Department of Mechanical and Aerospace Engineering

Improving the energy capture of solar collectors

[For cloudy regions by using controlled tracking system]

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A thesis submitted in partial fulfilment for the requirement of the degree

Master of Science

Sustainable Engineering: Renewable Energy Systems and the Environment

2012

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Signed: Haytham Ayoub Date: 05/09/2012

Abstract

This project investigated methods of harvesting solar radiation for a flat plate collector in cloudy sky condition in order to optimize the energy capture of the systems in this condition, and it proposed an improved method for irradiance optimization by using a controlled tracking system. It includes the development of a simulation model that built in ESP-r software which analysed the performance of the collector at different configuration in a chosen location in Glasgow which is assumed to be a cloudy region. The project has improved the performance of solar tracking devices in these regions. It is a common knowledge that the traditional 2-axis solar tracking system tracks the beam radiation during the day and it improves the capture efficiency by around 30 to 50% versus a system with optimum fixed tilt, this is effective in clear sky conditions only, because the beam component contributes by around 90% of the global radiation and only 10% for diffuse in that conditions. However, the study showed that, when considering a collector in cloudy conditions where the diffuse component contributes by a significant amount to the global radiation, the use of solar collector decrease the energy capture by 23%, thus because of the shortcoming of capturing most of the valuable diffuse radiation. When the collector was on the optimum fixed tilt mode the capture efficiency was the highest at 84%, and when mounting the collector horizontally the efficiency decreased but it captured all the available diffuse radiation. This observation lead to an improved control system which uses a simple algorithm to manage the settings of the collector instantaneously according to different conditions, in which a collector would track the beam directly during clear periods to collect most of the beam radiation, go to the optimum fixed tilt mode when the sky is partially cloudy to collect most of both radiation, and go to the horizontal mode when it is totally cloudy to collect all the diffuse ones. The paper investigated different approaches and after several attempts it has been found that, the controlled tracking system would increase the capture efficiency by 11% versus a model with optimum fixed tilt. The system can be applied by using sensors to measure the beam and diffuse radiation, controlled system with the suggested algorithm, sun-pointing programme to track the sun when needed and a step motor to rotate the collector. The project also showed that, although the initial cost of the tracking system is higher than fixed one but it would be attractive for investors since it has a slightly less payback period and with higher energy value. And in terms of energy, it has been found that the use of any other system would lead to exergy destroy.

Acknowledgment

This research project would not have been possible without the support of many people. Therefore, I would like to take this opportunity to thank everyone who has supported me during the period of my degree work to make this project comes into being.

First and foremost, I would like to thank the staff members of the Department of Mechanical and Aerospace Engineering for their efforts during the course. I wish to express my sincere gratitude to my supervisor Prof. Joe Clarke who was abundantly helpful and offered invaluable assistance, support and guidance. Deepest gratitude are also due to Doc. Paul Strachan for his valuable advices and works to make this course well organized. Besides, I wish to express my gratitude to the other staff members who rendered their help during the period and provided a very flexible environment. Also an honourable mention goes to my family for their understandings and supports on me in completing this project. And at last but not least, I wish to avail myself of this opportunity, express a sense of gratitude to all of my colleagues and friends that I meet during the year and who shared with me the experience. To Chris McGee for proofreading this paper, Will Laird for giving me some ideas and a special thank you to Mr. Jack Maitles for his ultimate encouragement during the year.

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1 Introduction

Solar energy is clean, renewable and is the largest natural source of energy. In an hour the earth receives an amount of energy that can meet the global energy consumption for almost a year “this is about 5000 times the input to the earth’s energy budget from all other sources”(Messenger & Ventre, 2012). For thousands of years this energy has been used to produce heat, light and to grow plants. Modern day, technologies are being developed to harness the utilization of such a clean energy applications in order to address the global challenges of climate change, energy security and sustainable development. Solar energy can be used used for electricity production and solar heating thus by harvesting the sun’s radiation through solar collectors. The current global demand on solar power is less than 1% and although this figure is small compared with other conventional sources but it offers a very promising future. According to the International Energy Agency, the global Photovoltaic (PV) capacity has been increasing since 2000 at an average annual growth rate of 40% and the roadmap envisioned for PV is to provide 11% of the global electricity production in 2050 which means a contribution of 4500TWh annually, to achieve this will requires installing 3000GW of PV capacity (IEA, 2010). However, achieving this require a strong optimal technology progress and cost reduction for the PV market. This target identifies technology goals and expansion areas to enable the most cost-efficient development of solar energy.

Solar applications are currently facing lot of challenges because of their limitations. It is unlikely that the current solar applications can not convert all the available solar radiation to DC energy and the amount of energy of the applications depends strongly on the efficiency of the technology being used. For example, the performance of a PV panel can be defined according to two types of efficiencies, cell and capture efficiency. Cell-efficiency can be defined as the collector’s ability to convert photons energy to DC energy; It is affected by voltage loss that can reach up to approximately 20% of the total power output, band gap loss (23%) and excess photon energy losses (33%) (Twidell & Weir, 2006) and the maximum cell-efficiency achieved to date is 43.5% (NREL c, 2012). The capture efficiency can be defined as the ability of the collector to harvest the maximum possible amount of solar radiation that are available at a specific site. This can be affected by the design of the system and the method of mounting the collector, and is going to consider improving the performance of solar collectors in regards to the energy capture only.

Different studies have been carried out to improve the amount of energy capture to increase the overall efficiency for solar applications. As a result of this, different applications have been invented that tend to maximise the utilization of solar power such as solar concentrators and solar towers. One of the applications that is currently being used very widely, especially in sunny climates is the solar tracking system. This system can be used as 1- axis which can increase the energy output of a collector by around 30% versus a fixed tilt, and 2-axis tracking this can increase the figure to 50% (Kelly & Gibson, 2009). But these figures change from one location to another and depend strongly on the climate condition at the specific site. For the 2-axis tracking system, it has been found that the system can collect approximately 50% more energy in summer and 20% in winter; this is for clear sky countries. In cloudy conditions where there is a high volume of clouds in the sky the system would collect around 35% in summer and 5% only in winter and it has been found that in some conditions the use of solar tracking devices can decrease the performance of the energy capture (Messenger & Ventre, 2012). This can make the system a relatively ineffective approach in cloudy regions especially because the cost of such systems is more expensive than the cost of a fixed amount collector.

In the past, different pieces of research have been focussed on analysing the effect of these systems in clear sky condition only. Most of these studies used the direct solar tracking DST system, which is designed to follow the position of the sun during the day without considering the effect of heavy clouds on the global radiation (Duffie & Beckman, 1991)(Messenger & Ventre, 2012). The studies concluded that use of solar tracking systems can be an ineffective option in regards to energy capture and they are costly in high forecast sky conditions as they are effective only in clear sky locations (Kelly & Gibson, 2009). Recent studies have tried to focus on improving the performance of tracking systems in different climates especially for a cloudy sky condition and it has been found that this can ultimately improve the performance of the system for regions that are considered to be cloudy throughout the year such as the UK, Ireland and the Northern Europe region(Armstrong & Hurley, 2009).

This paper will investigate different approaches to improve the energy capture of solar collectors in cloudy regions by using a 2-axis solar tracking system. It aims to find a way to optimize the performance of solar collectors by comparing different configurations that appear to be the most effective ones and will suggest a better method for ensuring energy optimization.

The next section of this paper is going to discuss the literature reviews relevant to the objective of the study. It will then look at the fundamentals of solar radiation in order to understand the characteristics and the nature of the solar resource, and illustrate some methodologies that this work will follow. After that it is going to discuss different approaches for optimizing the energy capture. The project is going to model each approach to examine its effect on the energy capture and it will suggest an improved approach using a simple algorithm. The discussion section will include a brief financial analysis as well as energy analysis. Finally this paper will refer to further related research considered to be relevant to this subject; however for the purpose of this study it is not discussed in detail.

2 Literature review

It is common knowledge now that the use of tracking systems increases the energy output of solar systems. However, it has been found that most of the research that has been implemented on solar systems and solar tracking mechanisms were focusing on improving the energy capture on clear sky condition only and did not consider the climate effect on the system.

For example, in 2001, The Worcester Polytechnic Institute carried out a study to investigate the performance of 2-axis solar tracking systems (Catarius, 2010). The aim of the study was to investigate increasing the energy output of a solar collector by using a 2-axis tacking system. According to their report, the 2-axis tracking system increases the annual energy by around 48% than a fixed model and by around 36% than a 1-axis system. And using of these systems can be very attractive in regards to the tracking advantage and the associated economic scale of the system. Also most of the studies that have implemented in the UK and in Europe such as the works that have been done by the European Photovoltaic Technology Platform were studying improving these systems on clear sky conditions only (European Photovoltaic Technology Platform, 2011). These studies did not consider the solar tracking performance in cloudy conditions, and therefore their results can be applicable for only clear sky locations.

Then some studies came to compare the performance of tracking systems in different locations. Messenger & Ventre have discussed maximizing of the irradiation on solar collectors (Messenger & Ventre, 2012). They have looked at optimizing the performance of flat solar collectors and discussed briefly the performance of solar tracking system under different conditions. They have chosen two locations at different climate condition, one at clear sky condition and another at somewhat cloudy condition. And they have found that the performance of a tracking system reduces with the increase of clouds layer at the location.

> “Approximately 50% more energy can be collected in the summer in dry climate such as Phoenix, Arizona, by using a tracking collector. During winter months only 20% more energy is collected. In Seattle, Washington which receives somewhat more diffuse sunlight than Phoenix the collector will capture 35% in summer and 5% in winter” (Messenger & Ventre, 2012).

The energy capture percentage has reduced from 50% for Phonix to 35% for Seattle in the same season. This reduction is a result to the relative decrease of the beam to diffuse radiation ratio in Seattle. The study concluded that the performance of a tracking system depends strongly on the location of the collector and the sky condition. However, it is important to note that Phoenix and Seattle latitudes are 33^0 and 45^0 respectively, and they are located in the most favourable belt for harvesting solar energy, between the latitude of 0^0 and 45^0 (see Appendix E, figure 18). It is expected that for locations above the 45^0 the energy capture percentage would show more decrease.

A study that has been done by the International Solar Energy Society has discussed the ineffectiveness of these systems in cloudy climates; it has been found the tracking systems can be ineffective in cloudier conditions when comparing it with a fixed mounted collector.

> "…the total energy available to a fixed flat plate collector is approximately the same as the direct beam available to a tracking collector and may exceed that of a tracked beam in cloudier climates"(ISEC, 2001).

In addition to that, the study has highlighted the difficulties of harvesting solar radiation in cloudy conditions where the diffuse radiation are higher than the beam ones and recommended using of different approaches for energy capturing according to the nature of the radiation at a specific site. For example it has illustrated the importance of using flat collectors instead of concentrating ones at these locations. In the Solar Radiation book the author has considered also the same point (Iqbal, 1983). It dealt with measuring of solar radiation according to the climate conditions and it developed models that classify these conditions as cloudless and cloudy skies.

It is important to note that all these studies have focused on a model that tracks the sun positions all over the year or in other words tracks the direct beam radiation, and according to this they concluded that implementing these systems in cloudier climates seems to be inefficient. Then some studies came to investigate improving of energy capture by considering different approaches that consider increasing the harvest of beam as well as diffuse radiation.

A study carried out in the National University of Ireland has addressed this issue (Armstrong & Hurley, 2009). It aimed to find a new method to maximise that solar energy harvest under cloudy condition which can be useful for a country such as Ireland. The study highlighted the problem of predicting the power output of the solar collectors in cloudy countries and included new method which improves harvesting of diffuse radiation that tend to be important approach for the Northern Europe countries.

> "For a climate susceptible to overcast skies, where the beam radiation is eliminated, a new approach is necessary that takes into account the frequency of clouds. The proposed methodology combines hourly observations of cloud conditions with monthly sunshine hour's data in order to determine the frequency of clear, partly cloudy and overcast skies in order to calculate the solar radiation. Using these solar radiation values and knowledge of cloud conditions, the tilt angle can be chosen that optimises the available solar radiation between the beam radiation on sunny days and the diffuse radiation on overcast days"(Armstrong & Hurley, 2009).

According to the research, for maximizing the solar energy capture it is important to part the solar radiation to direct beams and diffuse beams while predicting this energy, and then the optimized tilt sitting should be selected according to the two kinds of radiation together. The proposed method uses localized condition to determine a Sunshine Hours Ratio (r), this ratio is used to distinguish between clear, bright and dark forecast days and accordingly calculate the actual global horizontal radiation ($G_{h,act}$). After that a set of equations will calculate the optimum tilt angle for the collector.

$$G_{h,act} = r.G_h$$ Equation A: (Armstrong & Hurley, 2009)

Where G_h is the calculated global horizontal radiation.

The proposed approach seems to be suitable for all locations with different sky conditions and it has been tested in sunny locations.

