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MASTER’S THESIS

PERFORMANCE AND COST ANALYSIS OF SOLAR PHOTOVOLTAICS TRACKING SYSTEMS OPERATING IN DIFFERENT WEATHER CONDITIONS

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Abstract

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Nowadays, installation of solar photovoltaic systems is growing due to awareness in renewable energy and decreasing the cost of solar panels and batteries. Solar tracking system capture 5 to 50 percent more solar radiation compare to fixed tilted system.

The main objective of this thesis is to evaluate the performance of various tracking system compared with fixed tilted system for in Finnish weather conditions. This target was achieved by simulating and analysing with the help of PVSOL pro and Homer simulation software in different orientations of PV systems: Fixed optimally tilted, horizontal axis east-west, horizontal axis north-south, horizontal axis north-south optimally tilted, vertical axis optimally tilted and dual axis system. Three countries having different latitude angle and weather conditions: Lappeenranta (Finland), Kathmandu (Nepal) and Kisumu (Kenya) have been studied. The results show that dual axis system has the best performance. In case of single

axis tracking system, vertical axis optimally tilted and horizontal axis north south optimally tilted system have the best performance for Lappeenranta (Finland) having high latitude angle. In case of Kisumu (Kenya), located in equator need not to be tilted for horizontal axis system.

In case of clear sky condition, it is good to track the solar radiation. Nevertheless, during cloudy condition. Tracking system should be also good, because it tries to find the best position. The ground reflected radiation increase according to tilted angle. During three-spring months in northern countries like Finland reflection from snow increase the irradiation from 4 to 8 percentage.

The installation cost of each solar tracking system is higher than fixed system. Furthermore, operating and maintenance cost would be higher due to moving parts like bearing and motors. The cost of each tracking system is analyzed with 1.2€/Wp for a fixed 15 degree tilted system. Levelised cost of electricity was analyzed for 20, 25 and 30 years lifetime with interest rates upto 10-percent. Additional cost of each tracking system was calculated in order to maintain same levelised cost of electricity as fixed 15 degree tilted system. If the additional costs of tracking systems are higher than the calculated value, the system is considered as too expensive for that location.

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Lappeenranta, October 18, 2016

Arun Bhattarai

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Acronyms

PV	Photovoltaic
kW	Kilowatt
kWh	Kilowatt hour
GI	Global irradiance
GHI	Global horizontal irradiance
DHI	Diffuse horizontal irradiance
STC	Standard test condition
DC	Direct current
AC	Alternating current
FIT	Feed in tariff

Abbreviations

I_{bn}	Direct-normal solar irradiance, W/m^2
I_h	Global horizontal solar irradiance, W/m^2
$I_{h,b}$	Direct-normal component of solar irradiance on horizontal component, W/m^2
$I_{h,d}$	Global diffuse horizontal solar irradiation , W/m^2
I_{on}	Direct extraterrestrial normal irradiance, W/m^2
I_T	Solar irradiance on the tilted surface, W/m^2
$I_{T,d}$	Diffuse component of solar irradiance on the tilted surface, W/m^2
$I_{T,d,iso}$	Isotropic diffuse component of solar irradiance on the tilted surface, W/m^2
$I_{T,d,cs}$	Circumsolar diffuse components of solar irradiance on the tilted surface, W/m^2

$I_{T,d.h,d}$	Horizontal brightening diffuse components of solar irradiance on the tilted surface, W/m^2
$I_{T,d.g}$	Reflected ground diffuse component of solar irradiance on the tilted surface, W/m^2

Symbols

n	Day number
$\O$	Latitude angle (°)
δ	Declination angle (°)
Θ	Incidence angle (°)
ω	Hour angle (°)
β	Tilted angle (°)
ρ_g	Ground reflection coefficient (°)
α_s	Solar altitude angle (°)
γ_s	Solar azimuth angle (°)
θ_z	Zenith angle (°)
γ	Surface azimuth angle (°)

1 Introduction

In recent year renewable energys such as solar and wind are more popular and engages significant share. Due to the increase in price of fossil fuel and greenhouse gas emission, renewable energy is selected as best alternative energy. The main aim of Paris agreement on climate change 2015 is to hold increase in the global average temperature to well below 2°C above pre industrial levels and to pursue efforts to limit the temperature increase to 1.5 °C above pre-industrial levels. In order to achieve this goal, each country is promoting green energy by providing various incentives for various renewable energy. Both large-scale solar farm and small individual rooftop are popular recent years. Nevertheless, renewable energy sources are unpredictable, thus it is difficult to balance production and consumption of energy. Therefore, cost effective energy storage technology is needed in order to balance demand and supply. In the beginning, there is no need for energy storages, but in single cases, these will increase the own energy use.

Solar photovoltaics system market is growing due to awareness in clean energy and reduction in price of solar panels. Photovoltaic solar tracking systems harvest more energy as compare to fixed systems. Thus, various companies are interested on in solar tracking systems. Nevertheless, solar tracking systems increase the capital cost, operation and maintenance cost due to complication of the projects due to moving parts including bears and motors. Performance of solar tracking systems depends upon the methods of the tracking system, which corresponds to different geographical regions. Furthermore, performance of photovoltaic solar tracking systems equally depends upon the local weather conditions, which include clear days, partly cloudy days, rainy days, ambient temperature, humidity and snow.

1.1 Solar PV potential in Finland

Every part of the world has certain potential of solar energy. Solar irradiation depends upon the site location. Irradiation is best near equator and decrease within-crease in latitude angle. Since, Finland is located in far north near Arctic Circle irradiation is still not bad. Annual solar irradiation for the country about 900 kWh/m^2 and 1200 kWh/m^2 for fixed horizontal and optimally mounted surface as shown in Fig.1. Annual energy yield for Helsinki would be about 1100 kWh/kWp [2].

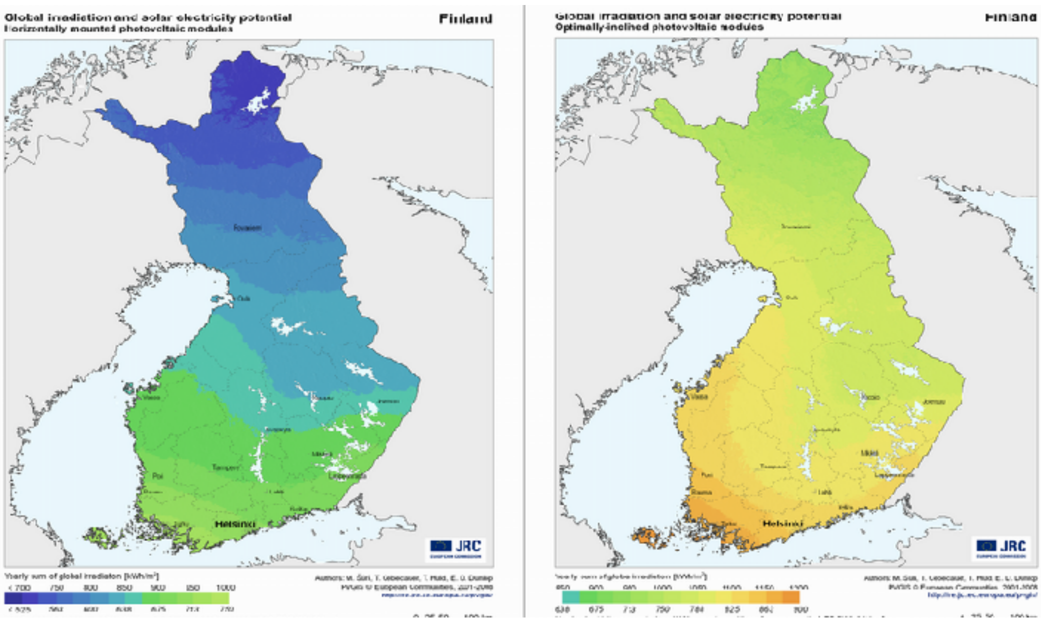

Fig. 1: Global irradiation with horizontal mounted system (in left) and optimally tilted system (in right) in Finland [1]

1.2 Objectives

The main objectives of this research is to analyse the performance of solar power for northern European countries by various solar tracking systems. For this analysis solar power production, various part of the world in different weather condition can be compared. Furthermore, the key objective of this research is to analyse cost effective solar tracking system for Finnish weather conditions.

1.3 Outline of the project

The research project is carried on in Lappeenranta University of Technology. Simulation software such as PVSOL Pro and HOMER is used to analyse performance of various tracking systems for different locations.

The project is carried in academic 2016. Solar panel is moved with tilted angles 0-90 degree for panel facing east and west. Tilted angle zero degree represents horizontal to the ground. Panel is moved manually for different weather conditions such as clear, partly cloudy and overcast days. Furthermore, daily power production of this manual tracking panel is compared with various other systems such as dual axis, flat rooftop tilted with 15 degrees, south wall and west wall. Economic analysis for various tracking systems was done on the basic of 1.2€/Wp for Fixed tilted with 15-degree system.

2 Solar radiations

Radiation is emitted from the sun over the whole spectrum, which include gamma to radio wave. In case of photovoltaic solar systems, solar radiation can be classified into short wave radiation and long wave radiation. Wavelength range for shortwave would be 0.3 to 3µm [2]. These wavelengths originate directly from the sun, which includes both direct and diffuse radiation. Wavelength for long- wave would be larger than 3µm [2]. These wavelengths can be created by atmosphere and other sources at temperature near ordinary ambient temperature [2].

Solar radiation is distributed in atmosphere with air molecules, humidity and dust. The atmosphere can absorb some part of solar radiation. Solar radiation that travels directly from the sun to the earth is direct solar radiation and other scattered part of radiation in atmosphere signifies diffuse radiations. Global solar irradiance represents direct and diffuse irradiance incidents on a horizontal surface. The total annual solar irradiation depends upon the geographical locations and various weather conditions. Incident solar energy for horizontal surface in different locations is shown in table1. Annual incident energy increase with decrease in latitude angle.

Table 1: Incident solar energy in horizontal surface for different locations [2].

Location	**Latitude**	**Annual incident energy [kWh/m^2]**
Helsinki, Finland	60 °N	950
Lerwick, United Kingdom	60 °N	775
Freiburg, Germany	48 °N	1100
Trapani, Italy	38 °N	1800
Israel	38 °N	2000
Sahara	25 °N	2500

3 Solar radiation models

Total solar irradiance on tilted surface is the combination of beam component from direct irradiation and diffuse component. Therefore, total irradiance on tilted surface can be described as follows [3].

$$I_{\mathrm{T}} = I_{\mathrm{T,b}} + I_{\mathrm{T,d,iso}} \qquad (3.1)$$

I_{T} represents total solar irradiance on tilted surface, diffuse component composed of an isotropic diffuse component $I_{T,\mathrm{b}}$ (uniform irradiance from sky dome), circumsolar diffuse component $I_{\mathrm{T,d},iso}$ (causing from forward scattering of solar radiation and concentrated in an area close to the sun), horizon brightening component $I_{\mathrm{T,d,cs}}$ (focused mainly at horizon in clear skies) and reflected component from ground $I_{\mathrm{T,d,g}}$. Therefore, total irradiance on tilted surface referred to (3.2) as follows:

$$I_{\mathrm{T}} = I_{\mathrm{T,b}} + I_{\mathrm{T,d,iso}} + I_{\mathrm{T,d,cs}} + I_{\mathrm{T,d,hb}} + I_{\mathrm{T,d,g}} \qquad (3.2)$$

Azimuth and altitude angle any location can be determined by applying geometrical relationships. Thus, incidence angle of beam radiation on tilted surface can be calculated.

3.1 Isotropic sky model

Isotropic sky model is the simplest model used all diffused radiation which are uniformly distributed in the sky dome and reflection on ground is diffused. When tilted angle is β from horizontal plane, total solar irradiance can be described by (3.3). However, horizontal brightening and circumsolar parts are assumed to be zero in isotropic sky model [3].

$$I_T = I_{\mathrm{h,b}} R_b + \frac{I_{\mathrm{h,d}}(1+\cos\beta)}{2} + \frac{I_{\mathrm{h}\rho}(1-\cos\beta)}{2} \tag{3.3}$$

3.2 Anisotropy sky model

Hay and Davis introduced a model for the calculation of direct and diffuse irradiation and published by Hay and McKay [3]. These model included circumsolar diffuse and horizontal brightening diffuse components of diffuse irradiation on tilted angle [3]. After the suggestion of Klucheer, Reindl upgraded the horizontal brightening part [3]. This upgraded standard model for defining direct and diffuse part of solar irradiance on tilted surface is known as Hay-Davis-Klucher-Reindl (HDKR) model. The main advantages of HDKR model is good output result with limited input data such as monthly data for global horizontal irradiation, diffuse horizontal irradiation, geographic coordinates and system geometry [3]. (3.4) to (3.5) and Fig.2 explained about Hay-Davis –Klucher-Reindl (HDKR) model [3].

$$\begin{aligned} I_T = {} & (I_{\mathrm{b}} + I_{\mathrm{d}}.A_{\mathrm{f}}).R_{\mathrm{b}} + I.\rho_{\mathrm{g}}.\frac{1-\cos\beta}{2} \\ & + I_{\mathrm{d}}.(1-A_i).\left(\frac{1+\cos\beta}{2}\right).\left[1+f.\sin^3\left(\frac{\beta}{2}\right)\right] \end{aligned} \tag{3.4}$$

$$A_{\mathrm{i}} = \frac{I_b}{I_0} \qquad f = \sqrt{\frac{I_{\mathrm{b}}}{I}} \tag{3.5}$$

$$I_0 = \frac{12.3600}{\pi} . G_{\mathrm{sc}} . \left(1 + 0.033 \cos 360 . \frac{n}{365}\right) . \tag{3.6}$$

$$\left(\cos\emptyset \cos\delta . (\sin\omega_2 - \sin\omega_1) + \frac{\pi(\omega_{2-}\omega_1)}{180} . \sin\emptyset \sin\delta\right)$$

In (3.4) to (3.6) total radiation on a tilted surface according to Hay-Davis-Klucher-Reindl (HDKR) model. Abbreviations stand for: irradiance tilted surface (I_{T}), irradiance beam horizontal (I_{b}), irradiance diffuse horizontal (I_{d}), anisotropy index (A_{i}), geometric factor (function of time, position of sun and surface) (R_{b}), irradiance global horizontal (I), reflection of ground (ρ_{g}), tilt angle (β), modulating factor (f) and extraterrestrial irradiance (I_0), solar constant (G_{sc}= 1367 W/m^2), day of the year (n), latitude (φ), declination of earth axis (δ) and hour angle of specific time 1 and 2 ($\omega 1,2$) [3].

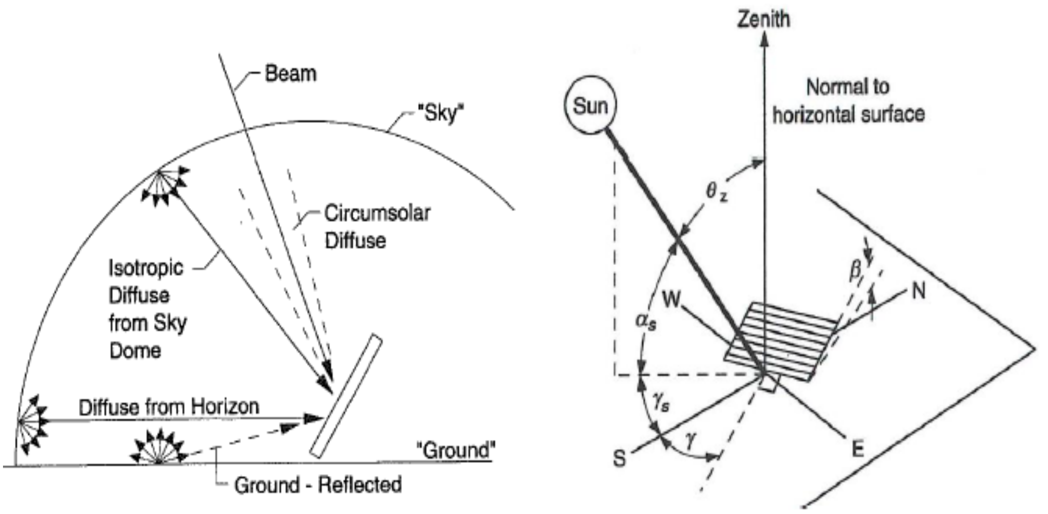

Fig. 2: Irradiation components of fixed tilted surface (Left) and geometric composition of coordinate systems of earth, sun and PV module (right). Abbreviations stand for: zenith angle (θ_z), solar altitude angle (α_{s}) solar azimuth angle (γ_{s}), surface azimuth angle (γ), tilt angle (β), north (N), east (E), south (S) and west (W) [3].

4 Photovoltaic Tracking Systems

Photovoltaic solar tracking system allow modules perpendicular to solar irradiation. This helps to increase the performance of solar power productions. According to orientation of modules, axis of movement and number of moving parts, there are various solar PV tracking systems.

4.1 Fixed optimally tilted system

The most common PV system refers to fixed tilted with optimal angle and used as the reference to compare with other tracking systems. The PV power plant cost components depends upon the area of the solar farm. Total area of the solar farm corresponds to tilted angle. Shading in the row increases with the increase in tilted angle. In order to minimise the shading effect solar farm occupies larger area [4]. Since, annual sunshine perpendicular to the ground relatively very low, thus, panels should be optimally tilted in order to cleaning affect by the rain to maximize annual energy production. Various literature suggest that optimal angle should be equal to latitude of specific site of solar farm [4]. Nevertheless, for the location higher than 60-degree latitude, optimal tilted angle would reduce upto 15 degree [4].

