*	*May*	*Jun*	*Jul*	*Aug*	*Sep*	*Oct*	*Nov*	*Dec*
S_O (kW/m^2)-day	1.40	1.39	1.37	1.35	1.33	1.31	1.31	1.32	1.34	1.37	1.39	1.40
S_{OH}(kWh/m^2)-day	4.71	6.19	7.98	9.78	11.00	11.48	11.22	10.23	8.62	6.71	5.10	4.38

Now the values of H can be calculated

Table A-5 Average total radiation on horizontal surface

	Jan	*Feb*	*Mar*	*Apr*	*May*	*Jun*	*Jul*	*Aug*	*Sep*	*Oct*	*Nov*	*Dec*
H (kWh/m^2)day	2.20	3.36	3.96	5.39	6.03	6.46	6.63	5.77	4.58	3.20	2.20	1.98

The next step is to calculate R_b, that is a function of the site's latitude, the panel's slope and the sunset hour angle on a tilted surface.

$$\overline{R}_b = \frac{\cos(\Phi-\beta)\cos(\delta)\sin(\omega_S') + \left(\pi/180\right)\omega_S' \sin(\Phi-\beta)\sin\delta}{\cos\Phi\cos(\delta)\sin(\omega_S) + \left(\pi/180\right)\omega_S \sin\Phi\sin\delta}$$

The sunset hour angle is given by equation $\omega_S' = \min\begin{bmatrix}\cos^{-1}(-\tan\Phi\tan\delta)\\ \cos^{-1}(-\tan(\Phi-\beta)\tan\delta)\end{bmatrix}$

Table A-6 sunset hour angle on a tilted surface

Panel Tilt	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
0	73.2	80.2	88.2	97.1	104.6	108.4	106.7	100.2	91.6	82.8	75.3	71.6
5	73.2	80.2	88.2	95.9	102.1	105.2	103.8	98.5	91.4	82.8	75.3	71.6
10	73.2	80.2	88.2	94.8	99.8	102.3	101.2	96.9	91.1	82.8	75.3	71.6
15	73.2	80.2	88.2	93.8	97.7	99.7	98.8	95.4	90.9	82.8	75.3	71.6
20	73.2	80.2	88.2	92.8	95.8	97.3	96.6	94.1	90.7	82.8	75.3	71.6
25	73.2	80.2	88.2	91.9	94.0	95.0	94.6	92.8	90.5	82.8	75.3	71.6
30	73.2	80.2	88.2	91.1	92.3	92.8	92.6	91.6	90.3	82.8	75.3	71.6
35	73.2	80.2	88.2	90.3	90.5	90.7	90.6	90.4	90.1	82.8	75.3	71.6
40	73.2	80.2	88.2	89.4	88.8	88.5	88.7	89.2	89.9	82.8	75.3	71.6
45	73.2	80.2	88.2	88.6	87.1	86.4	86.7	88.0	89.7	82.8	75.3	71.6
50	73.2	80.2	88.2	87.7	85.3	84.2	84.7	86.7	89.5	82.8	75.3	71.6
55	73.2	80.2	88.2	86.8	83.5	81.8	82.6	85.4	89.3	82.8	75.3	71.6
60	73.2	80.2	88.2	85.9	81.5	79.4	80.3	84.1	89.0	82.8	75.3	71.6
65	73.2	80.2	88.2	84.9	79.4	76.7	77.9	82.6	88.8	82.8	75.3	71.6
70	73.2	80.2	88.2	83.7	77.0	73.7	75.2	80.9	88.5	82.8	75.3	71.6
75	73.2	80.2	88.2	82.4	74.3	70.2	72.1	79.1	88.2	82.8	75.3	71.6
80	73.2	80.2	88.2	81.0	71.2	66.2	68.5	76.9	87.9	82.8	75.3	71.6
85	73.2	80.2	88.2	79.2	67.5	61.3	64.1	74.4	87.5	82.8	75.3	71.6