And finally a research has been done by the R&D Centre at General Motor Company to investigate new method of improving the energy output of photovoltaic systems in cloudy conditions by using solar tacking devices(Kelly & Gibson, 2009) (Kelly & Gibson, 2010). They have used the Duffie & Bechman model (B&C) to measure the amount of global radiation (G_h) on horizontal surfaces for different conditions. The aim of the study was to develop an algorithm for the 2-axis tracking system to improve the energy output of solar systems which can be applicable for cloudy and sunny days.

They proved that global horizontal radiation can be increased by increasing the beam horizontal (I_{bh}) and this can be achieved by minimizing the azimuth angle (θ_z) to reach zero

$(\cos 0 = 1)$. However, the positions of the sun change during the day the only way to achieve that is to keep the collector face perpendicular to the incoming light from the sun all over the day by using a Direct Solar Tracking (DST).

$G_h = I_{bh} + I_{dh}$ Equation B: (Kelly & Gibson, 2009)

$I_{bh} = I_{bn} \times \cos \theta_z$ Equation C: (Kelly & Gibson, 2010)

Where G_h is the global horizontal radiation, I_{bh}beam for horizontal surface, I_{dh} diffuse for horizontal surface, all in kWh/m^2.

On sunny sky conditions where 90% of the radiation contributed from the direct beam while the remaining 10% only from diffuse radiation, the 2-axis DST can dramatically increases the solar energy harvested because the direct beams are greater than the diffuse ($I_{dh} \approx 0$) and the response of the collector to the cosine of azimuth angle. According to their results the system increases the solar energy for a collector by 52% compared with a horizontal model and with 41% tracking advantage. Controversially, on cloudy days tracking the sun reduces the energy capture and that the horizontal surfaces increase the energy by 47% than a tracker system. And therefore it was thought to find a better way to maximise the diffuse radiation collected by a surface on a cloudy days. The study proposed an optimized tracking system to track the sun on clear sky periods and to tilt horizontally on cloudy periods. According to their results, this system can increase the solar energy capture by 25% than a horizontal model.

The study has highlighted the importance of using different tracking approach to track the sun positions on clear sky period and to adjust to different settings on cloudy sky periods. It focused on a mathematical analysis of Duffie & Beckman equations to optimize the global radiation conponant. However, it has been thought that the study was by somehow limitted sine it has been noticed that the work presented a concipt only and did not model this approach. In addition to that, the study has ignored to include the performance of the optimum fixed tilt model and the results are used to compare with a horizontal surface only.

Based on these studies, it has been found that using of solar tracking devices in cloudy climates can improve the ammount of energy capture of solar systems, this by applying some modification and inhansments to the system. Theroefre, this study is going to investigate that and it will try to improve the efficiency of solar systems by using of solar tracking devices.

3 Overview on solar radiation

Improving the performance of solar collectors to capture of solar radiation and to convert it to useful form of energy depends strongly on the understanding of radiation properties. Therefore this section is going to represent the importance of solar phenomena, atmospheric and location effect, calculation of sun positions and components of solar radiation on different tilted surfaces. It will include also some definitions, figures and equations that thought to be essential for this paper. It has been noticed that references use different symbols and terms for solar radiation and angles, therefore this section is going to characterize that.

3.1 Radiation from the sun

The sun has an effective blackbody temperature of 5777K, radiation emitted by the sun reaches the earth's surface at a maximum flux density of 1kW/m^2 as a short wave radiation. Depending on the time, place and weather the energy flux can vary from 3MJ/m^2 to 30 MJ/m^2 in a single day. This energy is a very high energy and can be used for thermally, photophysical or photochemical processes (Twidell & Weir, 2006)(Messenger & Ventre, 2012).

The emitted radiation reaches the earth atmosphere at almost fixed intensity at a solar constant of 1367W/m^2 (Duffie & Beckman, 1991). This number varies with the variation of the earth-sun distance and therefore it is dependant with the time of the year. Figure 1 shows that it shows the variation of these radiation during different seasons in one year. Beneath the atmosphere, the solar radiation will enter the earth surface as extraterrestrial beam radiation and it will varies widely due to local atmospheric variations, location (latitude), time of the day and season of the year. After entering the earth's atmosphere, the extraterrestrial beams will part to beam radiation[1] that received without having being scattered by the atmosphere and diffuse radiation[2] that received after its direction has been changed by scattering by the atmosphere. And the sum of both radiation called the global radiation. However, the amount of these radiation depends on the sky condition and therefore the portion of these radiation varies but there is always be at least 10% of diffuse radiation, this is because the effect of the particles and molecules radiation's absorption in the atmosphere (ISEC, 2001).

[1] Beam Radiation, The radiation that received from the sun without being scattered by the atmosphere. Some references called it as direct solar radiation (Duffie & Beckman, 1991).
[2] Diffuse Radiation, The radiation that received from the sun after have being affected by the atmosphere (Duffie & Beckman, 1991).

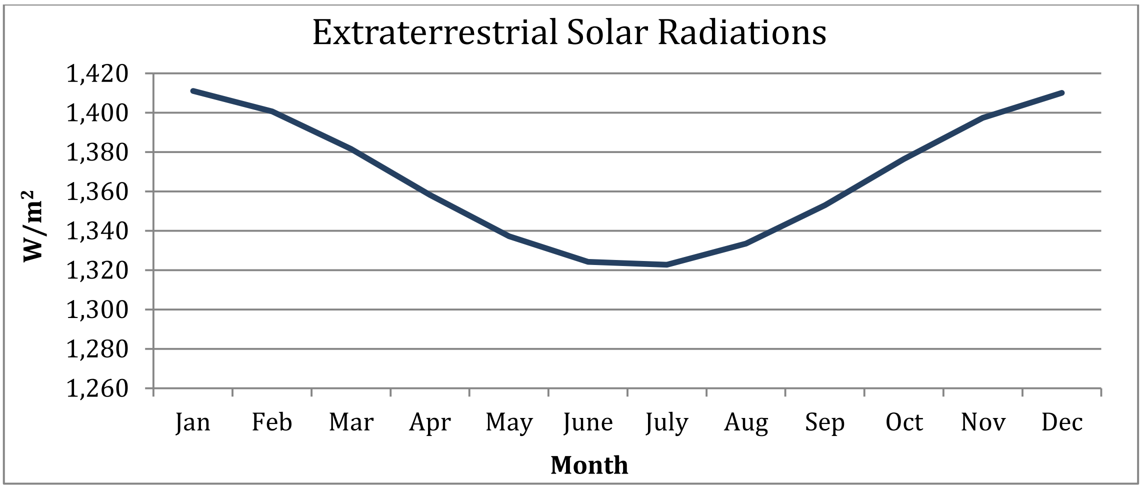

Figure 1: Change of extraterrestrial solar radiation in a year.

The radiation can be received by any surface on earth and the rate that describes it is the irradiance[3]. And this term can be used for beam, diffuse and global radiation. The fraction of beam to global irradiance can vary from 0.9 for a clear day for clear sunny day to 0.1 for totally cloudy day (Honsberg & Bowden, 2012).

3.2 Daily insulation, latitude and season change

A good term that can be used to easy compare the amount of energy received by a surface in a single day is the daily insulation[4] (H_h). The amount o daily insulation varies with the season of the year and the location. Figure 2 below shows how this can changes with change of the latitude and the season of the year for a horizontal surface. The greater the latitude the less insulation can be received especially in winter. For example, for a fixed location in the United Kingdom in Glasgow with 55^0 Latitude, the daily insulation vary from $25MJ/m^2$ in summer to $5MJ/m^2$ in winter, While for a location at the latitude of 35^0N, the winter figure can reach to almost $13MJ/m^2$. It shows also how the amount of radiation changes dramatically for higher latitudes during the year while the change is very small for smaller latitudes.

[3] Irradiance, The rate at which radiation received on a surface per unit area (W/m^2) (Duffie & Beckman, 1991).
[4] Daily Insulation, The energy received by a surface in a single day which can be used to compare the energy at different locations. Can be referred as hourly insulation (Twidell & Weir, 2006).

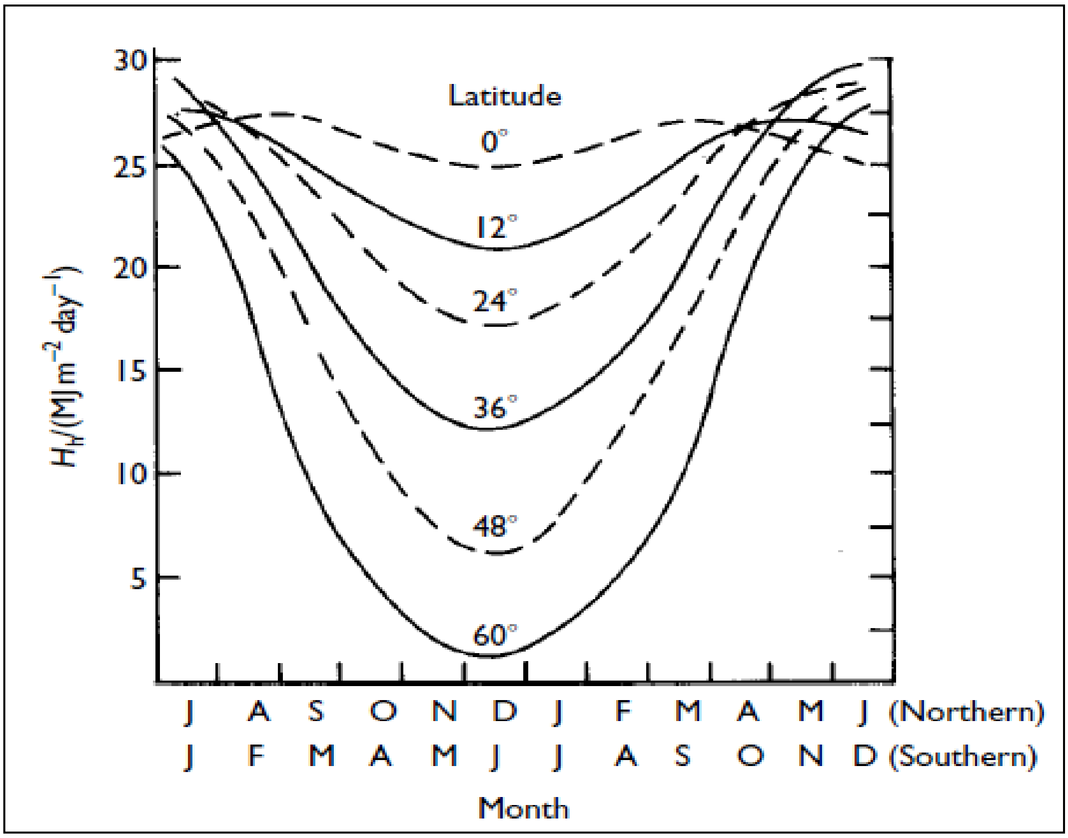

Figure 2: Daily insulation for a horizontal plane change with season and latitude. (Twidell & Weir, 2006)

3.3 Sun positions

As the earth travels around the sun and rotates daily about its own polar axis, it is important for designing of a solar system to locate the positions of the sun; this can be done by calculating Solar Altitude[5] ($\propto_s$) and Solar Azimuth[6] (γ_s) angles (Duffie & Beckman, 1991). The solar altitude is the angle between the horizontal plane and the acting line of the sun, this angle varies throughout the day and it is zero during the sunset and 90^0 when the sun is totally overhead. For an optimum solar system it is important to maximise the altitude angle which occurs usually at the solar noon, this will be discussed more widely in the next section. The Solar Azimuth is the angular displacement from the north of the projection beam radiation on the horizontal plane. The sun is directly south at the solar noon in the northern hemisphere and north in the southern hemisphere at solar noon (Honsberg & Bowden, 2012). This angle also varies throughout the day, for example in Glasgow the angle is 90^0 during sunrise and 270^0 during sunset in summer time (see appendix B figure 14).

[5] Solar altitude is the angle between the beam from the sun to the horizontal, it is the complement of the zenith angle (Duffie & Beckman, 1991).
[6] Solar azimuth is the angle displacement from the projection of the beam radiation on the horizontal plan, for this study this angle is measured from the north (Duffie & Beckman, 1991).

3.4 Solar irradiance on tilted surfaces

The solar energy is received on any surface on earth as components of different kind of irradiances. Different models have been made so far to calculate the total irradiance and this study is going to use the Isotropic Sky Condition which has been developed by Hottel and Woertz (Duffie & Beckman, 1991). This model assumes that any tilted surface is subjected to the three components of irradiances, beam irradiance (I_b), diffuse irradiance (I_d) and irradiance diffusely reflected from the ground (I_r), all together known as the global irradiance (G). And it assumes also that the sum of diffuse and ground reflected radiation is the same regardless of the surface position. It is important to note that some models include the reflected irradiance within the diffuse irradiance component and other deal with it independently depending on the model being used. And since this study is going to focus on comparing the beam to diffuse components only, the reflected term will be summed to the diffuse irradiance, as assumed by the isotropic sky model. Therefore the global irradiance can be obtained from the following equations, when the beam normal and the horizontal diffuse are given:

$$G = I_b + I_d$$ Equation 1: Global irradiance (Duffie & Beckman, 1991)

For titled surfaces the beam irradiance can be calculated from the following equation and depends on the incident angle. Where (I_{bn}) is the beam normal which is given usually by the climate data and (θ) the angle of incident[7].

$$I_b = I_{bn} \times \cos\theta$$ Equation 2: Beam irradiance (Duffie & Beckman, 1991)

The defuse radiation can be obtained by the following equation this is for the assumption of isotropic diffuse sky only, where (β) is the tilt angle[8] and (I_{dh}) is the horizontal diffuse radiation which is usually given from the climate data. This is the simplest formula for diffuse used for easy analysis and (I_d) in this case is a function of the tilt angle.

$$I_d = 0.5\,[1 + \cos\beta]I_{dh}$$ Equation 3: Diffuse Irradiance (Duffie & Beckman, 1991)

Appendix C, Figure 16 shows the geometry of an inclined surface with the projection of different angles.