According to the simulation results, optimal tilted angle for Lappeenranta, Finland which is situated in Latitude: 61°03′31″ N and Longitude: 28°11′19″ E is 45 degrees as shown in Fig.26. Optimally tilted angle increases the annual irradiance with 217.5 kWh/m^2 that is 22 percentages as compare to fixed plane surface [4]. (4.1) to (4.3) describe for fixed optimally tilted system [4].

$$\cos\theta = \cos\theta_Z . \cos\beta + \sin\theta_Z . \sin_\beta . \cos(\gamma_s - \gamma) \tag{4.1}$$

$$\beta = const \tag{4.2}$$

$$\gamma = \{+90° \; if \; \gamma_s > 0, \quad -90° \; if \; \gamma_s \leq 0 \tag{4.3}$$

In (4.1) to (4.3) precise geometric attentions for fixed optimally tilted PV systems. Abbreviations stand for: angle of incidence (beam and surface normal) (ϑ), zenith angle (ϑ_z), tilt angle (β), solar azimuth angle (γ_s) and surface azimuth angle (γ) [4].

4.2 Horizontal axis east-west system

Horizontal axis east-west continuous system has the axis in east-west direction. Since, this system optimises the panel orientation to zenith angle. This allows to track north-south direction for seasonal positions of the sun as shown in Fig.3. According to simulations results show that about 100 to 200 kWh/m^2 that is 6 to 9 percentage additional irradiance can be achieved from horizontal axis east-west system in Lappeenranta, Finland. Small increase in irradiance may not compensate the additional costs of tracking system as compare to fixed optimally tilted system [4].

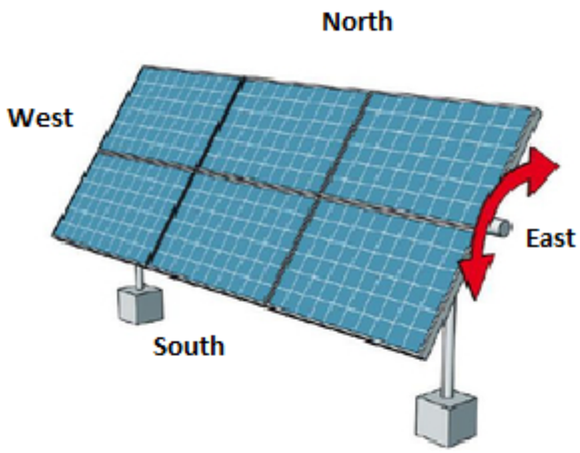

Fig. 3: Horizontal axis east-west tracking system [5].

The general geometric consideration of (3.4) to (3.6) is explained by (4.4) to (4.6) for Horizontal axis east-west tracking system [4].

$$\cos\theta = \sqrt{1-\cos^2\delta.\sin^2\omega} \quad (4.4)$$

$$\beta = \arctan\,(\tan\theta_z.\cos\gamma_s) \quad (4.5)$$

$$\gamma = \{\, 0^\circ \; if \; \gamma_s < 90 \quad (4.6)$$
$$180^\circ \; if \; \gamma_s \geq 90\}$$

In (4.4) to (4.6) definite geometric attentions for 1-axis horizontal north-south continuous tracking PV systems. Abbreviations stand for: angle of incidence (beam and surface normal) (ϑ), zenith angle (ϑ_z), declination of earth axis (δ), hour angle (ω), tilt angle (β), surface azimuth angle (γ) and solar azimuth angle (γ_s) [4].

4.3 Horizontal axis north-south system

Horizontal axis north-south system tracks the position of the sun and optimise the irradiation on daily basic. According to simulation results irradiation increase 500-800 kWh/m^2 for sunny region such as Nepal and Kenya. The relative increase in irradiance would be 20 to 30 percentage. Whereas, for moderate irradiation region such as Finland additional irradiance would be 100 to 300 kWh/m^2. Relative increase in irradiation percentage in these regions would be 10 to 20 percentage.

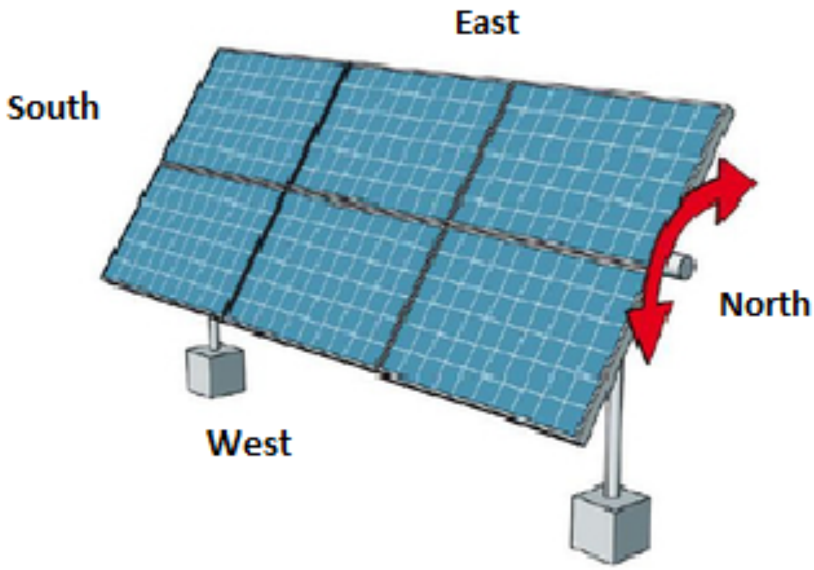

Fig. 4: Horizontal axis north-south continuous system [5].

The general geometric consideration of (3.4) to (3.6) would be extended by (4.7) to (4.9) for horizontal axis north-south system [4].

$$\cos\theta = \sqrt{(\cos^2\theta_z + \cos^2\delta . \sin^2\omega} \quad (4.7)$$

$$\beta = \arctan\left(\tan\vartheta_z . \cos(\gamma - \gamma_s)\right) \quad (4.8)$$

$$\gamma = \{+90° \; if \; \gamma_s > 0 \quad (4.9)$$

$$-90° \; if \; \gamma_s > 0\}$$

In (4.7) to (4.9) specific geometric considerations for 1-axis horizontal north-south tracking PV systems. Abbreviations stand for: angle of incidence (beam and surface normal) (ϑ), zenith angle (ϑ_z), declination of earth axis (δ), hour angle (ω), tilt angle (β), surface azimuth angle (γ) and solar azimuth angle (γ_s) [4].

4.4 Horizontal axis north-south optimally tilted system

Performance of horizontal axis north south system will drop during the peak energy production during the noon. This loss irradiation can be compensate if the panel is optimally tilted. Since, this system has combination of two strategies of optimally tilted system and one axis horizontal north-south system. Nevertheless, one directional shading effect would change to two directional causing increase in capital and operating costs [4].

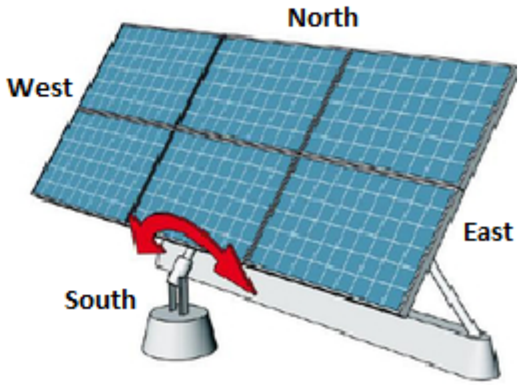

Fig. 5: Horizontal axis north-south with optimally tilted system [5]

The general geometric consideration of fixed optimally tilted system in (3.4) to (3.6) can be extended by (4.10) to (4.15) for horizontal axis north south optimally tilted system [4].

$$\cos\theta = \cos\theta_z . \cos\beta + \sin\theta_z . \sin\beta . \cos(\gamma_s - \gamma) \quad (4.10)$$

$$\beta = \beta'_0 + \sigma'_\beta . 180^\circ \quad (4.11)$$

$$\beta`_0 = \arctan \frac{tan\beta`}{\cos(\gamma - \gamma`)} \qquad \sigma_{\beta`} = \{0 \; if \; \beta`_0 \geq 0 \quad (4.12)$$

$$1 \; otherwise\}$$

$$\gamma = \gamma_0 + \sigma_{\gamma 1} . \sigma_{\gamma 1} . 180^\circ \quad (4.13)$$

$$\gamma_0 = \gamma` + \arctan \frac{\sin\theta_z . \sin(\gamma_s - \gamma`)}{\cos\theta` . \sin\beta`} \quad (4.14)$$

$$\sigma_{\gamma 1} = \{0\ if\ (\gamma_0 - \gamma^`)(\gamma_s - \gamma^`) \geq 0\ 1\ otherwise \quad (4.15)$$
$$\sigma_{\gamma 2} = \{1\ if\ (\gamma_s - \gamma^`) \geq 0\ -1\ otherwise$$

4.5 Vertical axis optimally tilted system

Vertical axis optimally tilted system has tracking axis in vertical configuration. This system is also known as azimuth tracking due to tracking of solar radiation from east to west. Since, it has also two direction shading due to tilted angle and vertical axis configuration [4]. In the result, the system need more land area causing higher capital and operational costs [4]. Single vertical axis system would be best for high latitude angle such as Finland.

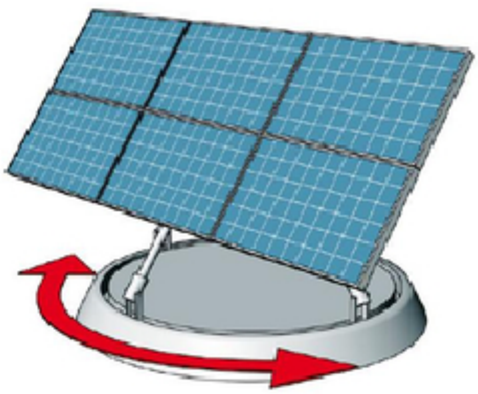

Fig. 6: Single axis vertical optimally tilted system [5].

According to simulation results about 35 percentage irradiation would be increase as compare to fixed optimally tilted system in Lappeenranta, Finland. (4.16) to (4.18) are expanded by single axis vertical optimally tilted system of the general geometric consideration of (3.4) to (3.6) [5].

$$\cos\theta = \cos\theta_z . \cos\beta + \sin\theta_z . \sin\beta \quad (4.16)$$

$$\beta = const. \quad (4.17]$$

$$\gamma = \gamma_s \quad (4.18)$$

4.6 Dual axis system

Dual axis system has two degree of freedom of rotation axes. Both horizontal and vertical axis are combination of dual axis system as shown in Fig.7. Highest irradiation on the modules can be achieved by dual axis system, if the position is based on sensor rather than time. Dual axis system achieves high irradiation on the modules Since, module surface is always perpendicular to the beam of solar radiation.

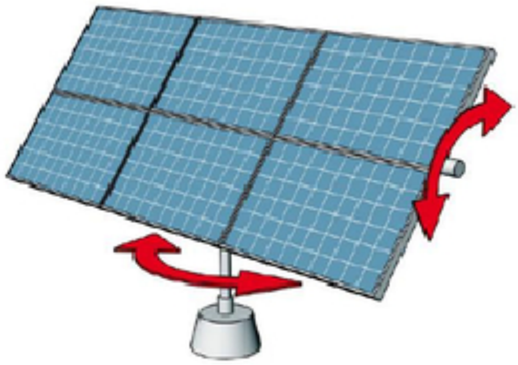

Fig. 7: Dual axis solar tracking system [5].

The general geometric consideration of (3.4) to (3.6) are modified according to (4.19) to (4.22) for dual axis tracking system [4].

$$I_{\mathrm{T}} = I_{\mathrm{b}}.R_{\mathrm{b}} \tag{4.19}$$

$$\cos\theta = 1 \tag{4.20}$$

$$\beta = \theta_{\mathrm{z}} \tag{4.21}$$

$$\gamma = \gamma_{\mathrm{s}} \tag{4.22}$$

5 Simulation software

Technical and economic analysis of different renewable energy must be essential for the efficient operation of renewable resources. Renewable system is quite complex and requires to be analyzed in detail. Software tools are needed in order to design, analysis, optimization and economic analysis. There is several simulation software are present among them Homer and PVSol pro software are used in this simulation.

5.1 Homer software

The Hybrid Optimization Model for Electrical Renewables (HOMER) is most popular and free software. Homer software is suitable for optimization and furthermore for a sensitivity analysis. HDKR anisotropic model is applied for photovoltaic system analysis [6]. Nevertheless, there is some limitation related to change in tilted angle and azimuth angles with single axis vertical and horizontal continuous system. Homer used the following equation to calculate output of PV array [6].

$$P_{\mathrm{pv}} = Y_{\mathrm{pv}} \cdot f_{\mathrm{pv}} \left({G_{\mathrm{T}}}/{G_{\mathrm{t,STC}}} \right) [1 + \alpha_{\mathrm{p}} (T_{\mathrm{c}} - T_{\mathrm{c,STC}})] \tag{5.1}$$

In equation (5.1), Y_{pv} presents power output under standard test conditions, f_{pv} is photovoltaic derating factor (%) G_t is incident solar radiation on PV array [kW/m^2] $G_{t,}$ STC is incident radiation at standard test conditions, α_p is temperature coefficient of power [%/°C] and Tc, STC is PV cell temperature under standard test conditions [25° C] [6].

If the model is chosen with no temperature effect on PV array, Homer assume that the temperature coefficient of power is zero [6]. Thus, equation (5.1) is simplifying as:

$$P_{pv} = Y_{\mathrm{pv}} \cdot f_{\mathrm{pv}} \, (G_{\mathrm{t}}/G_{\mathrm{c,STC}}) \tag{5.2}$$

5.1.1 Clearness index

Clearness index or average radiation for each month of the year can be entered into solar resource window [6]. Clearness index K_t is dimensionless number with in arrange from 0 to 1 which indicated the ratio of monthly solar radiation on horizontal surface of the earth H_{ave} to solar radiation striking on the top of atmosphere $H_{\mathrm{o,ave}}$ [6].

$$K_t = H_{ave}/H_{0,ave} \tag{5.3}$$

$H_{o,ave}$ for any month of year can be calculated according to latitude coordinates. If average radiation value is entered, HOMER will calculate corresponding clearness index [6]. Monthly radiation on horizontal surface can be easily calculated, if clearness index and extraterrestrial radiation is known [6].

5.2 PVSOL software

PVSOL was developed by Valentin Energy Software in Germany in 1998.Anisotropic sky model by Hay and Davies is used in PVSOL [7]. Irradiance, module voltage at Standard test conditions and efficiency characteristic curve are the factor responsible for performance of the system. Individually linear or dynamic temperature model can be applied in PVSOL.METEONORM, METEOSYN, NASA-SSE, PVGIS and SWERA is used as weather data [7]. The important features of PVSOL as compare to HOMER software is that ability to change the tilted angle and azimuth angles of single axis horizontal and vertical tracking system. Therefore, various single tracking system can be used with PVSOL. Furthermore, PVSOL provide capability to change all requirement in database and create own PV systems.

6 Simulation Results

6.1 Systems description

For this simulation 200 W polycrystalline PV modules is selected. Electrical and mechanical characteristics of PV modules are shown in table2. 10 kWp can be produced by 50 modules with total panel area of 83.8 m^2. The efficiency of PV panel under standard test conditions (STC) is 11.93 percent with panel temperature coefficient of power is -0.4%/K [7]. Nevertheless, nowadays efficiency of polycrystalline increase 15- 18 percentage. Similar PV array are used in all three locations

Table 2: Electrical and mechanical characteristics of PV modules [7]

Descriptions	Values
Output power	200 W
Maximum voltage	28.30 V
Maximum current	7.07 A
Open circuit voltage	36.10 A
Short circuit current	7.70 A
Fill factor	71.98
Efficiency (STC)	11.93%
Area	1.001 m *1.675 m
Weight	22 kg
Temperature coefficient of voltage	-123 mV/K
Temperature coefficient of current	2.6 mA/K
Temperature coefficient of power	-0.4%/K

Table 3: Inverter electrical characteristics [8].

Descriptions	Values
DC power rating	8.7 kW
AC power rating	8.5 kW
Stand by consumption	15 W
Maximum input voltage	1000 V
Maximum input current	30 A
Number of MPP Trackers	2
Max input current per MPP Trackers	15 A
Max input power per MPP Trackers	4.8 kW
Minimum MPP voltage	200 V
Maximum MPP voltage	950 V

Commercial inverter ABB TRIO 8-5-TL-OUTD was selected for this simulations. Major technical data of an inverter was shown in table3. This inverter has dual input section for two independent maximum power point tracking which can allow optimal energy harvesting from two arrays [8]. First array consists of two strings with 13 modules in series. The maximum total voltage in this array would be 367.9 V [8]. Next array allows single string with 24 modules in series so that maximum voltage would be 679.2 voltage [8]. The maximum power point tracking would be 4.76 kW, which is in the range of MPP trackers. Designed solar farm is shown in Fig.8.