90	73.2	80.2	88.2	77.1	62.7	55.0	58.5	71.2	87.0	82.8	75.3	71.6

So R_b will be

Table A-7 Ratio R_b

Panel Tilt	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
0	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
5	1.18	1.12	1.07	1.03	1.00	0.99	1.00	1.02	1.05	1.10	1.16	1.19
10	1.34	1.23	1.13	1.05	1.00	0.98	0.99	1.03	1.10	1.19	1.31	1.37
15	1.50	1.33	1.19	1.07	0.99	0.96	0.97	1.03	1.13	1.28	1.44	1.54
20	1.64	1.42	1.23	1.07	0.97	0.93	0.95	1.03	1.16	1.35	1.57	1.70
25	1.77	1.50	1.26	1.07	0.95	0.90	0.92	1.02	1.18	1.42	1.69	1.85
30	1.89	1.57	1.29	1.06	0.92	0.86	0.89	1.00	1.19	1.47	1.79	1.98
35	2.00	1.63	1.31	1.04	0.88	0.82	0.85	0.97	1.19	1.51	1.88	2.10
40	2.09	1.67	1.31	1.02	0.84	0.77	0.80	0.94	1.18	1.54	1.95	2.20
45	2.16	1.71	1.31	0.99	0.80	0.72	0.75	0.90	1.17	1.56	2.01	2.28
50	2.22	1.72	1.29	0.95	0.74	0.66	0.70	0.85	1.14	1.57	2.06	2.35
55	2.26	1.73	1.27	0.90	0.69	0.60	0.64	0.80	1.11	1.56	2.09	2.40
60	2.28	1.72	1.23	0.85	0.62	0.54	0.57	0.74	1.06	1.55	2.10	2.43
65	2.28	1.70	1.19	0.79	0.56	0.47	0.51	0.68	1.01	1.52	2.09	2.44
70	2.27	1.67	1.14	0.72	0.49	0.40	0.44	0.61	0.95	1.48	2.08	2.44
75	2.24	1.62	1.08	0.65	0.42	0.33	0.37	0.54	0.89	1.43	2.04	2.41
80	2.20	1.56	1.01	0.58	0.35	0.26	0.30	0.47	0.82	1.37	1.99	2.37
85	2.13	1.49	0.93	0.50	0.27	0.19	0.23	0.39	0.74	1.29	1.93	2.31
90	2.05	1.41	0.85	0.42	0.20	0.13	0.16	0.31	0.65	1.21	1.85	2.23

The ratio R of monthly average daily total radiation on a tilted surface to that on a horizontal surface is $R = \frac{\overline{H}_T}{H} = \left(1 - \frac{\overline{H}_d}{H}\right)\overline{R}_b + \frac{\overline{H}_d}{H}\left(\frac{1+\cos\beta}{2}\right) + \rho\left(\frac{1-\cos\beta}{2}\right)$

Table A-8 Ratio R

Panel Tilt	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
0	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
5	1.11	1.08	1.04	1.02	1.00	0.99	1.00	1.01	1.03	1.06	1.09	1.11
10	1.20	1.15	1.08	1.03	1.00	0.98	0.99	1.02	1.06	1.12	1.17	1.22
15	1.30	1.22	1.11	1.04	0.99	0.97	0.98	1.02	1.09	1.17	1.25	1.32