[7] Angle of Incident, The angle between the beam from the sun and the normal to the surface(Twidell & Weir, 2006).

[8] Tilt angle, The angle of the slop of the collector in this study it measure from the horizontal, however some references reference it from the vertical (Duffie & Beckman, 1991).

3.5 Horizontal surfaces

The easiest configuration for the collector is the horizontal model. For this configuration the title angle is equal to zero and the incident angle is equal to the zenith angle[9] (θ_z). The global radiation for the horizontal position can be obtained from the following equations (Duffie & Beckman, 1991):

$I_{bh} = I_{bn} \times \cos\theta_z$ Equation 4: Horizontal beam irradiance (Duffie & Beckman, 1991)

$I_d = I_{dh}$ Equation 5: Horizontal diffuse irradiance (Duffie & Beckman, 1991)

$G_h = I_{bh} + I_{dh}$ Equation 6: Horizontal global irradiance (Duffie & Beckman, 1991)

The global irradiance of the collector for this case depends on the $I_{dh,}$ I_{bn} and θ_z. The beam irradiance is a function of $\cos\theta_z$ and it will vary from unity when θ_z is equal to zero, to zero when θ_z is equal to 90^0. The diffuse component for the horizontal configuration is equal to the I_{dh}only, where for horizontal tilt β is equal to zero.

3.6 Fixed tilted surfaces

The aim of tilting the collector to a fixed angle is to increase the collection of the solar irradiance on the surface (Iqbal, 1983). From equation 2&3, the tilt and the incident angles of the collector can affect the beam irradiance component and the diffuse irradiance (the incident angle is a function of the title and the azimuth of the surface). It has been found that the best orientation for a solar collector is to be south facing for most of the locations (Messenger & Ventre, 2012). The tilt angle is usually chosen depending on the altitude angle of the sun at solar noon in a day in summer. It has been found also that the best approach is to choose the tilt angle in a way to keep the surface perpendicular to the beam irradiance. Figure 3 shows how the tilt selection affects the daily insulation of the collector at a specific location with a south facing orientation. The optimum tilt selection will be discussed in the next two sections.

[9] Zenith angle, The angle between the beam from the sun and the zenith vector (vertical) (Duffie & Beckman, 1991).

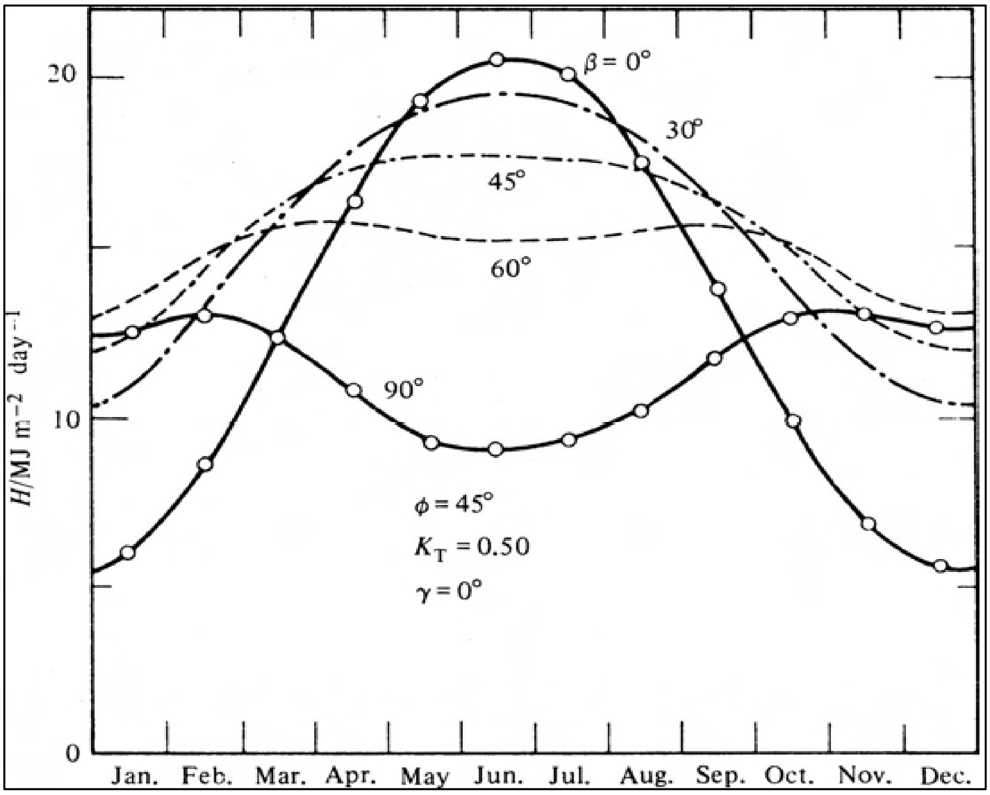

Figure 3: Insulation change with the tilt angle change all over the year for location 45^0 N latitude (Twidell & Weir, 2006).

3.7 2 axis – Direct Solar Tracking (DST)

The 2-axis direct solar tracking system is approach used to allow the collector to follow altitude and the azimuth of the sun all over the day. The approach is used to maximise the system performance comparing with a fixed system (Kelly, 1993). Following the azimuth is achieved by orienting the surface azimuth[10] (γ) typically to the solar azimuth across the year. The solar altitude can be followed by subjecting the collector perpendicular to the beams, this is achieved by tilting the collector to the zenith angle hence $\beta = \theta_z$ (Duffie & Beckman, 1991). And therefore, from equations 1&2 the beam and the diffuse components are equal to the following for collectors with tracking devices:

$I_b = I_{bn}$ Equation 7: Beam irradiance (Duffie & Beckman, 1991)

$I_d = 0.5\,[1 + \cos\theta_z]I_{dh}$ Equation 8: Diffuse irradiance (Duffie & Beckman, 1991)

Tracking the sun can be done by using a sun pointing programme that define the positions of the sun during the day and rotates the collector by using a step motor (Kelly & Gibson, 2010).

[10] Surface orientation (azimuth) the deviation of the projection on a horizontal plane of the normal to the surface from the location meridian, measured from north.

4 Review of optimizing energy capture

The collector configuration should be designed in a way to collect the maximum available from the total radiation at a proposed site. The characteristics of solar radiation change from region to another and thus due to different factors. The portion of beam to diffuse radiation also changes and depends strongly on the location and the sky condition at the selected site. The configuration of the collector should be designed to utilized most of the available radiation to increase the performance of the collector. This section is going to discuss that it will show how different climate and location effects on the global component of the solar irradiance and ultimately effect the design of solar system. And how assessing the solar source affect in designing of solar systems

4.1 Solar resource assessment

Solar resource assessment is a significant process in the design of solar applications. The process provides information about the sources characteristics and measurements that are important inputs for any system simulation, that can be used for feasibility studies and design purpose (ISEC, 2001). Assessing these data is important since it can address the major influences on any the application, especially for optimizing the system to make it effective in different seasons. As mentioned earlier, the solar irradiance for a specific location affected by different factors including the cloudiness and the change of the sun position. Therefore understanding the solar resource at the required location can significantly influence the performance of any system. According to Jeffery Gordon:

> "Informational parameters should allow a model to adjust to these major influences, especially if one wants this model to be valid in different climates. Therefore, the parameters should be able to characterize not only cloudiness, but also cloud opacity. They should do it independently of the influence of the solar zenith angle. Of course, the choice of parameters to be used for a model depends on what information is available as input to the model (ISEC, 2001)."

The components of beam and diffuse insulation can vary for different locations. For example, Appendix A, figure 13 compares the global, beam and diffuse insulation for cloudy and sunny sky condition on a horizontal surface in Detroit. The figure shows how the contribution of beam to diffuse can vary depending on the cloud cover at the sky. It is clear that in sunny days the beam normal is greater than the diffuse. For example, at 1:00AM the bean normal to diffuse horizontal (I_{bn}/I_{dh}) ratio reach to 1.03 and during a cloudy day the ratio is reduced dramatically to about 0.004. Assessing these data helps identify the parameters of the solar systems. For example, the increase of clouds in the sky would decrease the global radiation and the portion of the direct beam in the whole. And therefore, at clear sky condition that subjected to high beam radiation are seen to be most suitable for beam collectors only such as solar concentrators. And at cloudy condition which receives significant diffuse radiation, the non-concentration collectors such as flat plate collectors are more suitable for these conditions.

4.2 Current methods of energy capture

The performance of any solar collector system depends strongly on the method of mounting the system during early design stages. Two factors that affect the energy capture are the tilt angle and the orientation of the collector. These factors have to be designed to optimise the performance of the system to harvest the maximum possible amount of radiation. According to Duffie & Bechman equations 1&2, when the collector surface is perpendicular to the solar beams the power density will be at its maximum, and when the surface is subjected horizontally the diffuse power density will be at maximum. This then optimizes the energy capture by increasing the global irradiance.

After assessing the solar radiation data, a model can be developed to choose the best configuration for different systems Different methods can be followed to design a system with the optimum energy capture. For example, the horizontal configuration cannot optimise the energy collection but increase the collection of diffuse radiation. From equation 4, the beam irradiance component is proportional to the $\cos \theta_z$ for this configuration and this angle changes during the day and therefore the collector might not be perpendicular to the beam radiation. On the other hand the diffuse component will be maximized. From equation 3, the diffuse component is proportional to the $\cos \beta$ and will be equal to unity for this mode, as a result to this the surface diffuse will equal to the horizontal diffuse (equation 5). That makes the horizontal configuration attractive option for locations where there is great amount of diffuse radiation.

Another alternative method is the fixed tilt angle. As the sun change its position during the day the amount of insulation of any surface will change, and this portion will be at its largest at solar noon when the sun is highest in the sky in summer time. Therefore, the optimum tilt angle should be selected at the day that receives the highest amount of beam radiation. According to Messenger & Ventre:

> "Because (θ_z= latitude – declination) defines the position of the sun at solar noon, if a collector plane is perpendicular to this angle, it will be perpendicular to the sun at solar noon. This is the point at which the sun is highest in the sky, resulting in its minimum path throughout the atmosphere…"

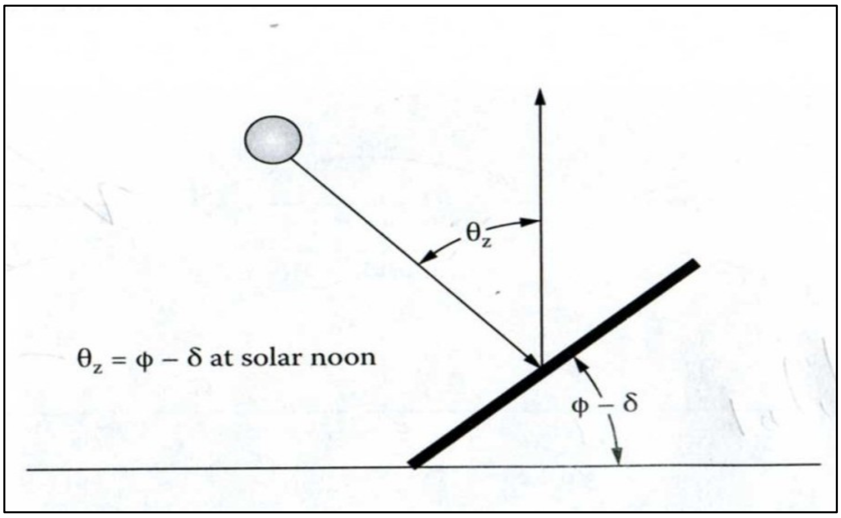

Figure 4: Tilt angle optimization of a collector (Messenger & Ventre, 2012).

The collector surface will be perpendicular to the normal beam at solar noon only. As the sun travels through 15^0 angles per hour this will make it almost perpendicular to the collector surface for around two hours during a day, and beyond this period the irradiance will decrease as the incident angle increases from zero.

If the collector mounted in a way to track that 15^0 travel angle, then the collector will always be perpendicular to the beam irradiance all over the day. This called the altitude tracking method (Kelly, 1993). Additionally the system can track the azimuth axis and this configuration called 2-axis or doula direct tracking system. It has been found that the 2-axis tracking system can improve the energy capture by about 50% in summer and by about 20% in winter, this is in sunny climate only where the proportion of beam component is much larger than diffuse one i.e. in Phoenix. In contrast with that, in Seattle where there is more diffuse radiation the figure drops to about 35% in summer and only 9% in winter (Messenger & Ventre, 2012).