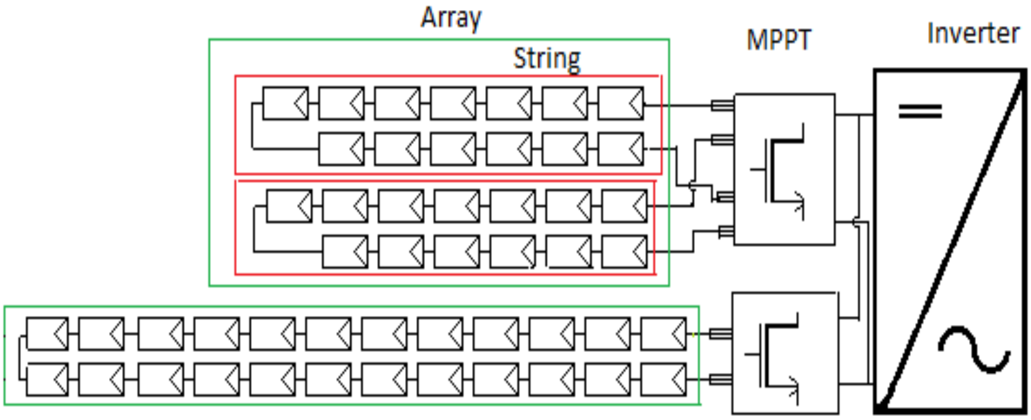

Fig. 8: layout of main components of designed solar farm

6.2 Case1: Kisumu, Kenya

Kisumu is located at latitude of 0°6′S and longitude of 34°45′E in Kenya. Climatic condition is fluctuating over the year. Average yearly high temperature reach upto 35 °C and average low temperature would be 12 °C resulting average yearly temperature about 23 °C [9].

For the fixed system, optimal angle would be zero in Kisumu, Kenya. Nevertheless, rain water would not clean the panel. Therefore, panel must be tilted 5 to 15-degree angle. This additional tilted angle has very less effect on annual irradiance produced. Thus, panel would be installed parallel to the ground with directly facing towards the sky. Yearly, irradiance reduce with increase of tilted angle. Similarly, for horizontal north south axis tracking system optimal angle would be the identical with fixed system. Consequently, in Case1 horizontal north south axis system is same as horizontal north south axis with optimal tilted angle. Furthermore, optimal angle for vertical axis tracking would be 40 degrees. Yearly mean irradiance for the fixed system, horizontal axis north south system and vertical axis system with respect to different tilted angle are shown in Fig.9.

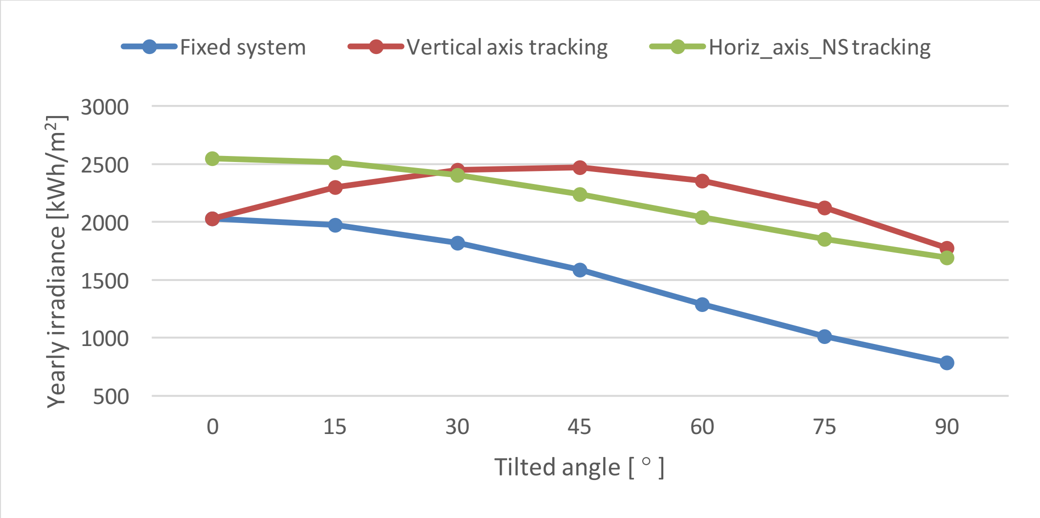

Fig. 9: Yearly irradiance for different systems with respect to different tilted angles in Kisumu Kenya

6.2.1 Annual analysis

Different systems have been considered in a typical year and the result are summarized in table4.Horizontal axis north south system has highest overall system efficiency 9.88 % this is followed by dual axis and vertical axis with optimal tilted angle 9.83% and 9.84% respectively.

Table 4: Annual analysis summarized results for Kisumu, Kenya

	Incident solar energy [MWh]	Energy Produced [MWh]	System efficiency [%]	Inverter efficiency [%]	Array efficiency [%]	Annual yield [kWh/kWp]
Fixed OptAng	169.95	16.45	9.68	97.57	9.91	1645
Horiz axis EW	179.92	17.49	9.72	97.63	9.96	1749

Vertical axis OptAng40	207.57	20.44	9.84	97.68	10.08	2044
Horiz axis NS	213.52	21.01	9.88	97.69	10.12	2101
Dual axis	220.31	21.67	9.83	97.70	10.06	2167

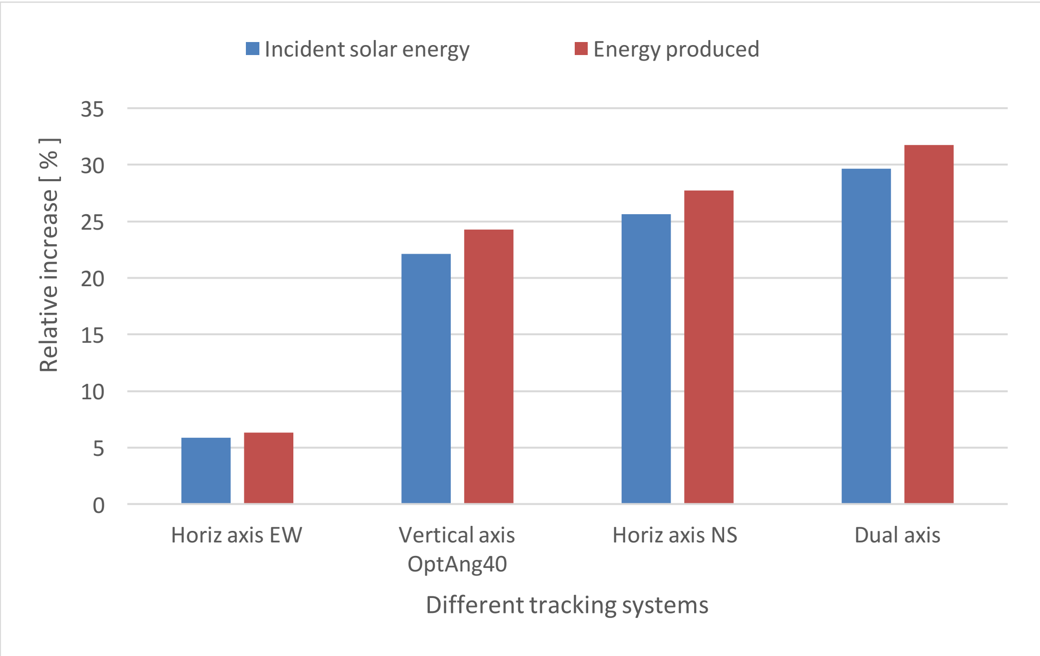

Fig. 10: Percentage increase compare to fixed tilted system in Kisumu, Kenya

Fig.11 shows that annual incident solar energy. Kisumu, Kenya has highest irradiance in the months of January and May, whereas, for other months it has almost constant irradiance. Dual axis tracking system has highest irradiance over whole year. Horizontal axis north south system can be simply compare with dual axis systems. Fixed system has almost linear irradiance over the year this is due to location falls in the equator and system has optimal tilted angle zero. Additionally, Fig.12 shows the average monthly ambient temperature.

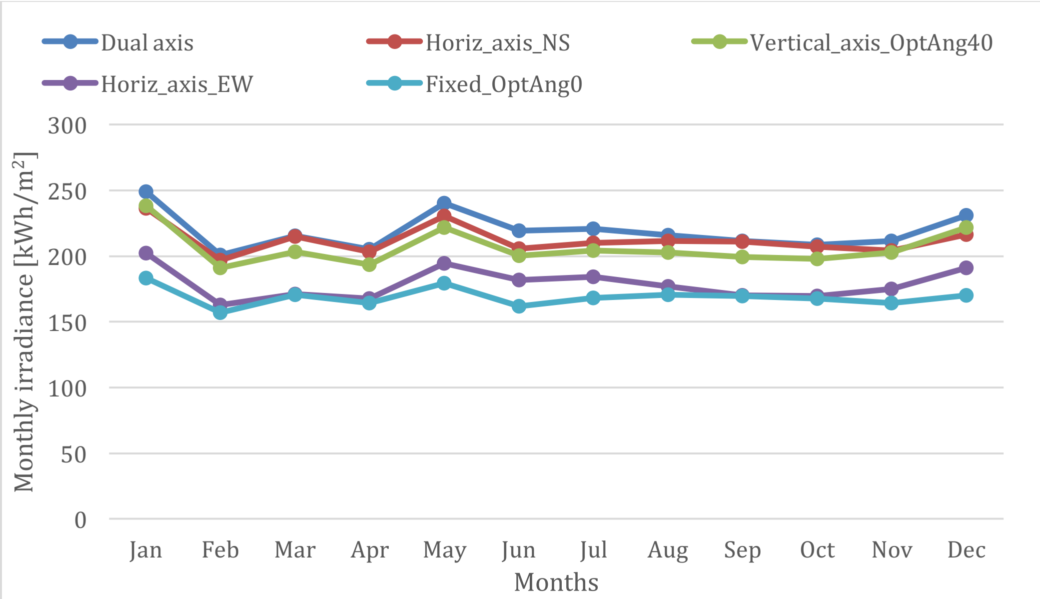

Fig. 11: Incident solar irradiance in Kisumu, Kenya

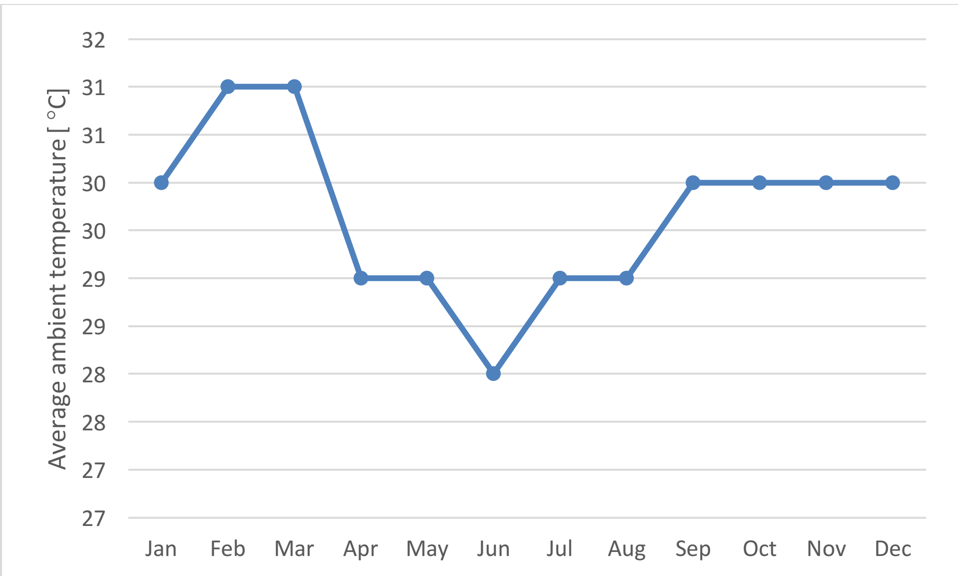

Fig. 12: Average ambient temperature of Kisumu, Kenya

6.2.2 Analysis for clear summer days

For the analysis of clear summer days, a warm summer day with high intensity of the radiation was selected. Two clear days is selected for the months of January and March. Fig.13 shows daily irradiance for clear summer days of January. Dual axis system has highest irradiance as usual. Vertical axis with optimal tilted angle can be comparable with dual axis system. Nevertheless, during the noon where the sun is overhead in the sky, its irradiance drop slightly since, solar radiation does not fall perpendicular to modules. Since, vertical axis system installed with optimal tilted angle 40 degree.

In case of another clear summer day in March as shown in Fig.14 horizontal axis north-south system has same irradiance compare to dual axis system. Vertical axis system has even lower irradiance compare to horizontal axis north-south system while, horizontal axis east-west system has same irradiance with fixed system.

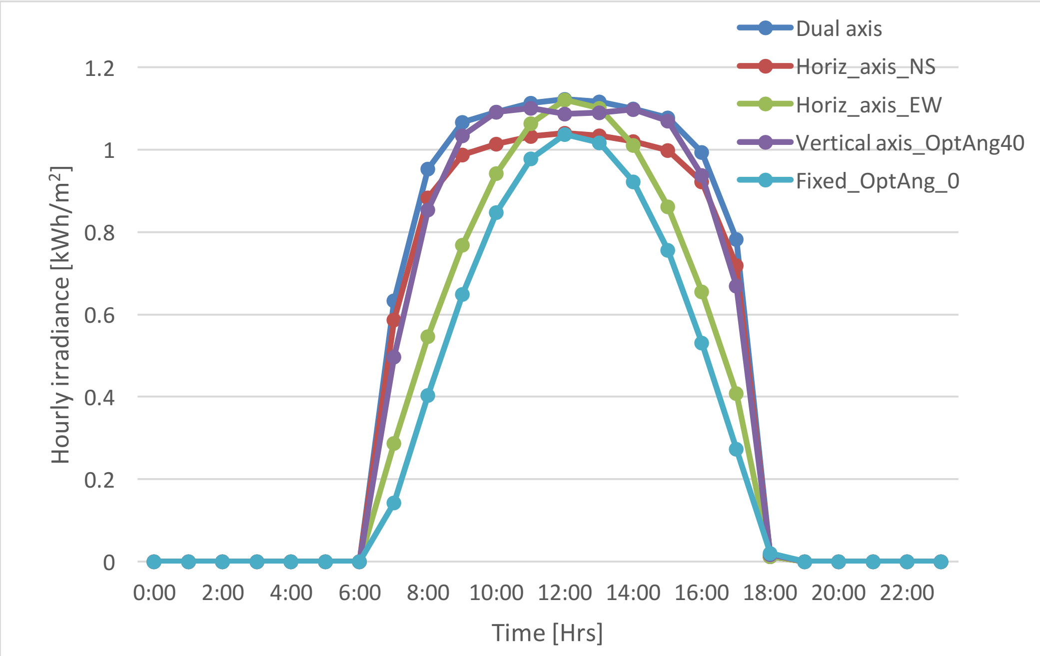

Fig. 13: Hourly irradiance for a clear summer day of January in Kisumu, Kenya

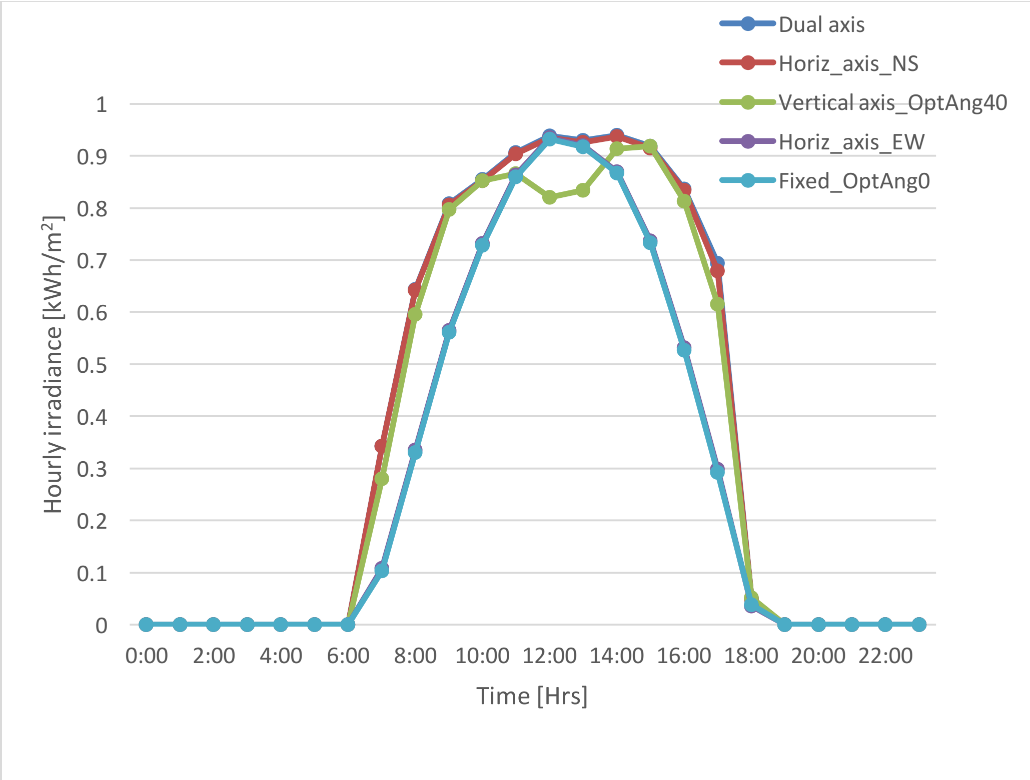

Fig. 14: Hourly irradiance for a clear summer day of March in Kisumu Kenya

6.2.3 Analysis for clear winter days

For the analysis of a clear winter days, clear sky day is selected for the month of October. The result from Fig.15 shows that horizontal axis north-south system has same irradiance as compare to dual axis system. Fixed system has same irradiance compare to horizontal axis east-west systems. Irradiance drops during peak production in the noon for vertical axis optimally tilted system. Analysis shows that percentage increase of irradiance compares to fixed system are up to 246%, 245%, 185% and 2% for dual axis system, horizontal axis north-south system, vertical axis with optimal tilted angle and horizontal axis east-west system respectively.