20	1.38	1.28	1.14	1.04	0.98	0.95	0.96	1.02	1.10	1.21	1.32	1.41
25	1.46	1.33	1.16	1.04	0.96	0.93	0.94	1.01	1.11	1.25	1.38	1.49
30	1.52	1.37	1.17	1.03	0.94	0.90	0.91	0.99	1.12	1.28	1.43	1.56
35	1.58	1.41	1.18	1.02	0.91	0.87	0.88	0.97	1.11	1.30	1.48	1.63
40	1.63	1.43	1.18	1.00	0.88	0.83	0.85	0.94	1.10	1.31	1.52	1.68
45	1.67	1.45	1.17	0.97	0.84	0.79	0.81	0.91	1.09	1.32	1.54	1.73
50	1.70	1.46	1.15	0.94	0.80	0.75	0.77	0.88	1.07	1.31	1.56	1.76
55	1.71	1.46	1.13	0.91	0.76	0.70	0.72	0.84	1.04	1.31	1.57	1.78
60	1.72	1.45	1.10	0.87	0.72	0.65	0.68	0.80	1.01	1.29	1.57	1.79
65	1.72	1.43	1.07	0.82	0.67	0.60	0.63	0.75	0.97	1.26	1.56	1.79
70	1.70	1.40	1.03	0.77	0.62	0.55	0.57	0.70	0.92	1.23	1.54	1.78
75	1.67	1.36	0.99	0.72	0.56	0.50	0.52	0.64	0.87	1.19	1.51	1.76
80	1.64	1.32	0.93	0.66	0.51	0.45	0.47	0.59	0.82	1.15	1.47	1.72
85	1.59	1.27	0.88	0.60	0.45	0.40	0.41	0.53	0.76	1.09	1.42	1.68
90	1.54	1.21	0.82	0.54	0.40	0.35	0.36	0.47	0.70	1.03	1.37	1.62

Finally, the average daily total radiation on a sloped surface will be H_T =HxR.

Table A-9 Daily irradiation in Sifnos (in kWh/m^2 –day) for a typical day in every month as a function of the panel inclination in degrees

Panel Tilt	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Annual**
0	2.20	3.36	3.96	5.39	6.03	6.46	6.63	5.77	4.58	3.20	2.20	1.98	4.31
5	2.43	3.63	4.13	5.50	6.04	6.42	6.61	5.84	4.74	3.40	2.40	2.21	4.44
10	2.64	3.87	4.28	5.57	6.02	6.36	6.56	5.88	4.87	3.58	2.58	2.42	4.55
15	2.85	4.10	4.41	5.62	5.97	6.26	6.48	5.88	4.98	3.73	2.75	2.61	4.64
20	3.03	4.30	4.51	5.63	5.89	6.14	6.37	5.86	5.05	3.87	2.90	2.79	4.70
25	3.20	4.47	4.59	5.61	5.79	5.98	6.23	5.80	5.10	3.99	3.04	2.96	4.73
30	3.35	4.61	4.64	5.57	5.65	5.80	6.06	5.71	5.12	4.08	3.16	3.10	4.74
35	3.47	4.73	4.66	5.49	5.49	5.60	5.86	5.60	5.11	4.15	3.26	3.23	4.72
40	3.58	4.82	4.65	5.38	5.30	5.37	5.63	5.45	5.06	4.19	3.34	3.34	4.68
45	3.66	4.88	4.62	5.24	5.09	5.11	5.38	5.27	4.99	4.21	3.40	3.43	4.61
50	3.72	4.90	4.57	5.07	4.85	4.84	5.10	5.07	4.89	4.21	3.44	3.49	4.51
55	3.76	4.90	4.48	4.88	4.59	4.54	4.80	4.84	4.77	4.18	3.46	3.53	4.39
60	3.78	4.87	4.37	4.66	4.31	4.23	4.49	4.59	4.61	4.12	3.45	3.55	4.25
65	3.77	4.80	4.24	4.42	4.02	3.91	4.15	4.32	4.44	4.04	3.43	3.55	4.09
70	3.73	4.71	4.08	4.16	3.71	3.58	3.81	4.03	4.23	3.94	3.39	3.53	3.91
75	3.68	4.59	3.90	3.87	3.39	3.24	3.45	3.72	4.01	3.81	3.32	3.48	3.71

80	3.60	4.44	3.70	3.57	3.06	2.90	3.09	3.40	3.76	3.66	3.24	3.41	3.49
85	3.49	4.26	3.48	3.26	2.74	2.56	2.74	3.07	3.49	3.50	3.13	3.32	3.25
90	3.37	4.06	3.24	2.93	2.41	2.24	2.39	2.73	3.21	3.31	3.01	3.21	3.01