This is because the 2-axis DST system tracks the beam radiation only. And therefore, the system is useful for only clear sky locations where the beam component is greater than the diffuse one. That makes it attractive solution for location between the latitudes of 5^0 N and 40^0 N – the favourable solar belt for capturing beam radiation (Armstrong & Hurley, 2009). For example, the greatest amount of radiation are received in countries located between the latitudes ok 15^0N and 35^0N such as Egypt where it receive the greatest radiation and the bean component contribute by 90% of the global irradiance at the country. Countries located between the latitudes of 35^0N and 45^0N such as Turkey and Spain receive fewer radiation because of the huge seasonal variations at these locations. The countries that located beyond the 45^0N (Northern Europe) are the least favourable locations for capturing beam irradiances such as Scotland, Ireland and Norway, these countries receive the least amount of beam irradiance, half of the global irradiance comes from the diffuse component and that's due to the heavy cloud cover(CIBSE, 2002). The table below illustrate the mean direct and diffuse irradiance in Edinburgh which is assumed to be a cloudy condition; the data has been collected for several years from 1981 to 1992 and it shows the importance of diffuse component and how it can be greater than the beam component with different orientations and tilt.

Orientation	**Direct**					**Diffus**				
	0 W/m2	**30** W/m2	**45** W/m2	**60** W/m2	**90** W/m2	**0** W/m2	**30** W/m2	**45** W/m2	**60** W/m2	**90** (W/m2
West	932	831	764	682	473	1483	1406	1304	1149	736
South-West	932	1125	1132	1073	790	1483	1476	1394	1256	857
South	932	1261	1306	1265	941	1483	1506	1435	1307	914
South-East	932	1164	1183	1133	852	1483	1484	1404	1268	868
East	932	878	820	743	530	1483	1413	1312	1158	745

Figure 5: Annual mean irradiance on tilted surfaces. Data for Edinburgh (1981-1992) (CIBSE, 2002).

Therefore, each region should be treated independently and the optimum approach will depend on the global-to-direct irradiance available at the proposed location(ISEC, 2001). In sunny locations where 90% of the irradiance comes from direct beam the 2-axis DST seems to be the most attractive solution to increase the capture energy. In cloudy conditions where diffuse irradiance is much significant, the tracking systems seems to be inefficient solution because the diffuse radiation are not aligned in a parallel shape such as the direct beams and because of the complexity of the cloud cover.

The DST tracking systems usually use a sun-pointing program to define the solar position so that the collector surface can face the solar disk and this make it track the sun regardless of the sky condition. Therefore, it has been thought that a new approach to a tracking system should be investigated to optimize the irradiance capture for cloudy regions. This approach has to consider the importance of capturing the diffuse radiation as well as the beam ones and consequently this can increase the global capture and improves the performance of the solar system. The system can combine different configurations such as the method that has been developed by GM to use a combination of DST and the horizontal configurations together(Kelly & Gibson, 2009). The optimized system has to utilize all the available radiation that can be harvested to generate more energy and to improve the performance of the system.

5 Experimental procedure

This section will examine the methods that are currently being used for improving energy capture of solar collectors that have been discussed in the previous section. It will investigate the performance of each approach in worst case scenario – in a cloudy region. The examination will also analysis each approach and it will observe how it effects the efficiency of the system. Based on that, it will present an improved approach which construct of a simple algorithm that used to control the positions of the collector during the day in order to optimize the performance of solar collectors.

That will be demonestrated by building a flexible simulation model in ESPR-r software. The model is shown in Figure 6, it contains different surfaces and each surface is set to different configuration. The analysis will be based on hourly step simulation, which will make the results accurate and practical for decision making. To validate the model's results, an excel tool has been developed by using mathematical equations based on Duffie & Beckman models. In addition to this PVWatts calculator that has been developed by the National Renewable Energy Institute, which is used to value the solar energy capture in different regions (NREL d, 2011). It has been found that the results that obtained by the model are slightly lower than the tool and the calculator results by an error of 8%.

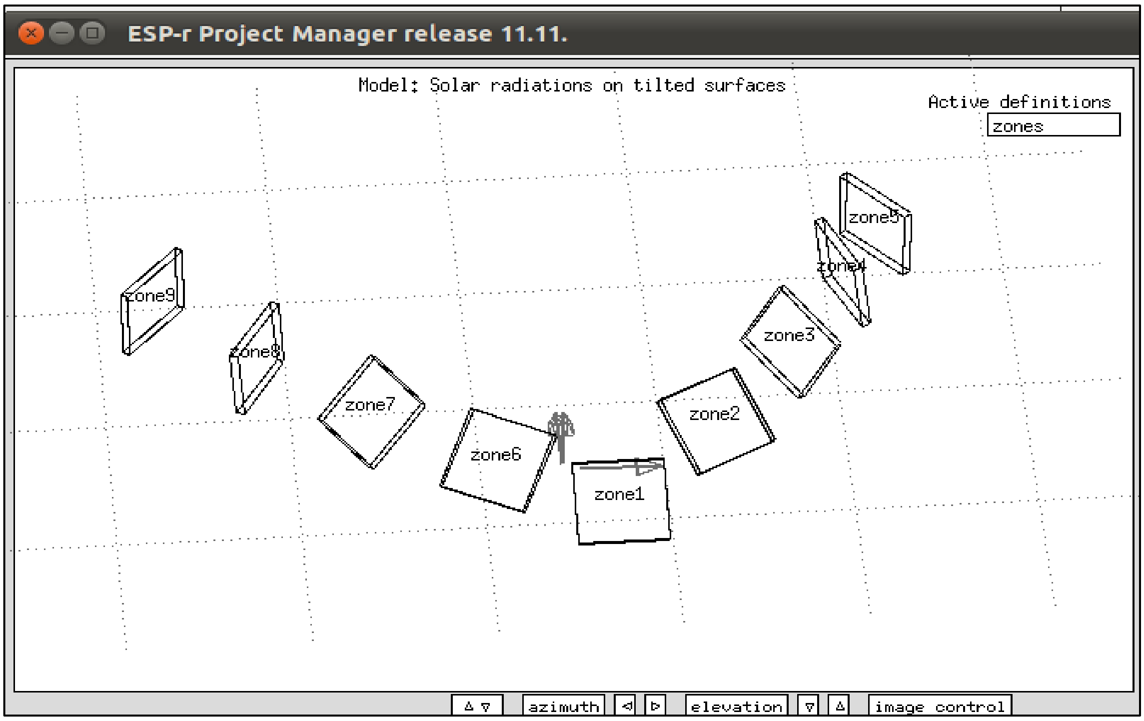

Figure 6: Model developed by ESP-r software.

5.1 Model description

The model analyses a flat plated surfaces each with an area of $1m^2$ as a solar collector. This to make the results applicable for different types of solar applications i.e. photovoltaic or solar thermal collector and especially that this study is going to focus on the solar energy capture only. Since the project is going to examine the performance of the solar collector in cloudy regions the location has been chosen in the north of Europe with latitude more than 45^0N and the selected site is Glasgow with latitude of 55^0N.

5.2 Resources assessment

The available radiation data for this location were obtained by using the software from the climate data file. The beam normal is the available direct irradiance at the location measured by tracking the sun after considering the sky conditions, while the diffuse horizontal is the available scattered measured irradiance at a horizontal surface. It has been assumed that the amount of global available radiation (G_{av}) at the site is the summation of the direct normal and the diffuse horizontal and based on this, the method of optimizing the solar collector will be achieved by capturing the maximum amount of this amount. Figure 7 and table 1, shows monthly available irradiance at the site during the year. It has been noticed that, the annual global irradiance at the location is $1145kWh/m^2$, in which 48% of the value was contributed from diffuse irradiance; the figure was $545kWh/m^2$ for diffuse horizontal irradiance and $600kWh/m^2$ for the beam normal. It has been noticed also that the monthly irradiance varied all over the year. For example, the beam normal peaked in May it reached around $100kWh/m^2$ and reduced to around $15kWh/m^2$ during December and January, and the diffuse horizontal reached its maximum in July by almost $90kWh/m^2$.

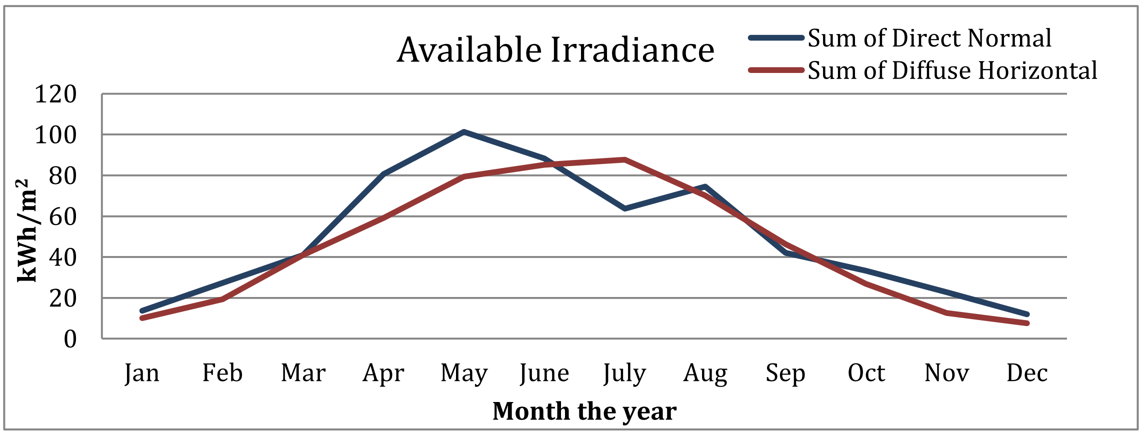

Figure 7: Monthly available direct normal and diffuse horizontal.

Table 1: Monthly available irradiance.

Month	Direct Normal Available kWh/m²	Diffuse Horizontal Available kWh/m²
Jan	13	10
Feb	27	19
Mar	40	41
Apr	80	59
May	101	79
June	88	85
July	63	87
Aug	74	70
Sep	42	46
Oct	33	26
Nov	22	12
Dec	11	7
Annual	**600**	**545**

Figure 8 shows the hourly irradiance in the 7th of May. It shows how the beam and diffuse irradiance varies dramatically during the day. For example, the maximum beam normal reached is 857Wh/m^2 at around 13:00 local time and the maximum diffuse reached is 200Wh/m^2 at 16:00. However, it is important to note that this figure show a day at summer time and the hourly beam and diffuse irradiance can change dramatically in different seasons.

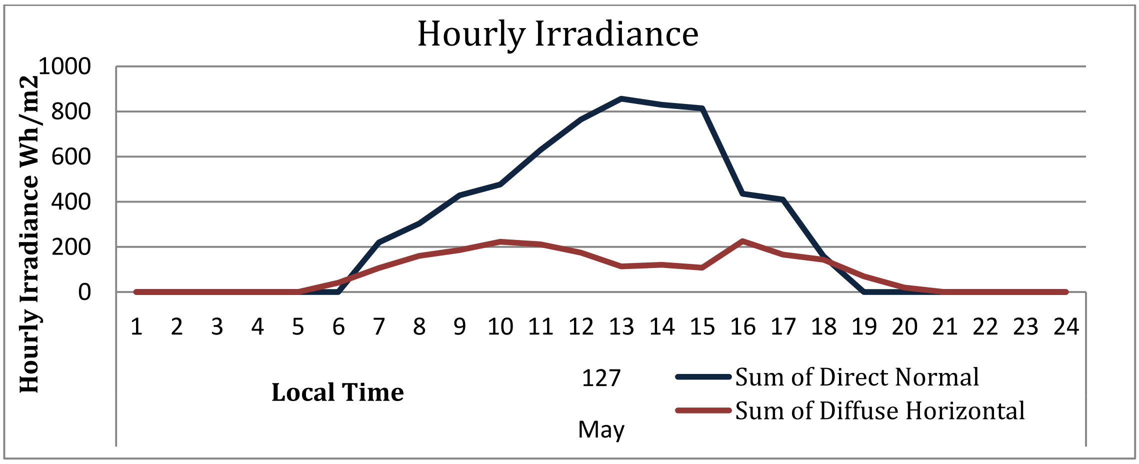

Figure 8: Hourly direct normal and diffuse horizontal at the 7th of May.

In regards to the change of the solar azimuth and altitude, Appendix B: figure14 summarize the change of sun positions during the year. The figure shows the change of the solar azimuth and altitude for any day in the year. It has been noticed that the solar altitude varies according to the season. For Example, it changes from 0^o during sunrise and sunset to around maximum 55^0 in summer at solar noon (zenith changes from 90^0 to minimum 35^0) and in winter it reach only 12^0 during solar noon.