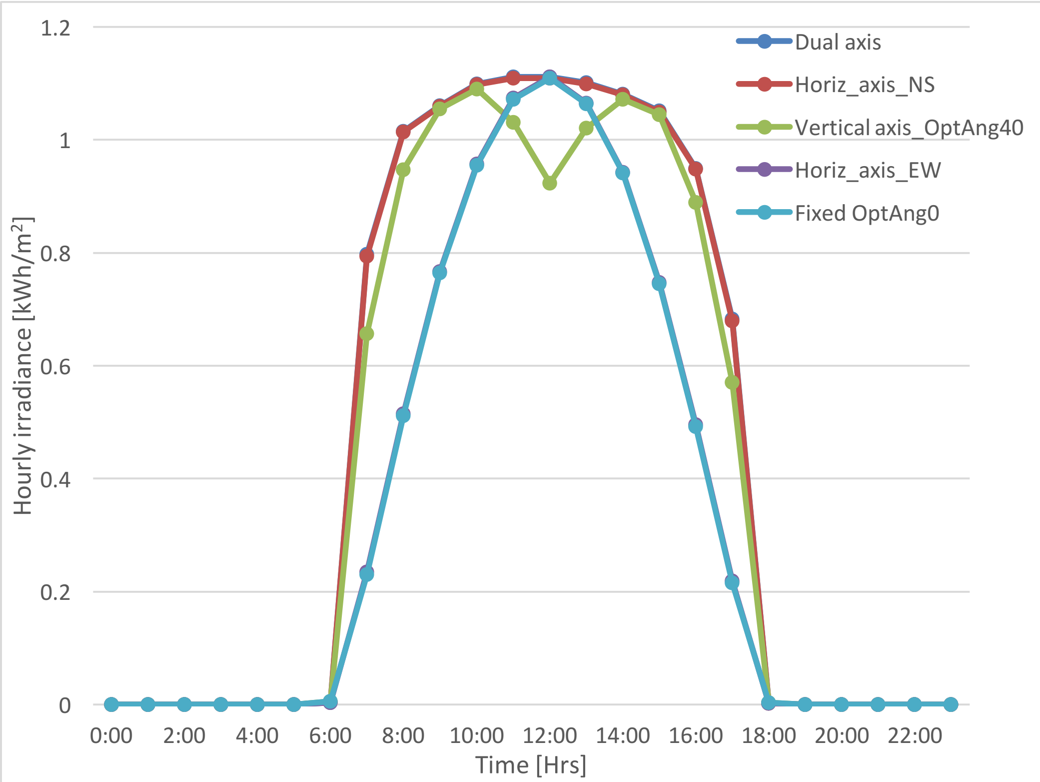

Fig. 15: Hourly analysis for a clear winter days of October in Kisumu, Kenya

6.2.4 Analysis for overcast days

In case of overcast day, major part of radiation is diffused, it shares about only 10 percentage of specific radiation in clear days. For the analysis of overcast day, winter day is selected for the month of August as shown in Fig.16.Fixed system has highest irradiance during overcast day. Irradiance decrease by using tracking systems. Analysis shows that percentage decrease in irradiance compare to fixed system is -40%, -40%, -33% and -9% for dual axis system, horizontal axis east-west system, horizontal axis north-south system and vertical axis with optimal tilted system.

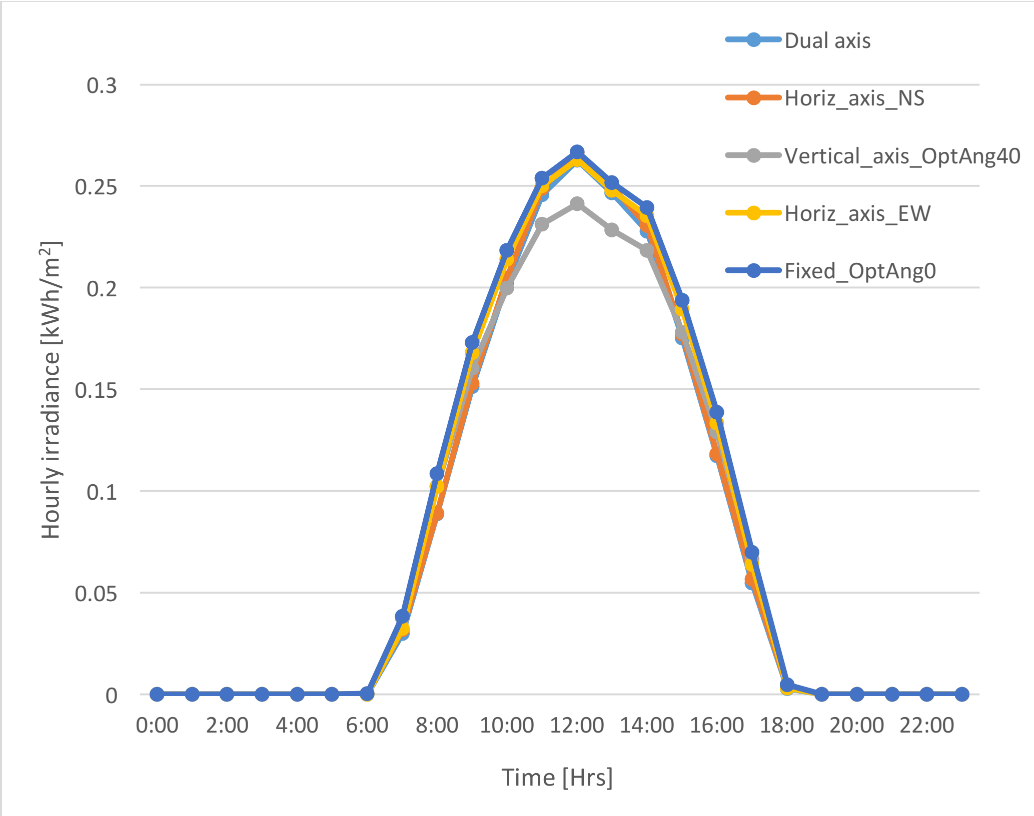

Fig. 16: Hourly irradiance for overcast winter day in August for Kisumu Kenya

6.2.5 Analysis for temperature

Temperature is also one of important factor for affecting performance of solar energy. Low temperature is the best for solar energy production. Fig.17 shows that different module temperature for different tracking system with respect to ambient temperature. As soon as sunrise in six am module temperature increase. Within one hour when ambient temperature is 15 degree centigrade modules temperature rise 21°C, 21°C, 33°C, 36°C and 36°C for fixed system, horizontal axis east-west system, vertical axis with optimal tilted system, horizontal axis north-south system and dual axis system respectively. During the noon when ambient temperature is about 30°C modules temperature rise up to double. This increase in modules temperature will affect the performance of solar modules.

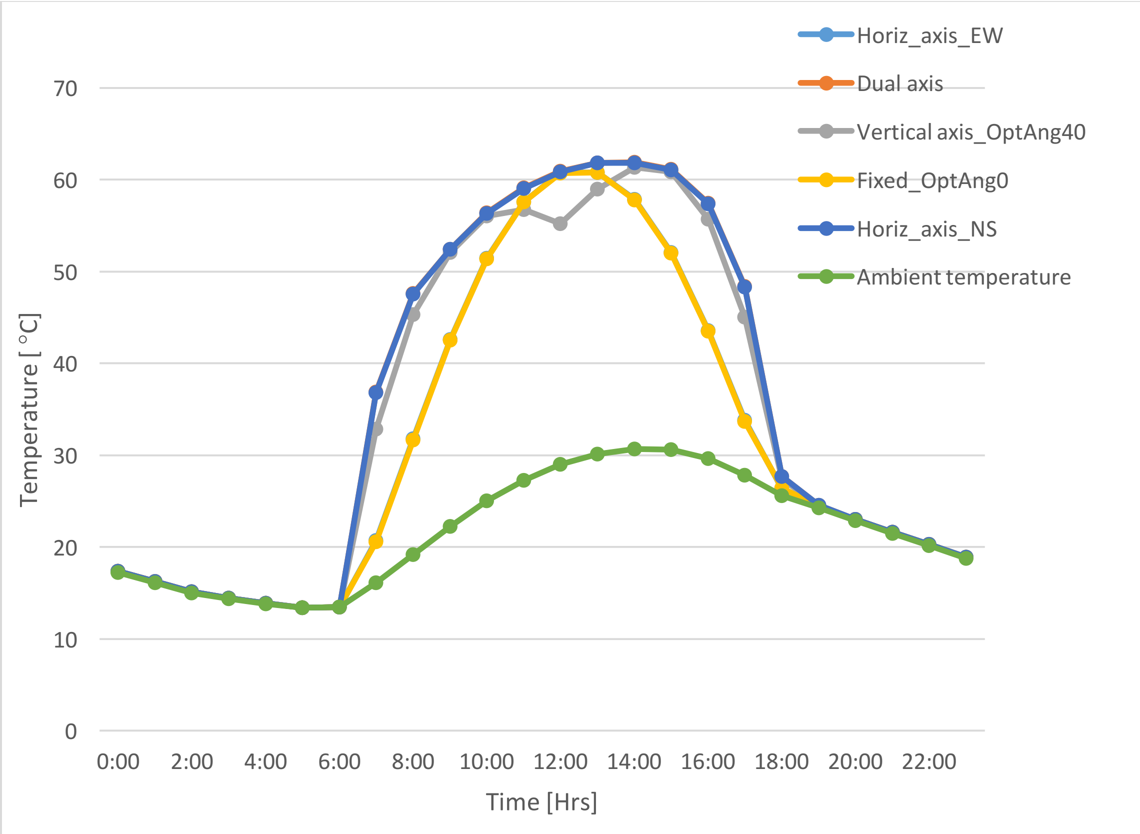

Fig. 17: Temperature analysis for clear winter day in October for Kisumu, Kenya

6.3 Case2: Kathmandu Nepal

Kathmandu, Nepal is located in latitude 27° 42' 2.7684" N and longitude 85° 18' 0.5040" E. The annual temperature varies from 3°C to 32°C and is rarely below 2°C or above 32°C [10]. The warm season lies from April to October with average high temperature 27°C similarly, cold season lies between December to February with average high temperature below 21°C [10].

6.3.1 Optimal tilted angle

Since the country is located in northern hemisphere, panel would get the maximum irradiance over the year, when facing towards the South direction (azimuth 0°C). Thus, for the fixed system panel should face toward the South with optimal tilted angle 30°. Similarly, for the horizontal axis north-south system optimal tilted angle would be same as Fixed system. Nevertheless, for vertical axis system tilted angle would slightly increase upto 45°C.Yearly irradiance for these systems with respect to various tilted angle is shown in Fig.18.

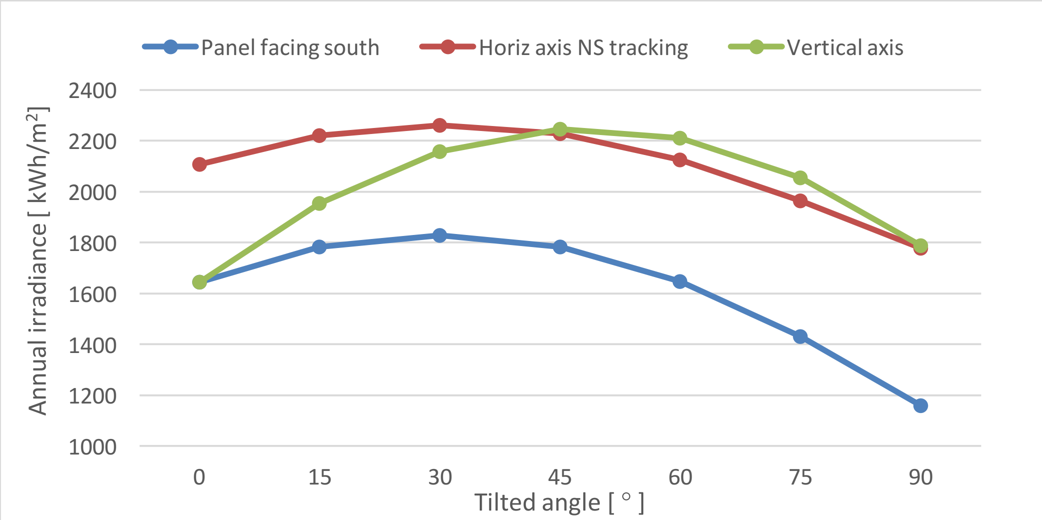

Fig. 18: Annual irradiance over various tilted angle in Kathmandu, Nepal

6.3.2 Annual analysis

Annual irradiance from the Fig.19 shows that March has highest irradiance in summer. During July and August, irradiance drop suddenly due to the rainy season and most of the time sky is covered by the thick cloud. In winter, months such as November, December and January irradiance are almost constant. Dual axis system has highest irradiance which is followed by horizontal axis north-south with optimal tilted angle. It is worst to tilt the horizontal axis north-south system for the months May to September. Nevertheless, for rest of month, irradiation will descent suddenly for horizontal north-south system as compare to its tilted system. Irradiance will descent for horizontal axis north-south system during the winter months. During December and January months, tracking with horizontal north-south system would be negative as compare to fixed tilted system. Similarly, horizontal axis east-west system can be comparable with fixed tilted. Additionally, average monthly ambient temperature is shown in Fig.20.

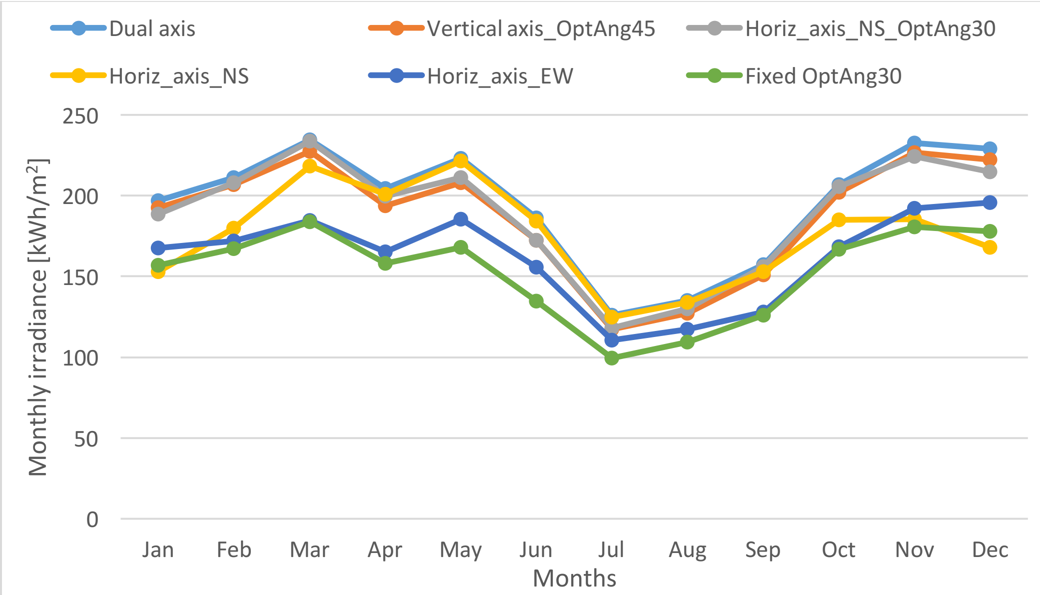

Fig. 19: Annual irradiance of Kathmandu, Nepal

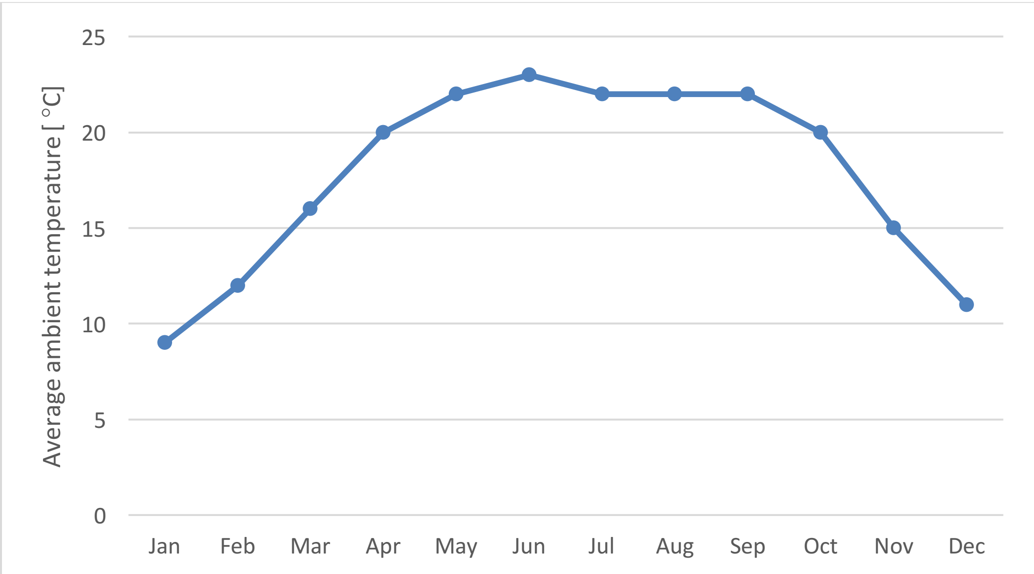

Fig. 20: Average monthly ambient temperature of Kathmandu, Nepal

This annual analysis is done in a typical year and result are summarized in table5.The result shows that horizontal axis north-south with optimally tilted system have maximum system efficiency of 10.10 percent. This is followed with horizontal axis north-south system with 10.9 percent system efficiency. Similarly, fixed tilted system has least efficiency as shown in table5.