GLASGOW-SCOTLAND

- Latitude 55.3^0
- Clearness Index

	JAN	*FEB*	*MAR*	*APR*	*MAY*	*JUN*	*JUL*	*AUG*	*SEP*	*OCT*	*NOV*	*DEC*
K_T	0.406	0.297	0.355	0.410	0.433	0.371	0.379	0.368	0.385	0.352	0.275	0.264

Using the same approach described in the previous section, the monthly average daily radiation on a sloped surface is found to be

Table A-10 Daily irradiation in Glasgow (in kWh/m^2 –day) for a typical day in every month as a function of the panel inclination in degrees

Panel Tilt	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Annual**
0	0.65	0.93	1.91	3.33	4.48	4.22	4.12	3.30	2.45	1.33	0.55	0.34	2.30
5	0.82	1.03	2.04	3.44	4.54	4.23	4.14	3.38	2.58	1.47	0.63	0.41	2.39
10	0.98	1.12	2.16	3.54	4.58	4.23	4.16	3.44	2.71	1.60	0.70	0.47	2.48
15	1.14	1.21	2.27	3.63	4.61	4.22	4.16	3.48	2.81	1.72	0.78	0.54	2.55
20	1.29	1.29	2.36	3.69	4.61	4.20	4.15	3.51	2.90	1.83	0.84	0.60	2.61
25	1.44	1.37	2.45	3.74	4.60	4.15	4.12	3.53	2.98	1.93	0.91	0.65	2.66
30	1.57	1.43	2.52	3.77	4.56	4.10	4.07	3.52	3.04	2.02	0.97	0.71	2.69
35	1.70	1.49	2.57	3.77	4.51	4.02	4.00	3.50	3.08	2.10	1.02	0.75	2.71
40	1.81	1.54	2.61	3.76	4.43	3.93	3.92	3.47	3.11	2.17	1.07	0.80	2.72
45	1.91	1.58	2.64	3.73	4.33	3.82	3.82	3.41	3.12	2.22	1.11	0.84	2.71
50	2.00	1.62	2.65	3.68	4.22	3.70	3.71	3.34	3.11	2.26	1.14	0.87	2.69
55	2.07	1.64	2.65	3.61	4.08	3.56	3.58	3.25	3.08	2.29	1.17	0.90	2.66
60	2.13	1.65	2.63	3.52	3.92	3.41	3.43	3.15	3.04	2.30	1.19	0.92	2.61
65	2.18	1.65	2.60	3.41	3.75	3.24	3.27	3.04	2.98	2.30	1.20	0.94	2.55
70	2.21	1.65	2.55	3.28	3.56	3.07	3.10	2.91	2.91	2.28	1.21	0.95	2.47
75	2.23	1.63	2.49	3.14	3.36	2.89	2.92	2.77	2.81	2.25	1.21	0.95	2.39
80	2.23	1.61	2.41	2.98	3.15	2.69	2.73	2.61	2.71	2.21	1.20	0.95	2.29
85	2.21	1.57	2.32	2.81	2.92	2.49	2.54	2.45	2.59	2.16	1.18	0.94	2.18
90	2.18	1.53	2.22	2.63	2.69	2.29	2.33	2.28	2.45	2.09	1.15	0.93	2.06

Appendix 2

System sizing, Sifnos Greece

Number of series connected modules

From table 6-3 panel KC 120 is chosen. The number of modules connected in series will be

$$N_S = \frac{V_{DC}}{V_m} = \frac{12}{17.7} = 0.7$$

the final number of modules is the nearest whole number above 0.7 which is 1. Therefore N_S=1.

Number of parallel connected modules

From equation 5-2 the equivalent load current is

$$I_L = \frac{E_L}{24V_{DC}} = \frac{9823}{24 \times 12} = 34.1A$$

The nominal current from the PV system (from equation 5-4) will be equal to

$$I_P = \frac{24I_L}{PSH} = \frac{24 \times 34.1}{4.25} = 201A$$

where PSH is numerically equal to the chosen value for irradiation (table 6-4) for a panel tilt angle of 60 degrees.