5.3 Results

After assessing the solar radiation data at the location, different surfaces have been implemented in the model and each one has been designed according to certain approach, and then a simulation has been done. This section will presents the simulation results for each approach. It will include five surfaces of five different approaches that showed the most important effect on the system. The first four approaches will demonstrate surfaces with the configurations that have been discussed earlier in the previous section, and approach five will present a surface with the improved method for optimizing energy capture for the surface.

5.3.1 Approach one – Horizontal configuration (h)

The collector tilt angle for this configuration has been set at zero degree. The table below summarises the irradiance capture by the collector, the annual global irradiance capture is 858kWh/m^2. However, it is important to note that the diffuse component contributed by the most to the global irradiance and the collector captured all the available diffuse horizontal radiation when it is on the horizontal mode. The efficiency of the energy capture of the system can be calculated by ($\eta = G_h/G_{av}$), for the horizontal configuration the capture efficiency is 75%.

Table 2: Monthly direct, diffuse and global irradiance capture. For the horizontal collector.

Month	Direct Irradiance kWh/m²	Diffuse Irradiance kWh/m²	Global Irradiance kWh/m²
Jan	2	10	12
Feb	8	19	27
Mar	17	41	58
Apr	43	59	102
May	62	79	142
June	56	85	142
July	40	87	128
Aug	43	70	113
Sep	19	46	66
Oct	10	26	37
Nov	5	12	17
Dec	1	7	9
Annual	**313**	**545**	**858**

5.3.2 Approach two – Optimum Fixed Tilt (OFT)

Appendix B, figure 15, shows the percentage of the irradiance for different tilts and orientations. It shows how the irradiance is affected with each setting. It has been noticed that, the optimum surface position is south facing with an angle between the 30^0 and 40^0.

Based on the figure and the method that presented earlier in section 3.6, the optimum tilt angle has been calculated at the day that receives the maximum beam normal irradiance which is the 1st of June, the collector receives the maximum beam irradiance at 13:00 local time at that day and the solar azimuth angle at that time is at around 180^0 (south facing) and the solar altitude is around 55^0. Based on that, the collector orientation that should be selected is 180^0 and the collector tilt should equal to the zenith of the sun at that day which is equal to 35^0 (90-55) that is equivalent also to the results that showed in the figure. Table 3 summarises the irradiance capture for this configuration. The efficiency of the system reached to 84%.

Table 3: Monthly direct, diffuse and global irradiance capture. For the optimum fixed tilt angle collector.

Month	Direct Irradiance kWh/m²	Diffuse Irradiance kWh/m²	Global Irradiance kWh/m²
Jan	9	10	20
Feb	19	20	40
Mar	28	40	70
Apr	60	57	119
May	70	74	148
June	58	78	140
July	44	81	128
Aug	54	66	123
Sep	30	45	77
Oct	24	28	52
Nov	15	15	31
Dec	7	8	16
Annual	**425**	**528**	**969**

5.3.3 Approach three – Direct Solar Tracking (DST) 2-axis system

When the configuration of tracking the sun has been applied, according to section 3.7, the efficiency of the system reached to 76%. Table 4 summarise the monthly irradiance for this configuration. It has been noticed that the tracking system has captured all of the available beam normal irradiance but the diffuse collection were very small. The collection of beam radiation is only 272kWh/m^2 in the year, and this reduced the global irradiance capture to 872kWh/m^2.

Table 4 Monthly direct, diffuse and global irradiance capture, for the DST 2-axis tracking system

Month	Direct Irradiance kWh/m²	Diffuse Irradiance kWh/m²	Global Irradiance kWh/m²
Jan	13	5	18
Feb	27	8	36

Mar	40	21	62
Apr	80	29	109
May	101	38	140
June	88	43	131
July	63	44	108
Aug	74	35	109
Sep	42	23	66
Oct	33	12	46
Nov	22	6	29
Dec	11	2	14
Annual	**600**	**272**	**872**

5.3.4 Approach four – Monthly Tilt Modification (MTM)

The aim of this approach is to changing the system configuration occasionally by sitting the collector at different settings at each period of time. Section 2 has discussed some of the studies that suggested the method of adjusting the collector tilt monthly. After several attempts it has been observed that the best method is to set up the collector monthly at only two settings, the optimum fixed tilt and the tracking configurations. The period that has been chosen is four month. The months that receive the highest amount of beam irradiance are between May and August and they are assumed to be sunny months, the rest of months are assumed to be cloudy. On sunny months the collector is set at the DST configuration and at cloudy months at the OFT mode. The capture efficiency of this system is 79%. Table 5 summarise the irradiance at each month.

Table 5: Monthly direct, diffuse and global irradiance capture. For the MTM configurations.

Month	Setting	Direct Irradiance kWh/m^2	Diffuse Irradiance kWh/m^2	Global Irradiance kWh/m^2
Jan	**OFT**	9	10	20
Feb	**OFT**	19	20	39
Mar	**OFT**	28	40	69
Apr	**OFT**	60	57	117
May	**DST**	101	38	140
June	**DST**	88	43	131
July	**DST**	63	44	108
Aug	**DST**	74	35	109
Sep	**OFT**	30	45	76
Oct	**OFT**	24	28	52
Nov	**OFT**	15	15	30
Dec	**OFT**	7	8	16
Annual		**524**	**388**	**913**

5.3.5 Approach five – Controlled Solar Tracking (CST) 2-axis system

After analysing each of the previous approaches and after several attempts, the controlled solar tracking configurations have been applied to the system. The aim of this approach is to control the collector to be able to adjust to different settings according to hourly amount of beam and diffuse irradiance those are available at the collector's surface. For this mode, the collector adjusts itself to the following conditions according to the beam-to-diffuse ratio (I_{bn}/I_{dh}) and according to a predetermined value. The predetermined value that has been chosen is one.

1. If the ratio is equal to zero – go to the horizontal configuration.
2. If the ratio is smaller than 1 – go to the OFT configuration.
3. If the ratio is greater than 1– go to the DTS configuration.

Table 6 shows the effect of this method on the system. The global irradiance capture for this mode is 1090kWh/m^2 and the overall efficiency of the system has improved to almost 95%.

Table 6: Monthly direct, diffuse and global irradiance capture. For the CST configurations.

Month	Direct Irradiance kWh/m²	Diffuse Irradiance kWh/m²	Global Irradiance kWh/m²
Jan	13	10	23
Feb	26	19	45
Ma	40	40	80
Apr	78	57	135
May	101	68	169
Jun	88	73	161
Jul	63	80	143
Aug	73	67	140
Sep	40	45	85
Oct	33	26	59
Nov	21	11	32
Dec	11	7	18
Annual	**587**	**503**	**1,090**

6 Discussion

Since the location is Glasgow with the latitudes of 55^0N this makes it in the least favourable region for beam radiation capture and the maximum available global irradiance can receive at the location is 1145kWh/m^2 annually. The diffuse component contributes by almost half of the global irradiance. This is due to the high volume of clouds covering the location in most time of the year. And therefore, the chosen approaches have been modelled to investigate the best scenario for improving the performance of solar system on worst case scenario in regards to the energy capture and the following have to be discussed. Table 7 summarises the results of the five configurations.

Table 7: Summary of the irradiance capture for the different configurations.

Configuration	Direct Irradiance kWh/m²	Diffuse Irradiance kWh/m²	Global Irradiance kWh/m²
H	313	545	858
OFT	425	528	969
DST	600	272	872
MTM	524	388	913
CST	587	503	1,090

Firstly, when adjusting the collector to the horizontal configuration and after analysing the results, it has been found that the collector captured all the available diffuse radiation - the 545,316 kWh/m^2. From equation 3, the diffuse component is proportional to the $\cos\beta$, and as discussed earlier for the horizontal configuration this angle is equal to zero, which results in $I_d = I_{dh}$(equation 5). On the other hand, the collection of the beam irradiance was very small; it captured only 313kWh/m^2. From equation 2, this is because the beam component is proportional to the $\cos\theta_z$ and the zenith angle changes during the day from 90^0 to minimum 35^0 (see Appendix B, figure 14) from 90^0 during sunrise and sunset to minimum 35^0 at solar noon in summer time. This means that the collector is never perpendicular to the beam irradiance during the entire year. As a result the amount of global irradiance captured was around 858kWh/m^2 only and the capture efficiency for the horizontal configuration is only 75%.

Secondly, when adjusting the collector to the optimum fixed angle, it has been found that the performance of the system was good with global irradiance capture of around 969kWh/m^2 per year. The tilt angle is fixed at 35^0 and with 180^0 orientation that allow the collector to be perpendicular to the beam for almost two hours per day during the solar noon, therefore it can collects more beam irradiance than the horizontal model, the beam collection reached 425kWh/m^2 per year. On the other hand, this configuration reduced the diffuse collection. From equation 3, adjusting the tilt to 35^0 has led to decrease the diffuse component comparing with the horizontal configuration, so that $I_d = 0.9\, I_{dh}$. It has been noticed that reducing this optimum angle would increase the diffuse component but unlikely it will reduce the beam component at the same time and as a result this will shrink the global capture. The contribution of beam irradiance was high enough to left the capture energy efficiency to 84%.

When tracking the sun with the DST configuration, it has been noticed that the energy efficiency reached to 76% which is less than the efficiency of the OFT configuration. The DST mode allows the collector to be perpendicular to the beam irradiance all the year and therefore to collect all available normal beam radiation. According to equation 7, the beam component is equal to the beam normal for this configuration and it collect the maximum available direct normal irradiance the 600kWh/m^2. On the other hand, the diffuse contribution was relatively very small, this because the collector is following the zenith angle all the year. From equation 8, as the zenith angle increases from zero the diffuse component decreases. To calculate the tracking advantage following formula can be used $\mathrm{TA} = [(1 - \mathrm{OFT/DTS})/(\mathrm{OFT/DTS})]$ it compares the tracking advantage to the OFT mode. The tracking advantage is -23% which means that the DST approach is inefficient for optimizing irradiance capture in cloudy conditions and there will be a performance drawback of 23% than the performance of the OFT model.

The DST approach does not consider the effect of heavy clouds on the global component. Although it capture all the available normal beams but lose most of the diffuse potential. The figure below shows how the tilt angle for the DST mode changes in a single day, and it show that the angle is greater than zero and greater than the optimum tilt angle during most of the day. From equation 3, when the collector is at the vertical position, the diffuse component reduces to $0.5\, I_{dh}$. That result to reduce the global irradiance collection of the system.

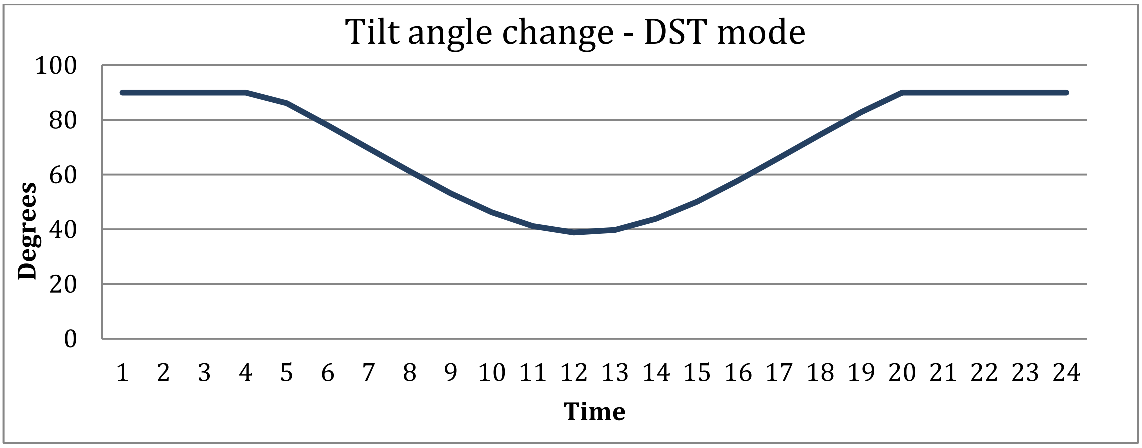

Figure 9: Change of the tilt angle, during the 7th of May.

It has been noticed also that there are days when there is significant potential of diffuse horizontal when there is no or small amount of beam normal and the collector losses these potential when it is on the DST mode. Figure 10 illustrates the small amount of beam direct available comparing to the diffuse horizontal at a specific day, it also highlights the ineffectiveness of the DST system of harvesting the diffuse radiation. All that reduced the performance of the system and as a result the performance of the DST mode showed a drawback. This makes the system effective in sunny conditions only where the beam component contribute by the most by around 90% of the global irradiance, in in countries located between the latitudes region of 15^0N and 35^0N.