Table 5: Annual analysis summarizing result of Kathmandu, Nepal

	Incident solar energy [MWh]	Energy Produced [MWh]	System efficiency [%]	Inverter efficiency [%]	Array efficiency [%]	Annual yield [kWh/kWp]
Fixed OptAng30	153.25	15.19	9.91	97.41	10.17	1519
Horiz axis EW	162.80	16.17	9.93	97.50	10.19	1617
Horiz axis NS	176.66	17.84	10.09	97.57	10.35	1784
Vertical axis OptAng45	180.81	18.19	10.06	97.58	10.31	1819
Horiz axis NS OptAng30	189.51	19.14	10.10	97.58	10.35	1914
Dual axis	196.34	19.72	10.05	97.58	10.29	1972

According to Fig.21 annual percentage increase in incident solar energy is 6.3, 15.3, 22.9, 23.7, 28.2 for horizontal axis east-west system, horizontal axis north-south system, vertical axis with optimally tilted system, horizontal axis north-south optimally tilted system and dual axis system. Conversely, percentage increase for energy produced would be slightly greater than percentage increase of irradiance.

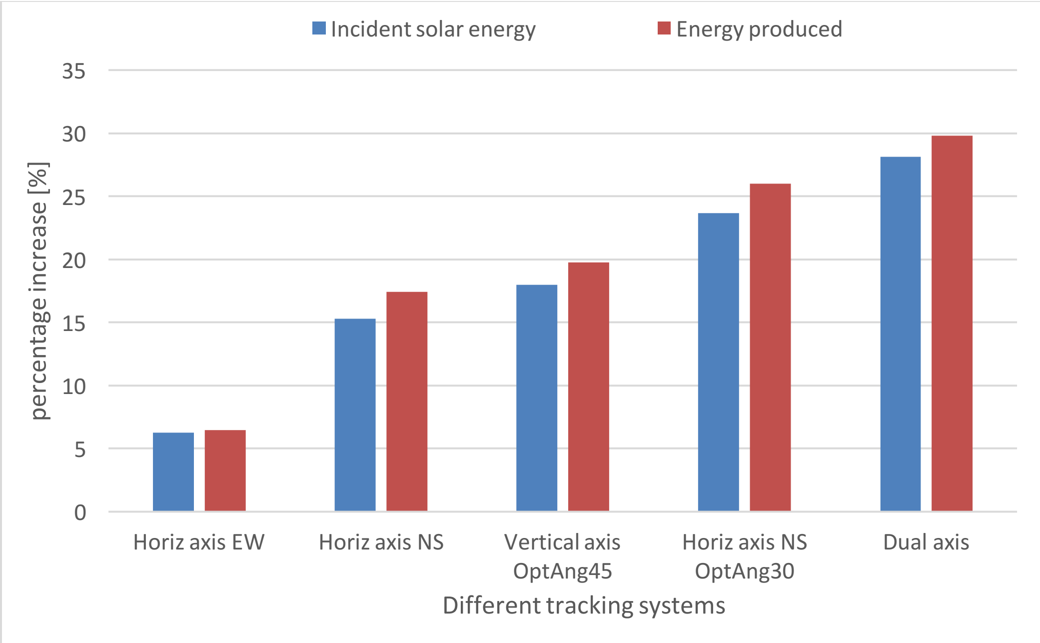

Fig. 21: Percentage increase compare to fixed tilted system in Kathmandu, Nepal

6.3.3 Analysis for clear summer days

A warm clear summer day with high intensity of the radiation was selected to analysed irradiance and energy production for a clear summer day. Clear day is selected from the month of March as shown in Fig.22. Analysis shows that irradiance produced by dual axis system, vertical axis optimally tilted system and horizontal axis north-south optimally tilted angle are almost same. For horizontal axis north-south system irradiance descent during noon where there will be peak irradiance. Fixed tilted system has almost same irradiance compare to horizontal axis east-west system. Tracking advantage for irradiance increase for a whole clear summer day as compare to fixed tilted system would be 30, 29, 27, 15 and 1 percentage for dual axis, horizontal axis north-south optimally tilted system, vertical axis optimally tilted system, horizontal axis east-west system and horizontal axis north-south system respectively.

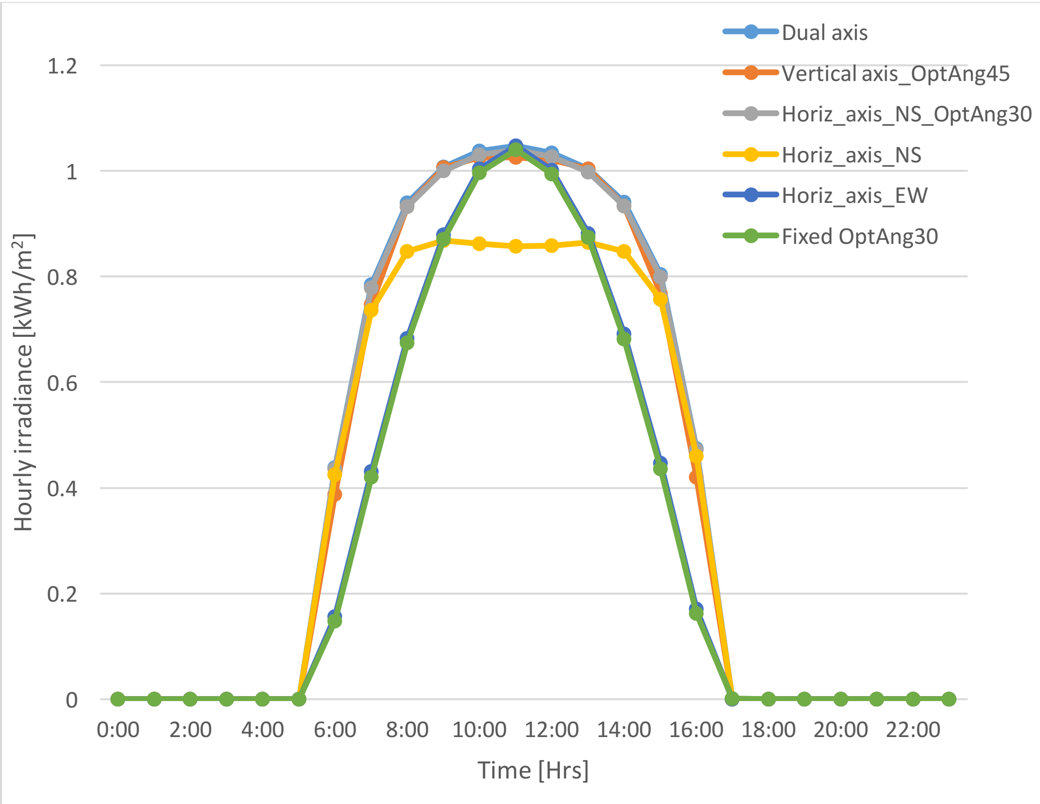

Fig. 24: Hourly irradiance for a clear summer day in March of Kathmandu, Nepal

6.3.4 Analysis for clear winter days

Analysis for irradiance and energy produced for clear winter days is done for the month of December. As usual, dual axis system has best irradiance. As compare to clear summer months, horizontal axis north-south optimally tilted system drop the irradiance during clear winter days. However, tilted system had clear advantage compare to its horizontal axis north-south. Horizontal axis east-west system has best irradiance during noon as compare to its clear summer days. Furthermore, tracking with horizontal axis north-south system has disadvantage compare to fixed tilted system for at least clear winter days. Irradiance reduce by 7 percentages. Nevertheless, for other systems have clear tracking advantage of 31, 27, 22, and 12 percent for dual axis system, vertical axis optimally tilted system, horizontal axis north-south optimally tilted system and horizontal axis east-west system compare to fixed tilted system.

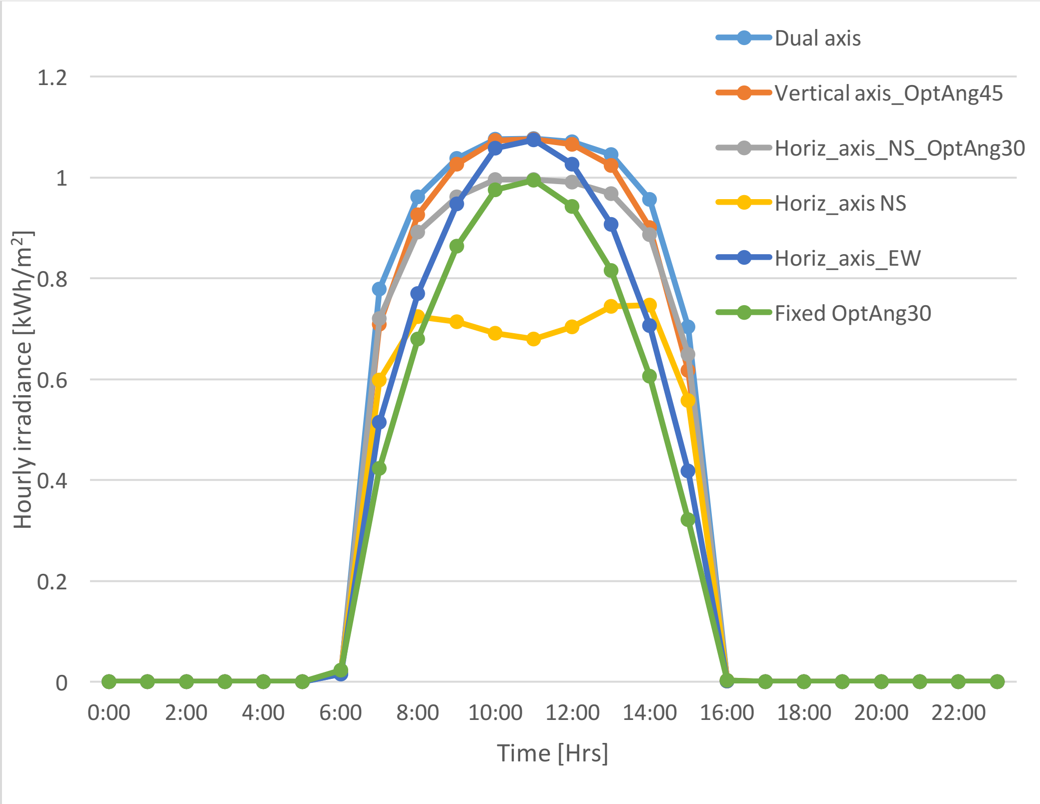

Fig. 24: Hourly irradiance for a clear winter days in December of Kathmandu, Nepal

6.3.5 Analysis for overcast days

For the analysis of irradiance and energy produced for overcast days is done in winter-overcast day. Analysis shows that tracking systems have disadvantage compare to fixed system. In fully overcast day, horizontal fixed system has more irradiance and produce more solar energy. Since, in overcast days most of the radiation is diffused and diffuse radiation has almost 10 percent share compare to direct radiation. Thus, tracking systems have not so difference in irradiance compare to fixed system during overcast days. According to Fig.24 tracking systems have negative advantages during overcast days. Percentage change in irradiance are -13, -12, -4, -4 and 1 for dual axis system, horizontal axis east-west system, horizontal axis north-south system, horizontal axis north-south optimally tilted system, vertical axis optimally tilted system respectively.

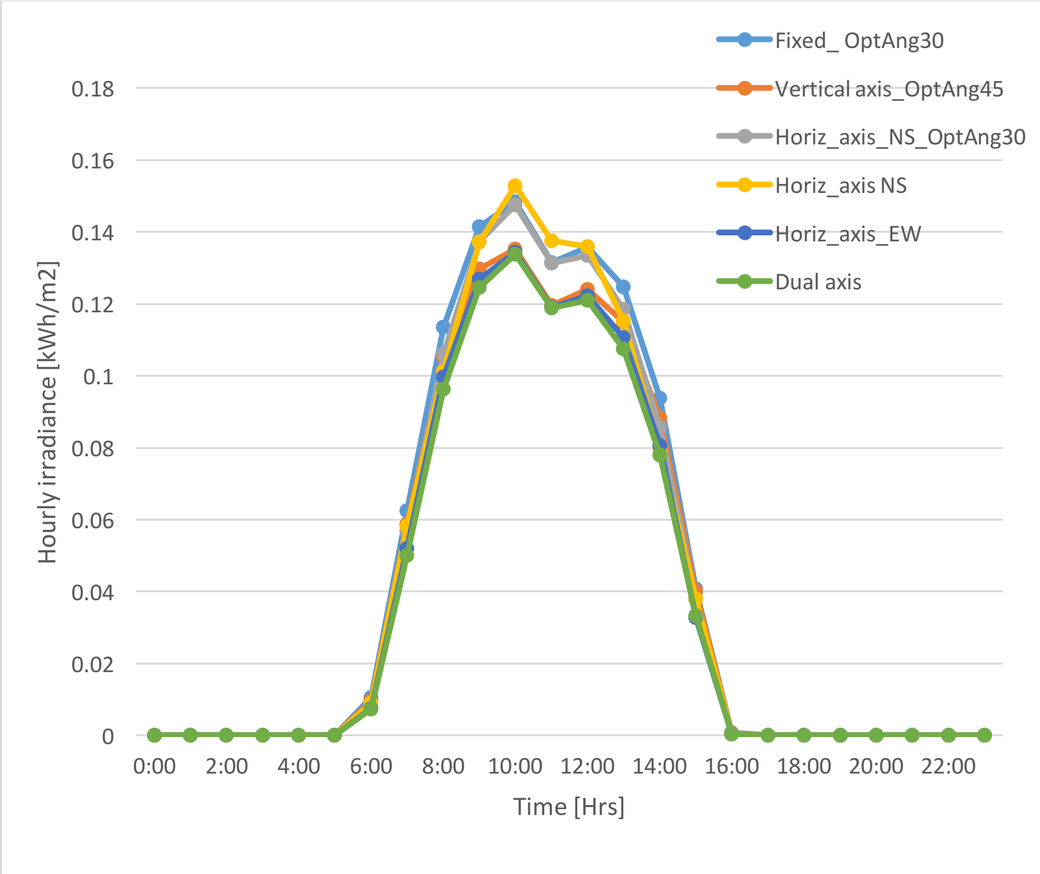

Fig. 24: Hourly irradiance for overcast winter day in December of Kathmandu, Nepal

6.3.6 Temperature analysis

Different modules and ambient temperature are analysed for clear winter days as shown in Fig.26. A clear day in the month of December is selected. Modules temperature and ambient temperature are same before the sunrise in 6 am. Modules temperature increase soon as panel get the irradiance. Within one hour when the ambient temperature is 8°C modules temperature will rise to 18°C, 20°C, 20°C, 22°C, 25°C and 27°C for fixed tilted system, horizontal axis east-west system, vertical axis optimally tilted system, horizontal axis north-south system, horizontal axis north-south optimally angle system. During the noon when ambient temperature is 18°C, modules temperature would be almost double expect for horizontal axis north-south optimally tilted system due to decrease in energy production during peak noon hours. This increase in modules temperature will affect the performance of solar modules as Standard test conditions of applied modules is at 25°C.