The number of parallel-connected modules is given by equation 5-5.

$$N_P = \frac{I_P}{I_m} = \frac{175}{7.1} = 28.3$$

So the final number will be N_P=29 modules. The total number of modules will be

$$N = N_S \times N_P = 1 \times 25 = 29$$

The same procedure is repeated for Glasgow and the results are shown in table 6-4.

Storage subsystem

The energy needed by the load every month is 9823 Wh per day. The energy produced by the system on a typical day is

$$E_{PV} = \text{Insolation} \times A \times E_f \qquad \text{(A2-4)}$$

where E_f is the efficiency of the modules and A is the total area of the array.

Table A2-1 Monthly energy balance

	Jan	Feb	Mar	April	May	June	July	Aug	Sep	Oct	Nov	Dec
Epv (kWh/day)	11.72	12.10	13.44	13.26	14.78	15.02	15.95	17.23	17.10	15.06	12.64	10.37
E_L (kWh/day)	9.82	9.82	9.82	9.82	9.82	9.82	9.82	9.82	9.82	9.82	9.82	9.82
En balance	1.90	2.28	3.61	3.44	4.96	5.20	6.12	7.41	7.28	5.23	2.82	0.55
Deficit (kWh/day)	0	0	0	0	0	0	0	0	0	0	0	0
Monthly balance	0	0	0	0	0	0	0	0	0	0	0	0

From the above table it is shown that the energy deficit ΔE during the year is zero, so the charge deficit Q_{Yd} will be equal to zero since $Q_{Yd} = \frac{\Delta E}{V_{DC}} = \frac{0}{12} = 0$.

Another charge deficit will be added (equation 5-8, $Q_{los} = I_L \times 24 \times n$). The chosen number of days with no energy input is chosen to be 5. So the value of Q_{los} is $Q_{los} = I_L \times 24 \times 5 = 34.1 \times 24 \times 5 = 4092\text{Ah}$

The total battery capacity needed will be

$$Q_B = \frac{Q_{Yd} + Q_{los}}{\Phi} = \frac{0 + 4092}{0.8} = 5115\text{Ah}$$

where Φ is the battery discharge, set to 80 percent. The number of batteries in parallel will be

$$N_{BP} = \frac{Q_B}{1\,\text{Battery Capacity}} = \frac{5115}{415} = 12.3 = 13$$

The number of batteries in series will be equal to

$$N_{BS} = \frac{V_{DC}}{V_B} = \frac{12}{12} = 1$$

The total number of batteries will be

$$N_B = N_{BP} \times N_{BS} = 13 \times 1 = 13$$

Appendix 3

LLC analysis

The capital cost for Sifnos is found from table 7-1. Total cost is given by equation (A3-1). Running cost for every year is 20 GBP and battery replacement as mentioned in chapter 7 is done ever seven years. Discount rate is set equal to 0.05 for the calculation of factor Pr (equation 7-2).

$$C = 27 \times 372 + 10 \times 278 = 12825\text{GBP} \qquad \text{(A3-1)}$$

A complete analysis for twenty years is shown in table A3-2. The PW for the costs in the 7th year of operation is calculated by adding all payments made that year. The discount factor for the 7th year will be equal to $\Pr_7 = \left(\frac{1+0}{1+0.05}\right)^7 = 0.71$. The final discounted value will be equal to the total cost for the year, multiplied by Pr.

Table A3-1 Yearly cost analysis for Sifnos

Year	Capital	Replacement	O&M	Total	Discounted
1	14525		18	14543	14542
2			18	18	16
3			18	18	16
4			18	18	15
5			18	18	14
6			18	18	13
7		2784	18	2802	1992
8			18	18	12
9			18	18	12
10			18	18	11
11			18	18	11
12			18	18	10

13		18	18	10
14	2784	18	2802	1415
15		18	18	9
16		18	18	8
17		18	18	8
18		18	18	7
19		18	18	7
20		18	18	7
			Total Discounted	18134

The life cycle cost for a PV system in Sifnos will be 18134 GBP. The same calculations are made for Glasgow. The results are shown in table 7-2.

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