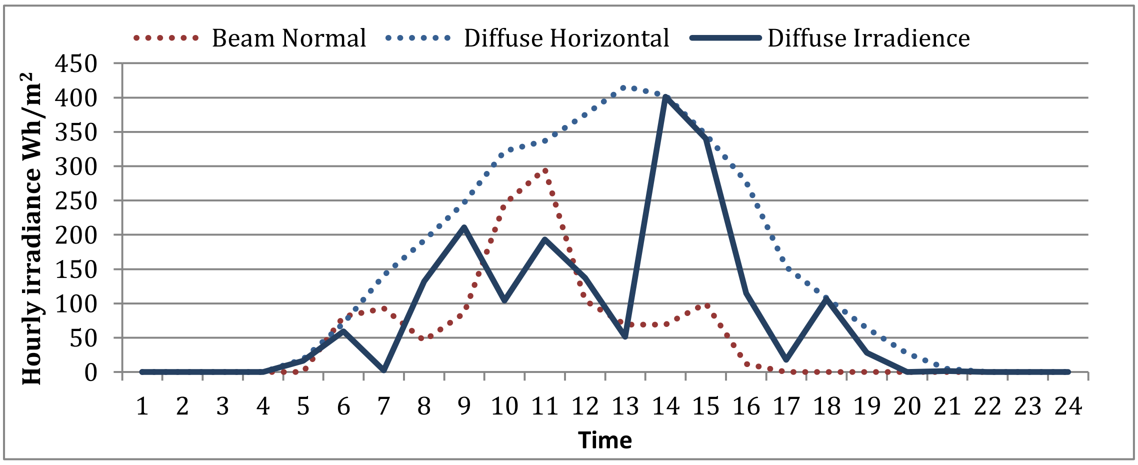

Figure 10: Ineffectiveness of the DST system. For the 7th of May.

Therefore, adjusting the tracking system to rotate the collector according to different approach is needed. The approach should get advantage from the potential diffuse irradiance that the DST system is incapable to harvest in cloudy conditions. A Method that has been investigated is the monthly tilt modification and it showed a better performance of the DST model. By adjusting the collector to track the beam normal irradiance on sunny months and to collect the maximum possible of the beam and diffuse irradiance on cloudy months, the capture efficiency for this system reached to 79%. The system has been adjusted to go on DST mode on the sunny months and to the OFT on cloudy ones. This has increased the annual global capture to 913kWh/m^2 from 872kWh/m^2 for the DST. The figure bellow shows how the system can improve slightly the global irradiance capture on cloudy months by adjusting the angle at the optimum configuration.

However, according to the study that has been carried out by GM company (Kelly & Gibson, 2009), it suggested to use the same approach but with different settings. Their concept is to use the same configuration on the sunny periods to track the sun and to adjust to the horizontal mode instead of the OFT mode on the cloudy periods. But it has been found that applying this would reduce the global capture instead of increasing it for this location. That is summarized in figure 11.

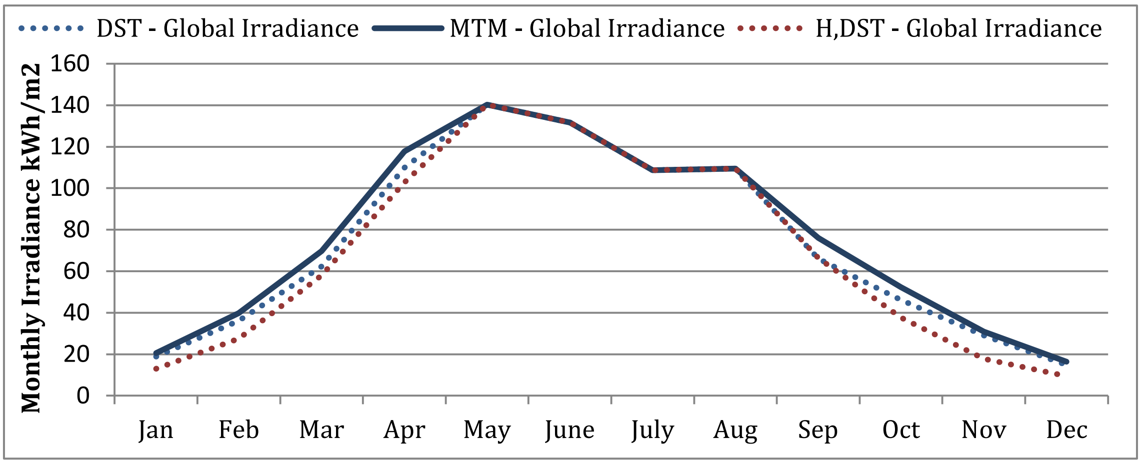

Figure 11: Performance comparison of MTM system with the DST system and the H,DST system (suggested by GM).

And finally, the last approach that has been investigated is the controlled tracking system. This approach has improved the capture efficiency of a 2-axis tracking system from 76% for the DST to 95%, and the tracking advantage of the systems reaches to 11%. The three control conditions allow the system to adjust itself according to the amount of irradiance available. The collector will still be perpendicular to the beam normal irradiance only when this amount is greater than the diffuse ($I_{bn}/I_{dh} > 1$), when the diffuse component overcome the beam component ($I_{bn}/I_{dh} < 1$) it will adjust itself to the OFT mode this will allow the collector to collect both types of irradiance, and when there is no beam normal on the surface ($I_{bn}/I_{dh} = 0$) it will adjust to the horizontal mode to get benefit from all the diffuse horizontal irradiance when occurred at the location. This enable the system to captures most of the valuable diffuse irradiance that the DST system is unable to harvest on cloudy sky. The figure bellow summarize that it shows a comparison between the two systems. Although the CST system did not harvest all the available beam radiation but comparing with the DST results it increased the diffuse component significantly from 272kWh/m^2 to 587kWh/m^2. Thus improved the capture of global irradiance it reached 1,090kWh/m^2 annually. This approach makes the solar tracking system more attractive than being ineffective in the cloudy countries.

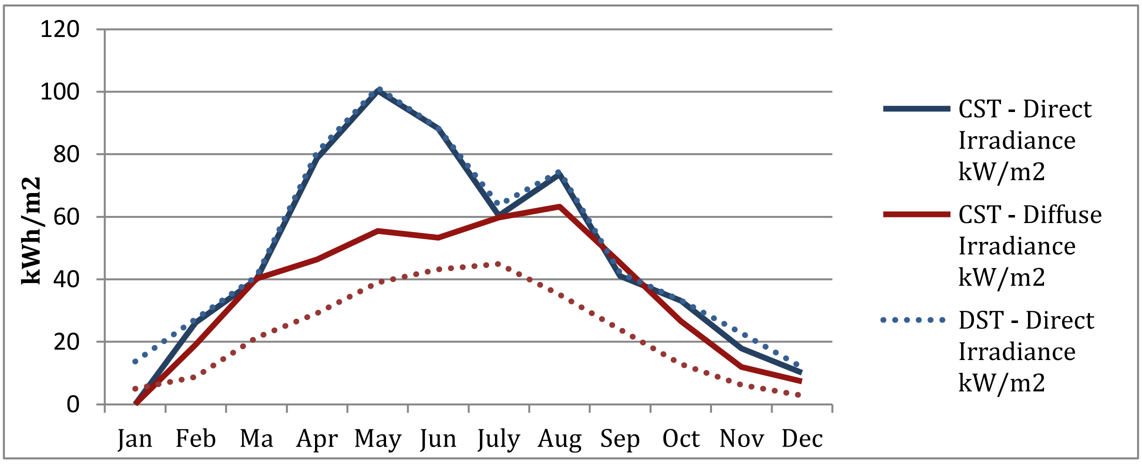

Figure 12: Performance comparison the CST with the DST systems.

In conclusion, it has been noticed that adjusting the tilt hourly can ultimately improve the performance of the system. The CST approach optimises the energy capture of the system. It can be very efficient way to collect the maximum possible of beam and diffuse irradiance together by a single collector. The capture efficiency for the system reaches the 95% with tracking advantage of 11%. Other models such as the DST and the horizontal configurations focus on optimizing only one component of the global irradiance. For example the horizontal mode maximise the diffuse component without considering the beam one and the DST model maximise the beam collection only. The DST model can be more practical for sunny conditions where the beam component contributes by 90% of the global irradiance and therefore focusing of the beam irradiance for that would be very attractive solution. The horizontal configuration cannot be used in either sunny or cloudy locations because it reduces dramatically the beam collection. However, this configuration can be very useful during intervals of a day when there is an only diffuse radiation. The monthly tilt modification approach also improved the performance of the solar collector system but was not enough to overcome the performance OFT model. The tracking advantage for the MTM configuration was only -5% which mean that there will be a drawback by the system performance by 5% when comparing with the OFT model.

6.1 Implementing the CST system

To set up the solar collector at the CST system some enhancements are required to add to the embodiment of the DST system. The simplest method is by using historical data of solar irradiance at the selected site and uses it to manage the tilt angle of the collector. It has to be hourly step data for around 20 years and after analysing this data a specific algorithm would be created into a computerized control system. For example, when the available beam radiation is greater than a predetermined value according to the algorithm used, the control system will give a signal to the collector to align with the step motor and to adjust to the DST settings by using a sun pointing programme, and when the beam radiation is less than the predetermined value the control system will adjust the collector to either the horizontal or the OFT settings. However, this method requires historical data and it can vary from year to another and therefore the efficiency of this method can be very limited.

The other method which it is the preferred one is by using solar radiation sensors to measure the global-to-direct irradiance (ISEC, 2001). This require two sensors the first can be pyroheliometer which measures the beam normal irradiance and the second solarimeter which measures the global irradiance. According to the ratio of the two measurements a predetermined value would be set to determine the mode of the collectors and when to align to the tracking motor. This method can be more accurate than using historical data since it measures the irradiances instinctually. The sensors can be mounted in different ways and this is beyond the study of this paper but is highly recommended for further research and studies. Both options require computerized control system with a defined algorithm, step motor to rotate the angles of the collector and sensors or sun pointing programme (Kelly & Gibson, 2010). Different embodiments can be applied for the CST approach and different technologies have been developed so far to measure the solar radiation. For example, the Single Detector Rotating Shadowband Radiometer SDR-1 can be used to replace the sensors, this measure the three types of radiation (pyrheliometer/pyranometer/shaded pyranometer) (Yankee Environmental Systems, Inc, 2003).

6.2 Financial analysis

The economic problem of solar systems design is to find the lowest and size for the same capacity. Although the financial scale of solar collectors is not the focus of this paper but it is important to highlight the effect of solar tracking system on the cost. This section is going to discuss briefly the cost of using a solar tracking system the photovoltaic (PV) application have been chosen.

It has been found that the use of controlled system in cloudy conditions would have tracking advantage than the fixed tilt system by 11% and it increase the energy output of the collector. But at the same time the installation of tracking system requires more equipment such as sensors, control system and step motor to rotate the collectors that can increase the initial cost of the investment and can make it ineffective in regards to the total cost of the system. Therefore, it is important to investigate also the cost of the system and to look at how it can effect investor's decisions.

To compare the cost of control solar tracking system with a system with the fixed tilt mode a case study has been made, in which two solar plants of the same size have been selected one with the CST configuration and another with the OFT mode. The size of each plant is 4kW which is corresponds to 35m^2 of PV (NREL a, 2011). The panel energy conversion efficiency has been assumed at 30% which includes the percentage of converting photons to DC and DC to AC (NREL c, 2012). Based on the new feed and tariffs rate of 21p/kWh for a 4kW capacity for a new built PV system (DECC a, 2011), the initial cost of the plant has been taken as £3,300/kW for <50kW plant capacity (DECC b, 2011) and the tracking system cost is £45 per m^2 of PV (Kelly, 1993). The controlled tracking system will have 11% tracking advantage, this effect the annual AC energy output to increase by 1365kWh which result to save £288 annually.

Table 8: Annual return & initial cost of OFT & CST systems. This is for 4kW plant size, 34m^2 of PV.

Annual energy capture	**Annual AC Energy**	**Annual return/Energy Value**	**Initial cost**
kWh	kWh	£/year	£/4kW
33,600	10,080	2,117	13,200
38,150	11,445	2,404	14,775

After a financial analysis and the comparison it has been noticed that although the use of control solar system will increase the initial cost of the plant, but it would payback its investment cost at slightly lower period than the OFT system, this is summarised in the table below. This can make the CST system attractive not for designers only but also for investors since the annual energy value of the plant would increase from £2,117 to £2,404 by using the system. It is expected that the cost of CST system would be more attractive for bigger scale plants but can be relatively costly for standalone PV applications. However, these figures are for a 4kW plant size only and they can vary according to different capacity. The results do not include the operating and maintenance cost assuming that it will be almost the same for both plants. Table 9 summarise the discount cash flow and the payback period for the two systems.

Table 9: Discount cash flow and payback period for the OFT and CST plants. Showing first 10 years only, with 4% discount rate.

System configuration		**OFT**	**CST**
Simple Payback	Years	6.2	6.1
Discount Cash Flow	Year 1	£2,035	£2,311
	Year 2	£1,957	£2,222
	Year 3	£1,882	£2,137
	Year 4	£1,809	£2,054
	Year 5	£1,740	£1,975
	Year 6	£1,673	£1,899
	Year 7	£1,607	£1,826
	Year 8	£1,546	£1,756
	Year 9	£1,487	£1,689
	Year 10	£1,430	£1,624
Discount Payback	Years	24.4	24.3

6.3 Energy analysis

Comparing the performance of complex energy systems can be difficult due to the confusion of using different terms of energy, especially when dealing with energy conversion applications, with limited resources and different losses. The second law of thermodynamics provided a very powerful term Exergy[11] (Cengel, 2006) which is very useful for the optimization of energy systems to compare between different systems.