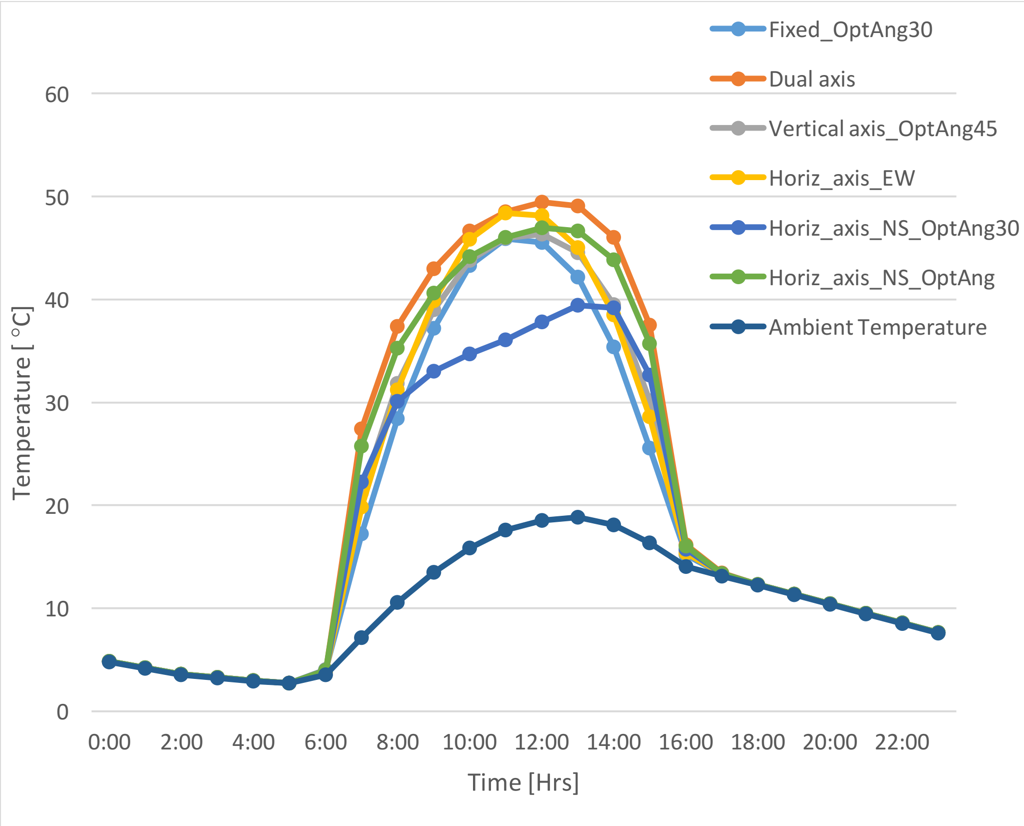

Fig. 25: Temperature analysis for different systems during clear winter day in December in Kathmandu, Nepal

6.4 Case 3: Lappeenranta Finland

6.4.1 Optimal tilted angle

Photovoltaic panel collect the solar radiation directly from sun, diffuse light from atmosphere or ground reflected light. PV panel must be oriented in the direction of the sun and tilted to maximize the energy production. Panel would collect the solar energy more effectively when they are oriented perpendicular to solar radiation. Angle of the sun varies throughout the year. Tilted angle can varies for summer and winter. Therefore, panel must be kept in optimal tilted angle for maximizing annual energy production. For the countries situated in northern hemisphere, sun is oriented in south direction must of the time throughout the year. Thus, it is wise to face the solar panel south direction.

In order to achieve the peak energy demand in winter, optimal angle must be increase. Since, the sun is oriented in horizon most of time. Solar modules collect more radiation when they kept almost perpendicular to the ground. Nevertheless, solar energy production will increase rapidly during the summer days. Thus, in order to maximize the annual energy production panel must be tilted according to summer days. Optimal angle for Lappeenranta Finland would be 45 degree as shown in Fig.26. Optimal tilted angle is same for single axis horizontal north south continuous system. Nevertheless, optimal angle increases up to 60 degree for single axis vertical system.

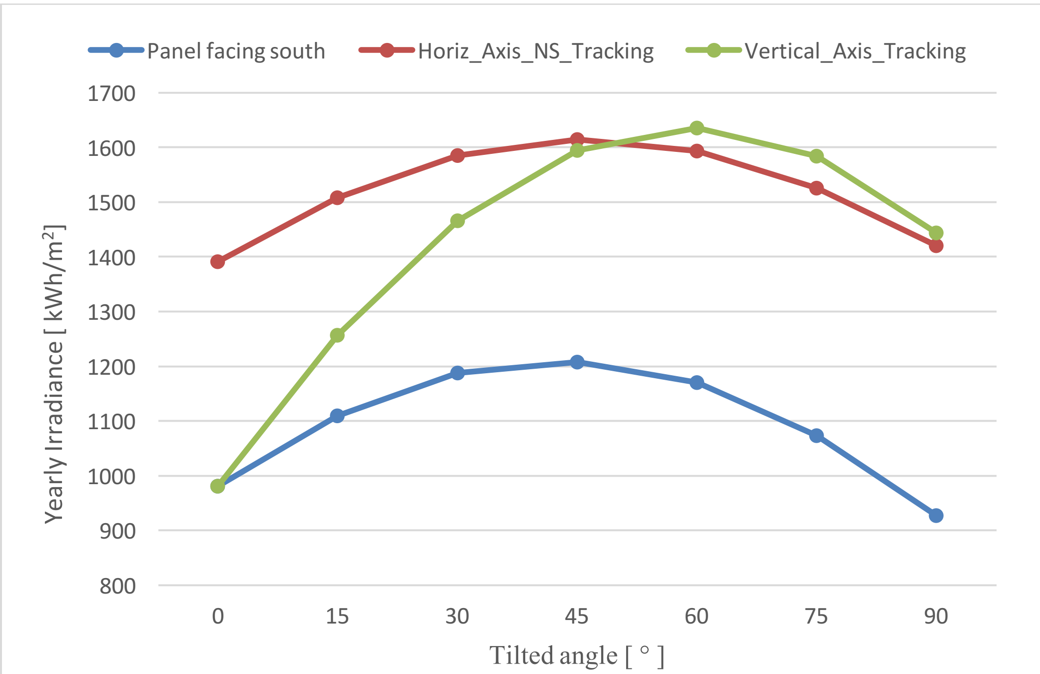

Fig. 26: Yearly mean irradiation of panel tilted at various angle for different systems in Lappeenranta Finland

6.4.1 Annual analysis

Energy production has been studied in single year and the result is resumed as shown in Table 6. Various tracking system are compared with fixed optimally tilted system. According to annual incident solar energy dual axis tracking system is best with 38 percent dual axis is followed with single axis vertical and horizontal axis north-south direction by 35 and 33 percent respectively. For the single axis tracking system, vertical system and horizontal axis north-south with optimally tilted system are best and can be easily comparable with dual axis systems. Nevertheless, horizontal east-west axis and horizontal north south axis might not be suitable options as compare to fixed tilted system.

Table 6: Annual PV energy analysis for Lappeenranta, Finland

	Incident solar energy [MWh]	Energy Produced [MWh]	System efficiency [%]	Array efficiency [%]	Inverter efficiency [%]	Annual yield [kWh/kWp]
Fixed OptAng	101.23	10.54	10.41	10.77	96.67	1054
Horiz axis EW	110.08	11.53	10.47	10.8	96.92	1153
Horiz axis NS	116.76	12.28	10.52	10.52	97.02	1228
Horiz axis NS OptAng	134.60	14.44	10.73	11.04	97.17	1444
Vertical axis OptAng	134.85	14.69	10.89	11.21	97.18	1469
Dual axis	139.28	15.01	10.78	11.09	97.20	1501

Since, the relation between irradiation and relative efficiency of PV system is not linear, increase in incident solar energy percentage is not equal to energy production percentage increase. Overall efficiency of the panel increase by using tracking system as compare to fixed tilted system. This is due to change in array and inverter efficiency with respect to incident solar energy. Total energy production of the tracking systems as compare to fixed optimal tilted system is 42%, 39% and 37% more for dual axis, single vertical axis and horizontal axis north south with optimal tilted angle respectively shown in Fig.27.

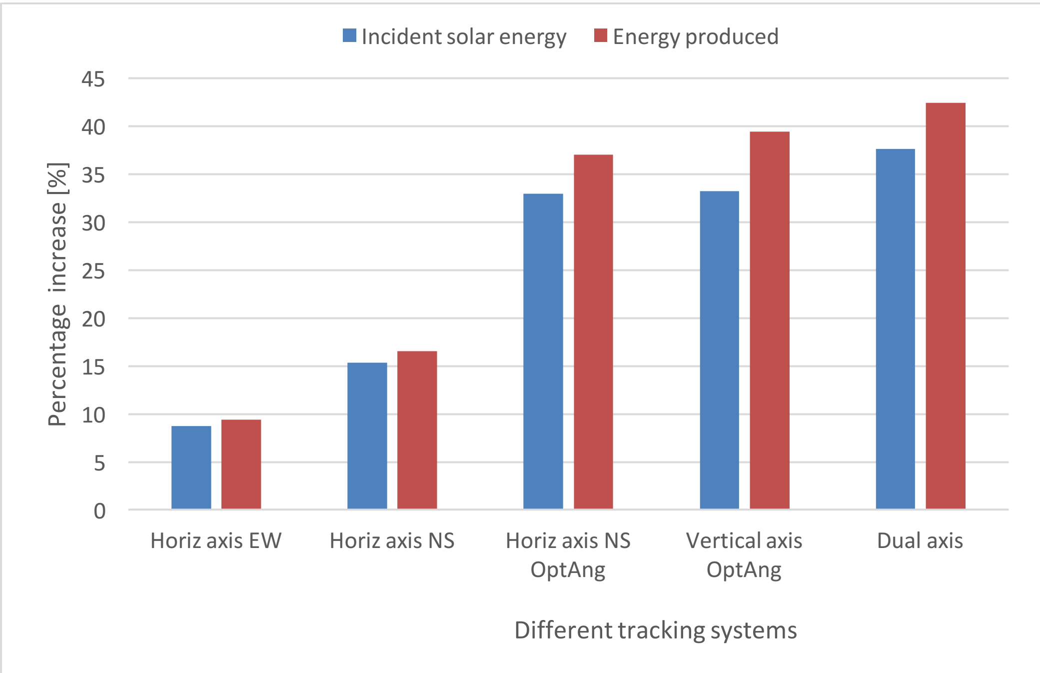

Fig. 27: Increase percentage for different tracking systems with respect to fixed tilted system

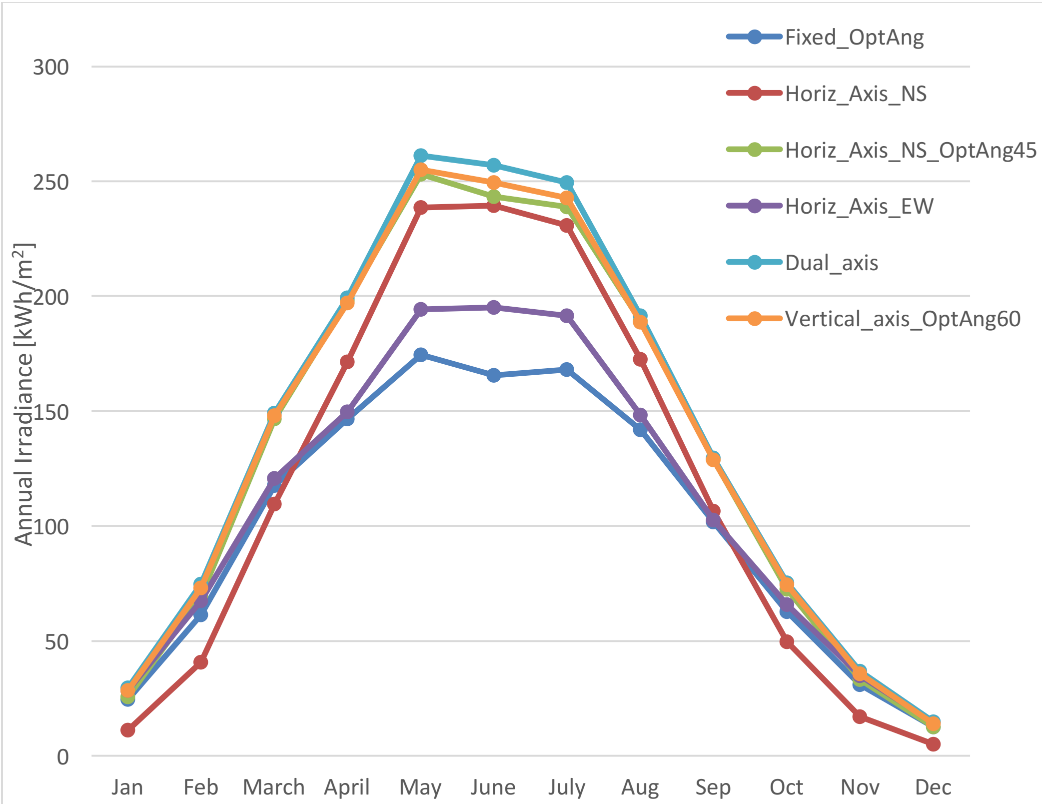

Fig. 28: Annual irradiation of Lappeenranta, Finland

Incident solar energy on fixed tilted system is significantly higher than horizontal fixed system. However, in the summer for few months they acquire quite comparable solar energy. This is a due to sun moves across the sky to the path near overhead and Horizontal fixed system is perpendicular to direct radiation. Tracking system has huge advantage during the summer months when intensity of the sunlight is high. For horizontal axis east-west system has slightly increase in summer months. About 15 percent increase in solar irradiation annually in case of horizontal axis north-south system. This will increase further upto 33 percentage with optimal tilted angle.

6.4.1 Analysis for clear summer days

Energy production in summer is high due to high intensity of radiation and long day length. Fig.29 represents that incident solar energy in clear summer day. Here, Dual axis system is best performance. Single vertical axis has absorbed almost same amount of radiation as dual axis tracking, however, at noon when the sun is almost above in the sky it has low performance since, solar beam radiation is not perpendicular to modules. Similarly, horizontal axis north south reduce its performance in peak hours, this can be compensate by installing the panel with optimal tilted angle. Thus, horizontal axis north-south at optimal tilted angle has same performance as dual axis in peak day hours. Horizontal axis east-west system has only good performance in morning and evening however, during the day time it has same performance as fixed optimal tilted angle. According to a clear summer day analysis Fig.29 increase percentage of irradiance for different tracking systems compare to fixed tilted system 70, 66, 64, 52 and 16 percentages for dual axis system, vertical axis system optimally tilted system, horizontal axis north-south optimally tilted system, horizontal axis north-south system and horizontal axis east-west system.

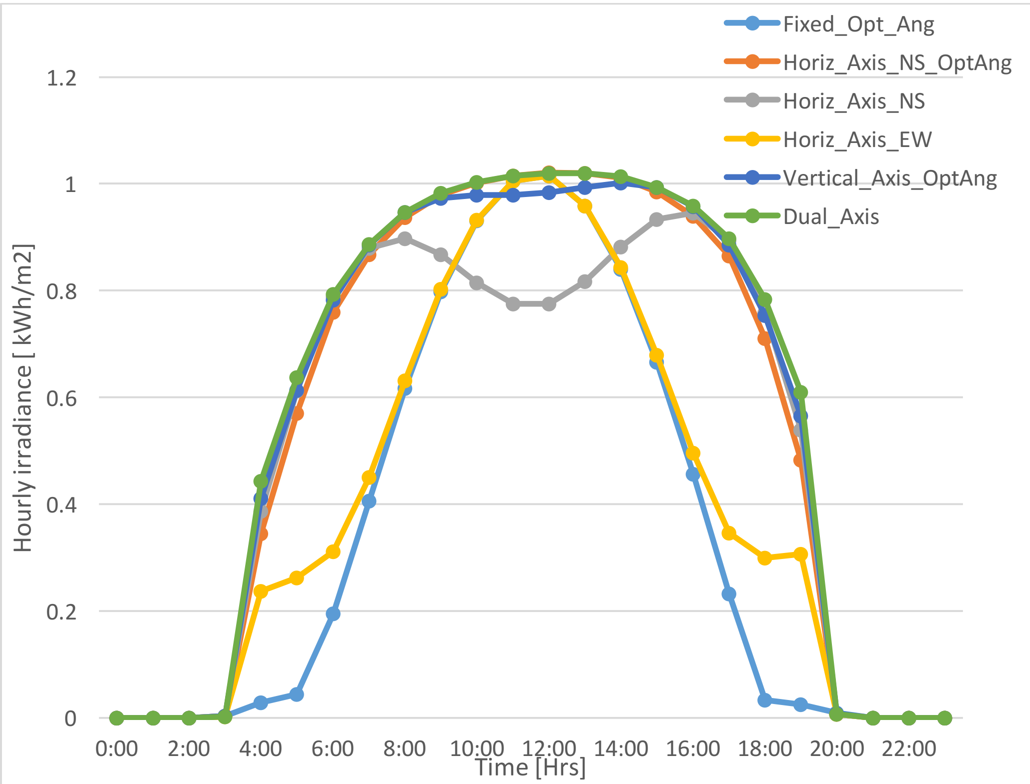

Fig. 29: Hourly irradiation produced by winter overcast day in January of Lappeenranta, Finland

6.4.1 *Analysis for clear spring days*

For the analysis of clear spring days, a clear day for the month of March is selected. Analysis shows that dual axis system would be best similarly to other clear days. dual axis system is practically identical with vertical axis tilted angle. Tracking with horizontal axis north south system in the spring days are worst as compare to fixed tilted system. However, horizontal axis north south system can be compensate with installing optimal tilted angle. According to analysis clear spring days in Fig.30, change in irradiance percentage for different tracking system as compare to fixed tilted system are 28, 26, 22, 7 and -19 percentage for dual axis system, vertical axis with optimally tilted system, horizontal axis north-south system, horizontal axis east-west system and horizontal axis north-south system respectively.

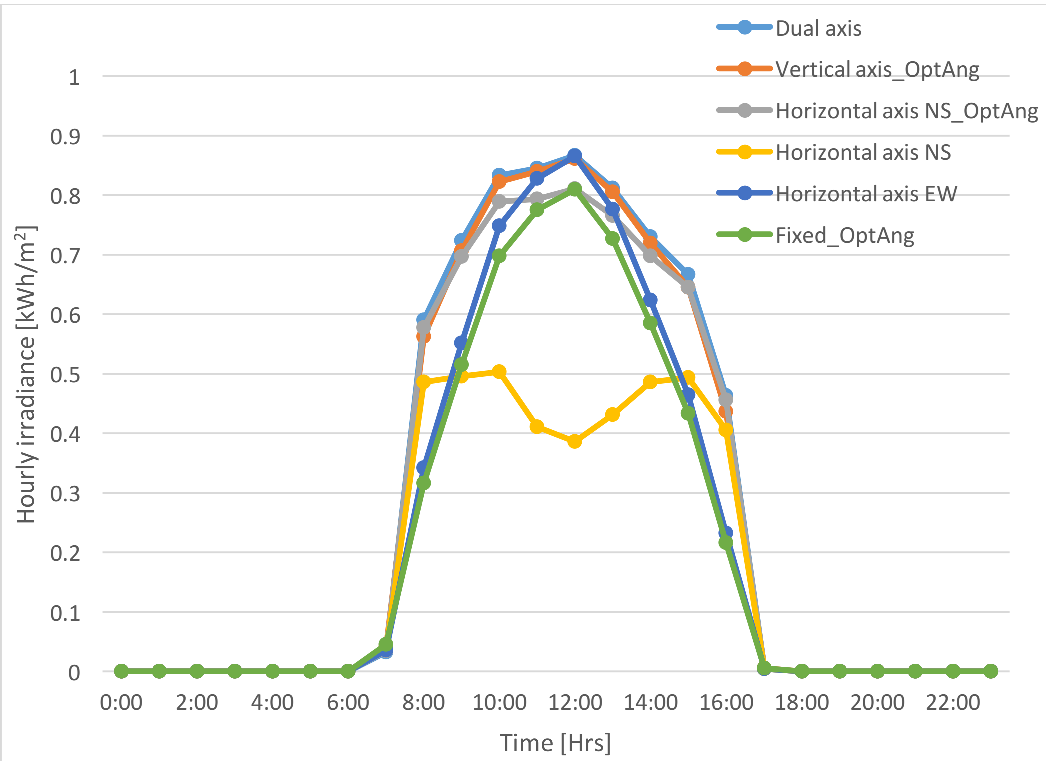

Fig. 30: Hourly irradiance produced during clear spring day of March in Lappeenranta, Finland

6.4.2 *Analysis for clear autumn days*

A clear day for the month of September is selected for analysis of clear autumn days. Similarly, clear spring day analysis, tracking with horizontal axis north south system would be the worst for clear autumn days. Moreover, dual axis system would be best which is followed by vertical axis tilted system. According to Fig.34, changes in irradiance with different tracking systems as compare to fixed tilted system are 33, 31, 29, 4 and -7 percentage for dual axis system, vertical axis optimally tilted system, horizontal axis north-south optimally tilted system, horizontal axis east-west system and horizontal axis north-south system respectively.

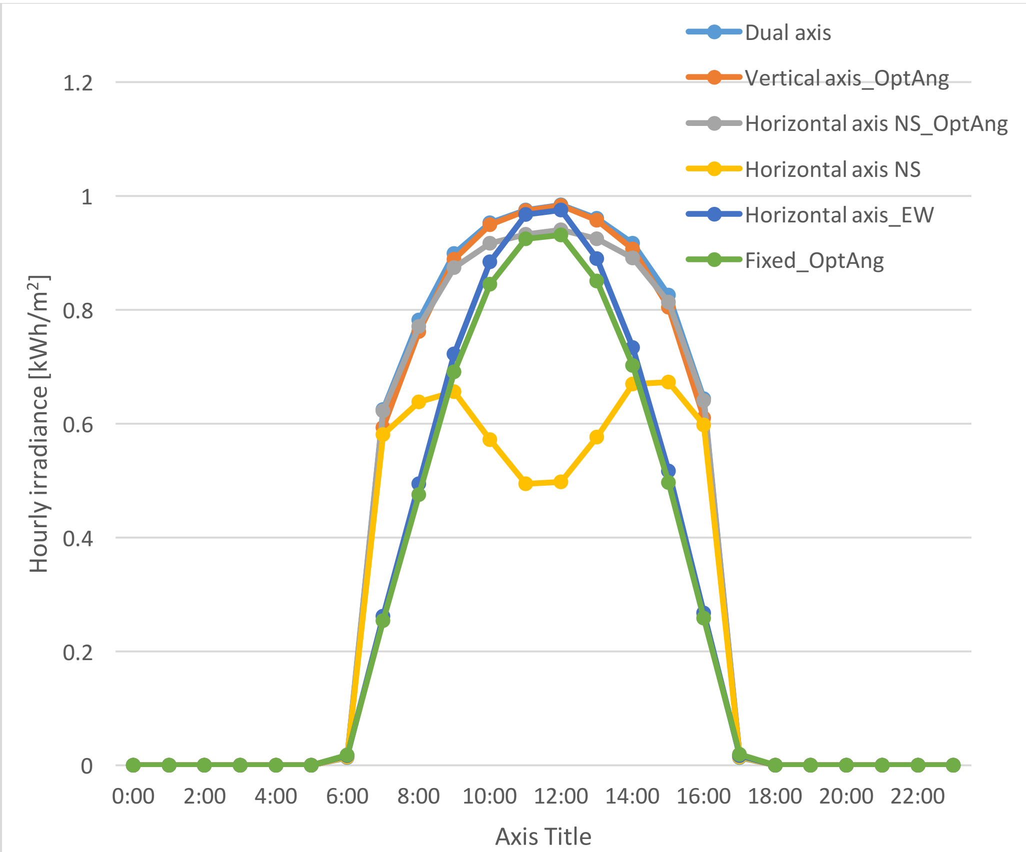

Fig. 31: Hourly irradiance for a clear autumn day of September in Lappeenranta, Finland

1.1.1 Analysis for clear winter days

Fig.32 shows that energy production in clear winter days in Lappeenranta. As usual, dual axis system receive more radiation. Similarly, in summer vertical axis receive almost same amount of radiation as dual axis however, at noon its performance decreases. For horizontal tracking systems, east-west axis system has best performance at least in the winter whereas; north-south axis has worst performance compare to summer days. Furthermore, horizontal axis north-south with optimally tilted system has almost same performance as fixed system. According to a clear winter day analysis, percentage change with tracking systems as compare to fixed tilted system would be 25, 24,17, 2 and -70 percentage for dual axis systems, vertical axis optimally tilted system, horizontal axis east-west system, horizontal axis north-south with optimally tilted system and horizontal axis north-south system.

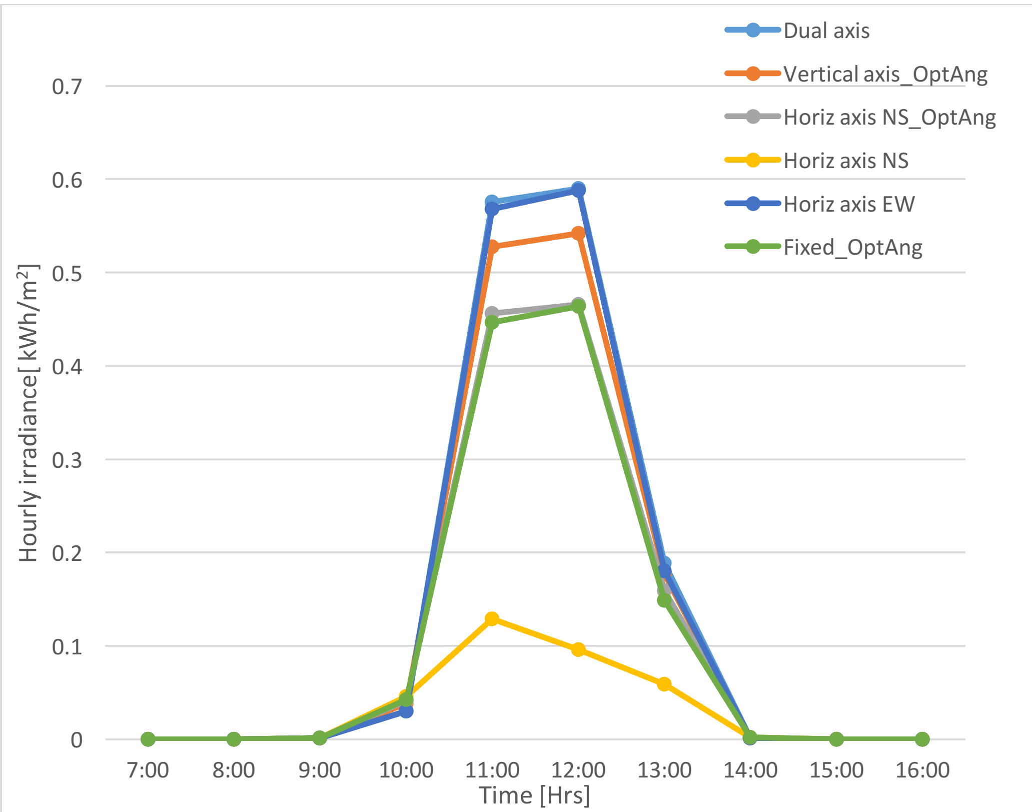

Fig. 33: Hourly energy production in clear winter day of January in Lappeenranta

1.1.2 Analysis for overcast days

Fig.34 shows hourly energy production during an overcast day where, major part of radiation is diffuse radiation. Tracking systems have no more advantage to collect more irradiance and solar energy production during fully overcast days. Dual axis system would be worst one. Fixed horizontal system is considered as best one. Thus, in overcast days tracking systems must face the panel up to the sky. However, energy production in overcast day is very low as compare to clear days. Thus, tracking system has still huge benefit over fixed system. According to an overcast day analysis Fig.34, percentage change in irradiance by using different tracking systems compare to Fixed tilted system are -26, -25, -8, -2 and -1 percentage for dual axis system, horizontal axis east-west system, vertical axis optimally tilted system, horizontal axis north-south with optimally tilted system and horizontal axis north-south system.

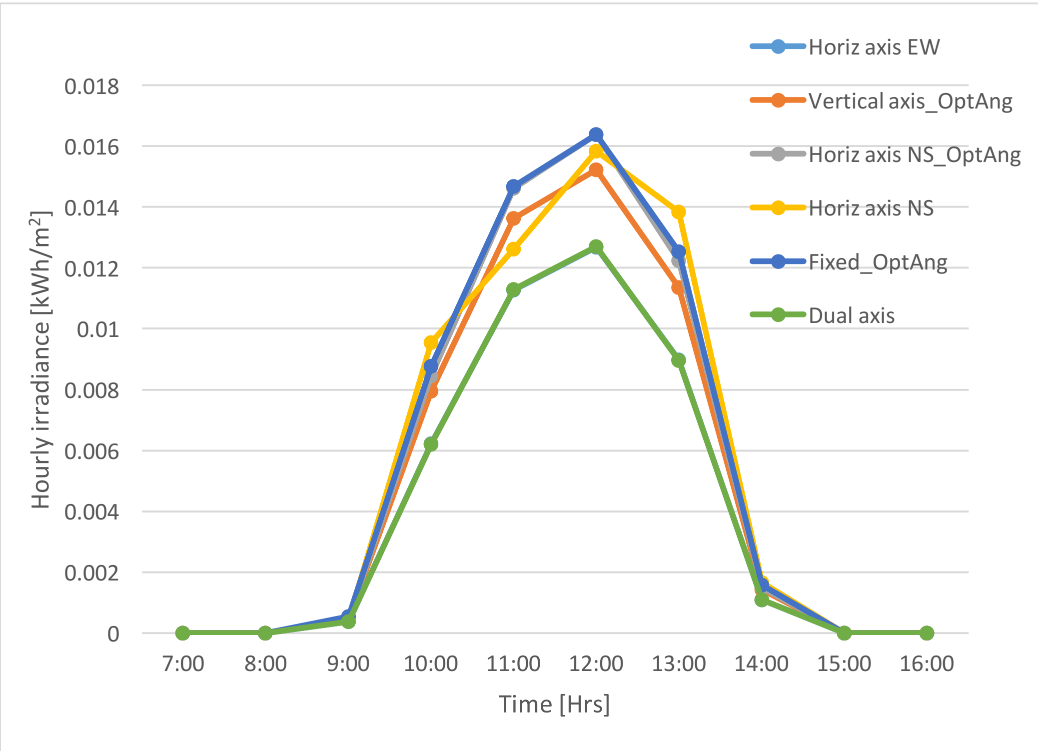

Fig. 34: Hourly irradiation produced by winter overcast day in January of Lappeenranta, Finland

1.1.3 Temperature analysis

For the cold countries similar to Finland during the winter morning panels are covered by snow as modules temperature are same as ambient temperature. It might take delay for energy production. Panel will produce energy with some part which are not cover by snow. Temperature of modules rises consequently whole snow will melt within early hour, similarly direct solar radiation would also help to melt snow. Furthermore, efficiency of modules increases with decreasing ambient temperature. Figure 8.4.8 shows that module and ambient temperature for different systems. During the noon, when ambient temperature is 4°C module temperature would 18°C to 22°C for different systems. However, for horizontal axis north-south system temperature rises only 7°C. This is due to energy production for horizontal axis north-south system is less during clear winter days as compare to other systems.

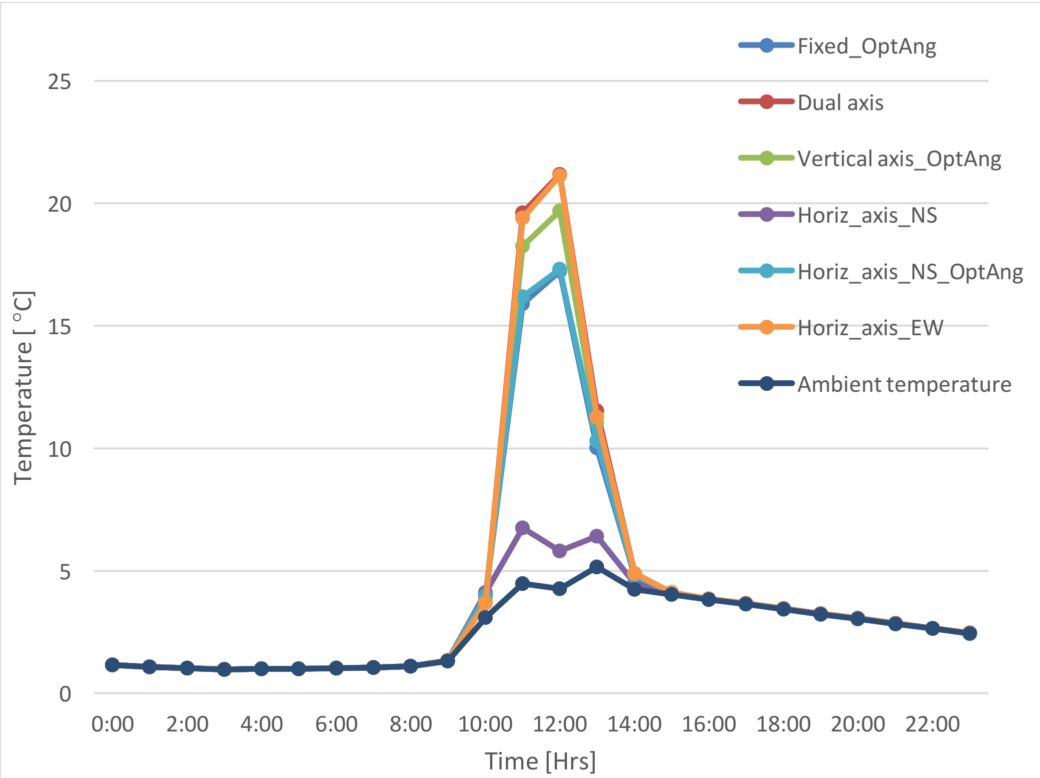

Fig. 35: Module temperature analysis for a clear winter day in Lappeenranta, Finland

1.1.4 Albedo factor analysis

Ground reflection radiation also affect amount of array irradiance. Mostly, ground cover with water, ice and snow increase the ground reflection radiation. These reflection radiations from the surrounding expect from the atmosphere itself is called Albedo. Basically, albedo factor value varies from 0 to 1. This mean, object with no reflection is consider as zero albedo factor. For fresh snow has albedo 0.8 to 0.9 [12]. In this project, albedo factor 0.8 is considered for the spring months January, February and March. Result show that for fixed tilted system about 4 percent energy production increase as compare to total energy production for these 3 months. For fixed horizontal surface has least affect by with increase of albedo factor, this is the fact that panel are facing upward in the sky. With the increase of tilted angle, ground reflection radiation increases. Ground reflection radiation is maximum at 90 degree where panel are perpendicular with respect to ground. Additionally, it can be vary with different tracking system as shown in Fig.36. Therefore, ground reflection must be considered mainly in northern country like Finland where ground is covered by the snow for long duration time.

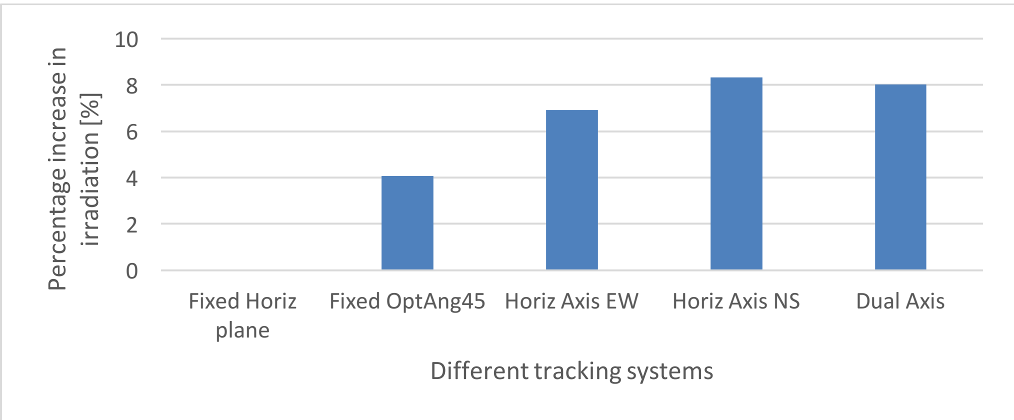

Fig. 36: Increase in solar irradiance for 3 spring months January, February and March when reflection from snow is increased from 20 to 80 percentage.