The maximum useful energy available at the plant is 12,022kWh which can be impossible for any system to obtain this amount of energy due to the fact that a single collector has to adjust to different positions and tilts during the year, but achieving the nearest amount of energy to the figure is the objective of this project. According to the results, it has been showed that the annual exergy of the CST system reached to 11,445kWh which make it the optimum configuration, and using any of the other examined approaches would decrease the figure. For Example, the use of the OFT system will give annual exergy of 10,080kWh and this can mean that the plant would loss an amount of 1,365kWh annually as exergy destroyed.

[11] Exergy is the maximum useful work that could be obtained from the system at a given state in a specified environment (Cengel, 2006).

Table 10: Exergy comparison of the OFT and CST systems.

	Single PV	4kW plant
	Global available Irradiance kWh/m²/year	**AC Energy kWh/year**
	1,145	12,022
	Global captured Irradiance kWh/m²/year	**Exergy kWh/year**
OFT	969	10,080
CST	1,090	11,445

7 Conclusion

Solar energy is a valuable renewable source that can be utilized to provide electrical and thermal power. It offers the greatest energy potential compared with other currently known renewable resources. Harnessing the use of solar energy requires more research and development to improve the efficiency of solar applications. The solar energy received by any surface on earth as component of beam and diffuse radiation and the total amount of daily insulation varies according to location, season and time. Understanding of these factors is important for the design of any solar application because it can affect its performance. Optimizing the mounting of the solar systems can ultimately improve the energy capture and ultimately increase the performance of the system.

According to the study, 2-axis solar tracking devices are designed to improve the performance of solar collectors by following the sun positions. The traditional tracking systems track the normal beams directly and it increases the performance of solar collectors by around 50% in summer and around 30% in winter for a clear sky condition. It has been established that these figures can vary widely in a cloudy conditions and the efficiency decreases as the volume of the clouds in the sky increases. It is clear that the tracking devices are useful for sunny countries where they receive a significant amount of direct radiation; however the system is less efficient in cloudy conditions or in countries that are assumed to be cloudy throughout the year. The study has showed how the beam-to diffuse radiation can dramatically vary from 0.9 to a minimum of 0.1 in different locations and sky conditions; it draws attention to the importance of diffuse radiation in cloudy regions. This paper investigated different mounting methods that can improve the performance of solar collectors by using a 2-axis solar tracking system in cloudy regions.

The project specifically included a model which investigated different approaches for mounting the collector in a chosen location in Glasgow. It has been found that, when the collector is on the optimum fixed tilt angle configuration the capture efficiency is at 84%. When the collector is aligned to a direct tracking device the energy capture of the system reduced to 23% which means that the direct tracking system is inefficient in cloudy regions. The paper suggested an approach to use a controlled tracking system, which aimed to manage the collector to adjust to different settings during the day according to different conditions. This can be achieved by using a simple algorithm that controls the collector according to the beam-to-diffuse ratio. When the beam component is higher than the diffuse the collector will track the solar beams, when the beam component is less than the diffuse it will adjust to the optimum fixed tilt angle and when there is no beam radiation the collector will take the horizontal position. The approach increased the energy capture by 11% and the efficiency of the system reach to 95%, making it the optimum solution for improving the energy capture for the chosen case. The study suggested recommends embodiment of the controlled tracking system by using sensors to measure the beam and diffuse radiation, sun-pointing programme, control system and step motor to rotate the collector.

In regards to the financial scale of the system, an analysis has been done to compare the cost of two solar plants, one uses moving collectors aligned to tracking device and another with a fixed collectors mounted according to the optimum tilt settings. It has been concluded that the controlled tracking system saves £288 annually, and although its initial cost is higher than a fixed collector, the system pays its investment in slightly shorter period.

Finally the paper introduced the term exergy to compare the useful power of the suggested system with the optimum fixed tilt approach. According to the case study, the use of the system will give an annual exergy of 11,445kWh, whilst implementing any other approach will lead to energy loss. It used an example to show that there will be an amount of 1,365kWh of exergy destroyed annually when using the optimum fixed tilt approach.

In conclusion tracking devices can be useful to increase the harvesting of solar energy not only in clear sky conditions but also in cloudy ones. Assessing the solar radiation during early design stages is important, since it helps choosing of the optimum configuration for the solar system. The diffuse component in cloudy regions is very important to consider during design of the system. Finally, the study concludes the improvement of solar collectors in cloudy regions can be achieved by using a controlled tracking system, which is designed in such a way as to consider both beam and diffuse components.

8 Further research

The objective of this paper is to focus solely on improving the performance of flat solar collectors in regards of energy capture. It should be noted that there are other inter-related subjects not covered in detail in this paper but where further research would be relevant. These are:

8.1 Embodiments of controlled solar tracking system

Using the concept of the CST system require different embodiments than a normal tracking system. The paper suggested two types of flat plate collectors with controlled tracking system by using either historical data or by using instantaneous measuring devices such as sensors to measure the available direct and diffuse radiation. The embodiments of such systems require more investigation to address the best eco-efficient approach. However, this kind of research can be classified under the measurements of solar radiation area, which is a very wide subject and it is not the scope of this study.

8.2 Algorithm improvement

The model included a very simple algorithm that manage when the collector has to follow the sun, when to adjust to the OFT position and to the horizontal position. The predetermined value has been taken as one as it is found to be the best value for a collector in Glasgow, and this value can vary according to different locations and different sky condition at the location. Therefore, an improved algorithm can be further investigated to manage the tracking system to make it valuable for all conditions and locations.

8.3 Balance of plant for solar farms with solar tracking system

The major problem effecting the development of solar energy is the initial cost of the system and especially for PV. Although finding ways to optimize the energy capture of solar systems are seriously needed but this should be achieved in a way not to increase the cost and the size of the system. CST 2-axis tracking systems require more equipment and configurations than the fixed tilt systems that will increase the initial and the operating cost of the system and therefore research is needed to investigate the cost of different equipment's, to compare the effect of CST system for different plants size. Thus can be done by implementing a balance of plant analysis for solar plants, this subjected method would give more figures and numbers in regards to the finical factor of installing a solar tracking system in cloudy conditions.

9 Bibliography

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Appendix A

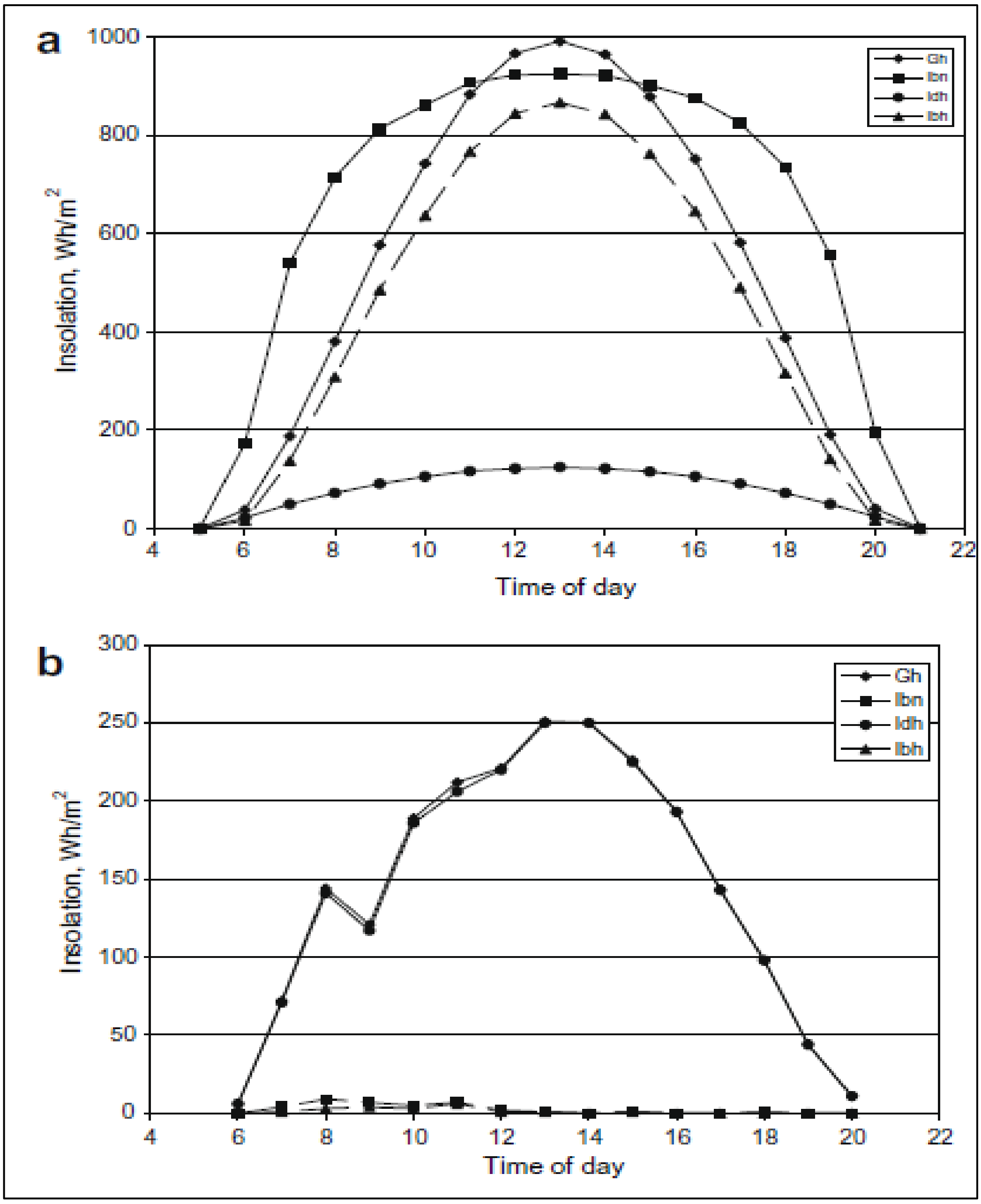

Figure 13 Global horizontal (Gh), diffuse horizontal (Idh), beam normal (Ibn), and beam horizontal (Ibh) insolation (hourly integrated irradiance) for a – sunny days (June 2, 1986). b – cloudy days (May 12, 1980). The data are taken from hourly NSRDB in Detroit USA (NREL b, 2011).

Appendix B

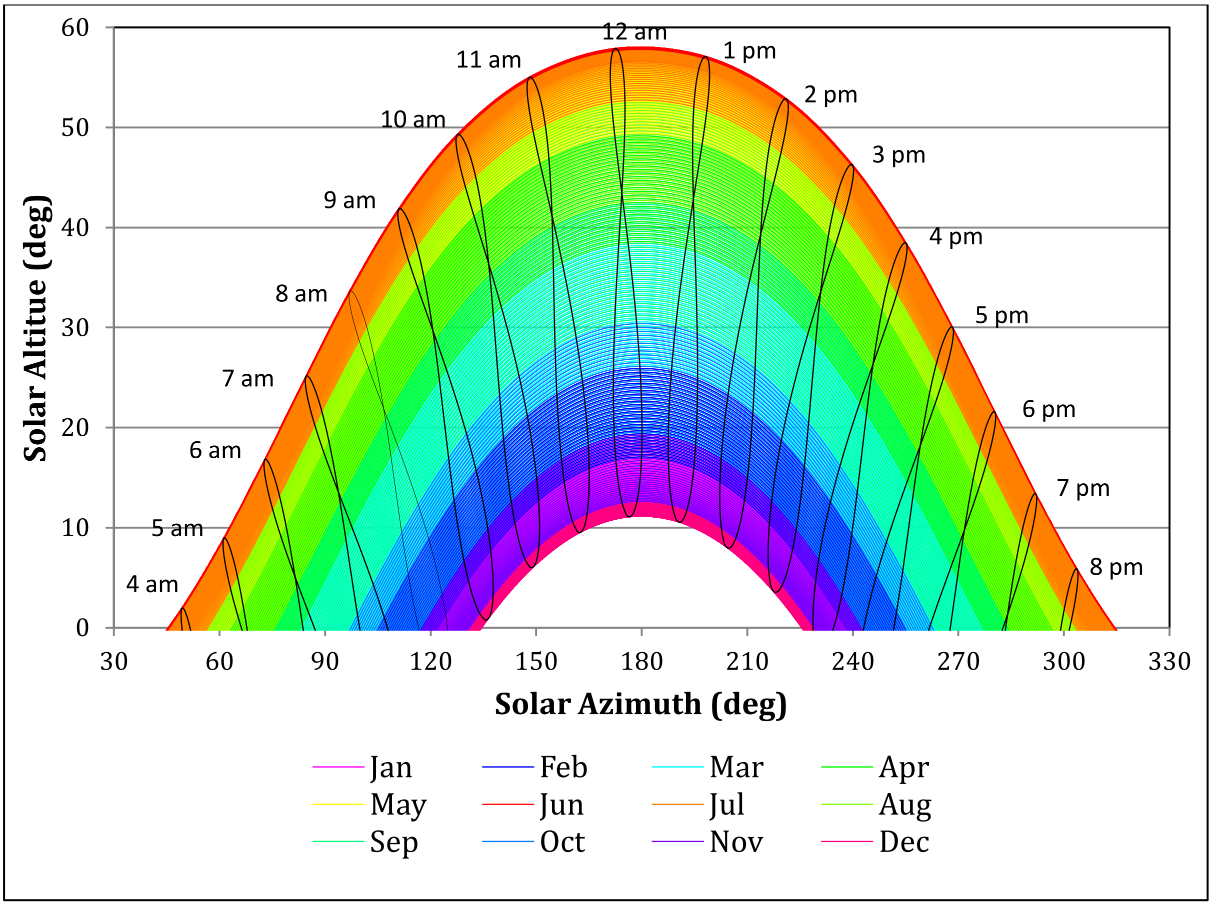

Figure 14: Sun positions for Glasgow 55^0 N

Surface Orientation (deg)

Surface tilt (deg)	West	255°	240°	SW	210°	195°	South	165°	150°	SE	120°	105°	East
Horiz.	90	90	90	90	90	90	90	90	90	90	90	90	90
10°	89	91	92	94	95	95	96	95	95	94	93	91	90
20°	87	90	93	96	97	98	98	98	97	96	94	91	88
30°	86	89	93	96	98	99	100	100	98	96	94	90	86
40°	82	86	90	95	97	99	100	99	98	96	92	88	84
50°	78	84	88	92	95	96	97	97	96	93	89	85	80
60°	74	79	84	87	90	91	93	93	92	89	86	81	76
70°	69	74	78	82	85	86	87	87	86	84	80	76	70
80°	63	68	72	75	77	79	80	80	79	77	74	69	65
Vert.	56	60	64	67	69	71	71	71	71	69	65	62	58

Figure 15: Solar irradiance percentage according to different tilts and orientations.

Appendix C

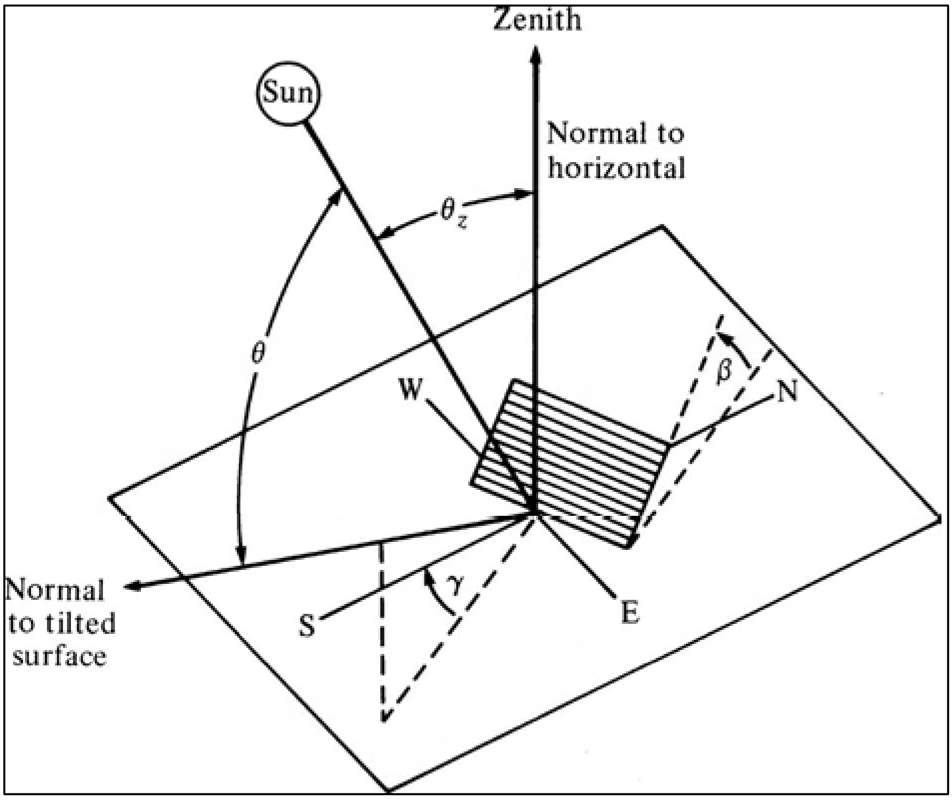

Figure 16 Geometry of a collector

Zenith Angle Θ_z, is the angle between the solar disk and the normal to the horizontal surface ($\Theta = 90 - \alpha$).

Solar altitude α, is the angle between the beam from the sun to the horizontal, it is the complement of the zenith angle.

Solar azimuth Υ_s, is the angle displacement from the projection of the beam radiation on the horizontal plan, for this study this angle is measured from the north.

Angle of incident ϴ, it's the angle between the normal to the tilted surface and the direct beams. Note: for horizontal configuration $\Theta_z = \Theta$

Tilt angle β, is the angle of the slop of the collector in this study it measure from the horizontal, however some references reference it from the vertical.

Surface Azimuth (orientation) ϒ: the deviation of the projection on a horizontal plane of the normal to the surface from the location meridian, measured from north.

Appendix D

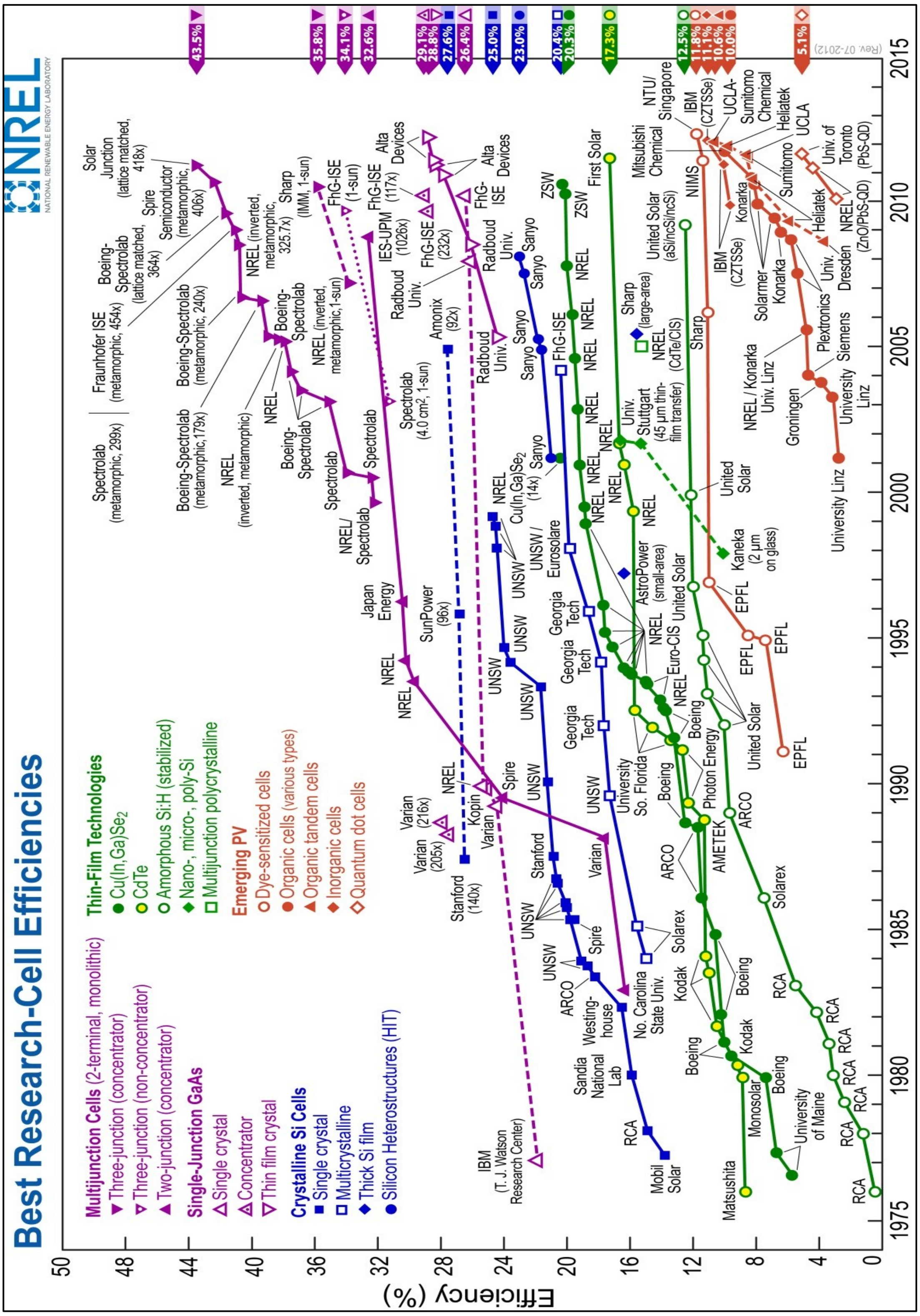

Figure 17: Cell Efficiency

Appendix E

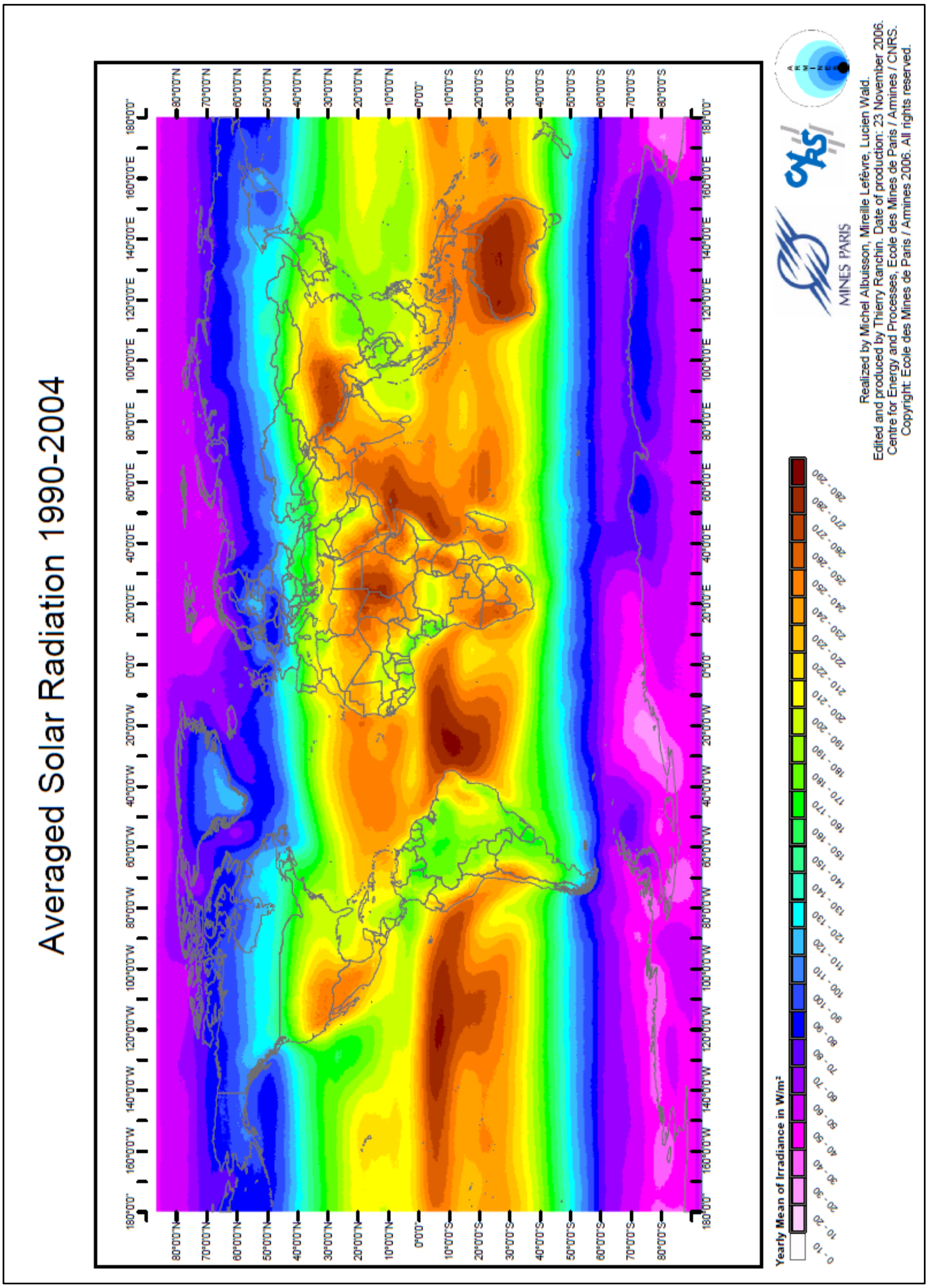

Figure 18: Averaged global solar radiation map. (Centre for Energy and Processes, Ecole des Mines de Paris, 2006)