7 Solar Farm Results

Solar farm situated in Lappeenranta University of Technology is considered as Finland's largest solar farm untill 2013 that has generation capacity of 220 kW [13]. Total surface area of solar panel will be about 1500 square metres [13]. According to the orientation of the solar panels there are flat roof system, dual axis system, car port system, south wall and west wall. Flat roof system with 51.5 kWp is situated on the roofs of the university which are installed panels facing south with 15 degree tilted angle [13]. Carport system 108 kWp are also installed panel facing south with 15 degree tilted angle. Dual axis system, south wall system and west wall system content of 5 kWp, 18.36 kWp and 18.36 kWp respectively [13].

For this project, manual tracking system with rated power 250 Wp is moved for various tilted angle 0 to 90 degree for panel facing east and west in different Finnish weather conditions. This experiment is done during summer month May, June and July. Daily PV power production from this panel is recorded for clear summer days and overcast days. Forecast of daily weather date was done on the basic og Finnish Meteorological Institute [14]. These results are compared to PV power production with dual axis, flat roof system, south wall and west wall system. For this comparison all the system's power production is converted with 10 kWp system. During these analysis fix shading such as buildings or trees are not considered.

7.1 Analysis for clear summer days

7.1.1 Panel facing east

Manual tracking panel is moved daily for various tilted angles with panel facing east. Power production for panel facing east is compared with power production with different systems for clear summer days. Dual axis system has sharp power production as soon as sunrise early in the morning nevertheless, for other systems only after 8 am power production will increase. This is due to geographical location of solar farm. Dual axis system got the direct radiation early in the morning at 4 am. For other systems, permanent shading such as buildings and tree will affect from direct radiation. In case of panel facing east with the decrease in tilted angle peak production will shift towards right that means, towards noon.

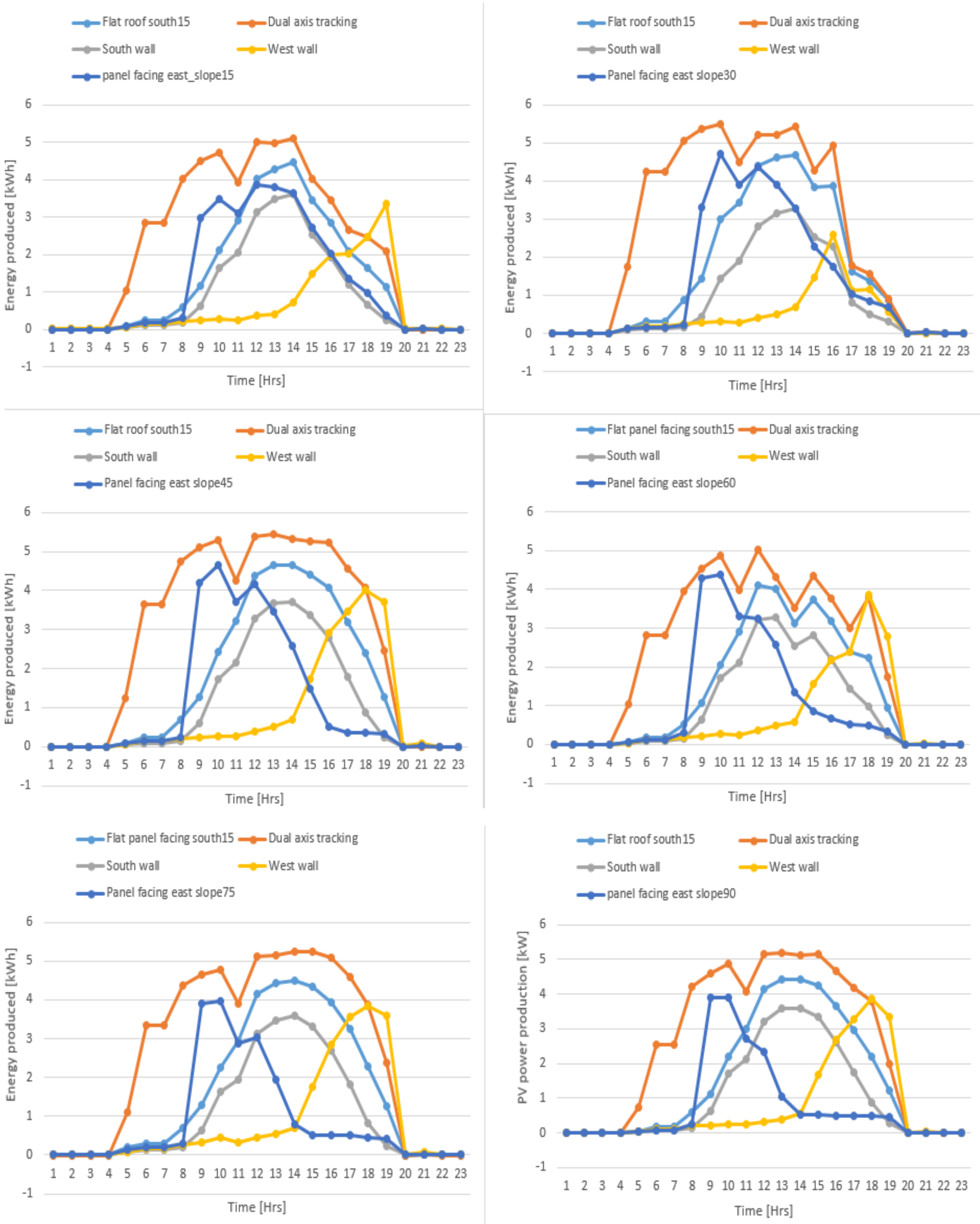

Fig. 37: PV power production by 10 kWp each system during clear summer days in Lappeenranta

7.1.2 Panel facing west

Fig.38 shows comparison between PV power productions for different systems with panel facing west for different slope angle. According to clear summer days analysis south wall produced more energy than west wall. For the west-facing panel, energy production in the morning will from diffuse radiation. Energy production gradually increase in afternoon as the panel will start to get direct radiation. West facing panel has peak production in late afternoon within 3 pm to 6 pm. With the increase of slope angle, peak production shift toward right such that peak production will be at 6 pm when the panel are perpendicular with respect to ground. While comparing energy production with flat roof south with tilted 15 degree, daily percentage increase of power production for panel facing west be would be best at tilted angle 30 degree.

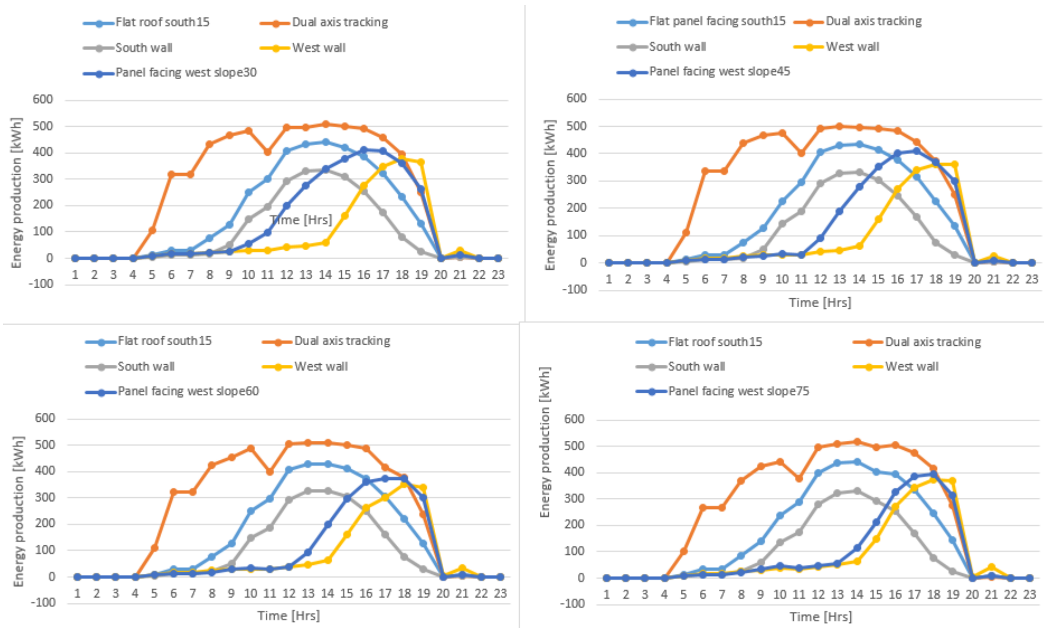

Fig. 38: PV power production by 10 kWp each system during clear summer days in Lappeenranta

7.2 Analysis for overcast summer days

7.2.1 Panel facing east

Fig.38 represents that panels facing east with different tilted angle is compared with other systems such as dual axis tracking, flat root with south facing tilted with15 degree, south wall and west wall during overcast day in Lappeenranta, Finland. Result shows that during fully overcast day power production does not depend upon the panels facing direction. However, power production strongly depends on the tilted angle. Therefore, during the fully overcast days horizontal panel has best power production whereas, vertical wall has lowest.

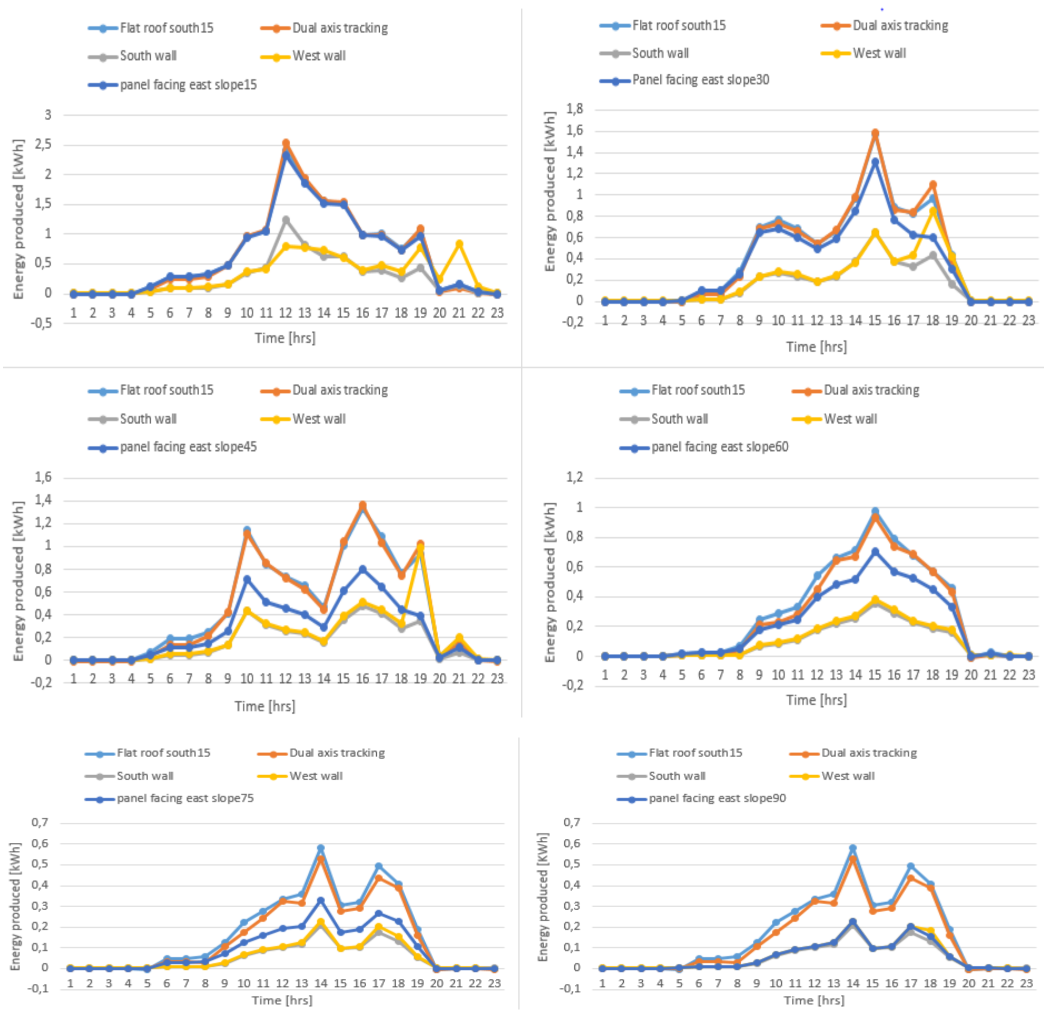

Fig. 38: PV power production comparison of panel facing east with other different systems in overcast day in Lappeenranta, Finland

7.2.2 *Panel facing west*

In this section, panel facing west for different tilted angle during overcast summer days is compared with different systems such as dual axis, flat roof system, south wall and west wall system. According to PV power production during fully overcast day from Fig.39 shows that power production from vertical wall system is minimum compare to flat horizontal system. Power production for vertical wall is same for each direction as the result shows that south facing wall and west facing wall have identical power production. Thus, during fully overcast days, power production is independent to direction (azimuth angle), but strongly dependent on tilted angle. Since, flat horizontal system has maximum power production and percentage change in power production will fall with increase in tilted angle.

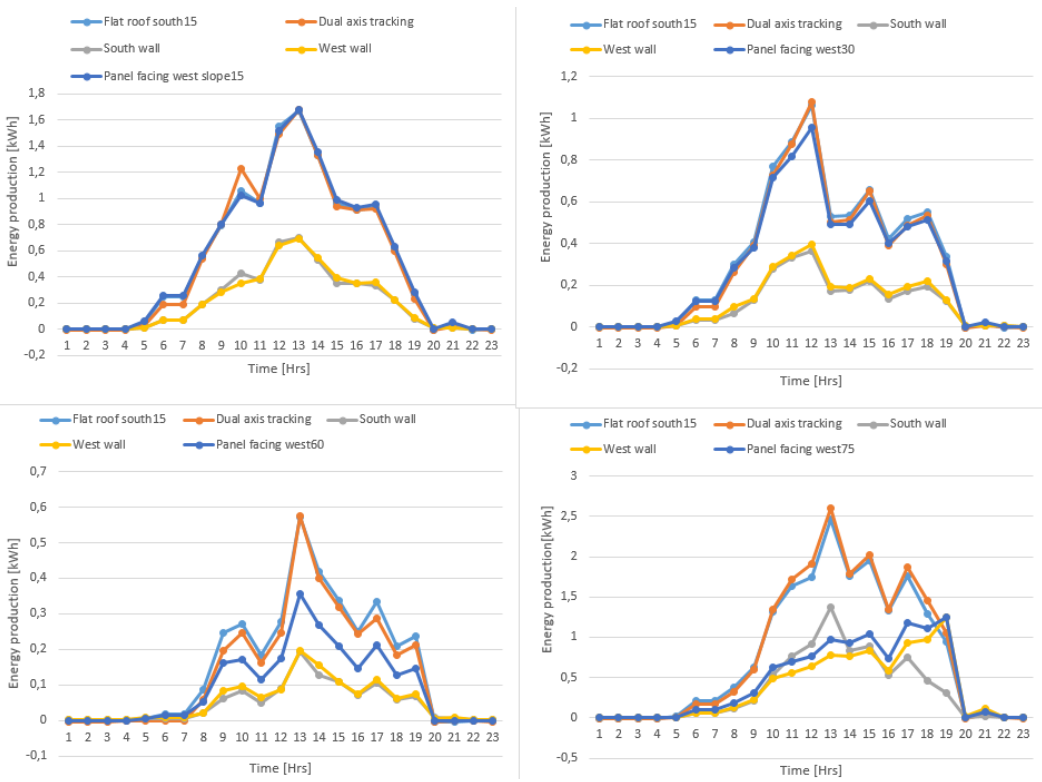

Fig. 39: PV power production comparison of panels facing west with other different system during overcast day in Lappeenranta, Finland

8 Cost Analysis

Cost analysis of the energy are mainly done with Levelized cost of electricity LCOE. Levelized cost of electricity can be calculated with total life cycle cost by total lifetime power produced.

$$LCOE = \frac{Total\ life\ cycle\ cost}{Total\ lifetime\ power\ produced} \tag{8.1}$$

Total power produced for whole lifecycle of the system is total lifetime power produced. However, power production for each year degrades. Degradation factor is denoted as δ, and output power for the year 'n' [15].

$$Q_n = Q_0 * (1 - \delta)^n \tag{8.2}$$

Where Q_n is power produced for that year and Q_0 is amount of power produced for previous year [15].

$$\sum_{j=1}^{n} Q_0 * (1 - \delta)^n \tag{8.3}$$

Therefore, LCOE eq.8.1 becomes:

$$LCOE = \frac{cost\ per\ watt * total\ installed\ power}{\sum_{j=1}^{n} Q_n * (1 - \delta)^j} \quad [8.4]$$

In case of Finland fixed tilted with 15-degree system installation cost would be 1.2 €/watt for 2016. Therefore, total cost for 10-kilowatt peak system would be 12000 euro.

According to the PVSOL simulation software, annual solar energy produced in Lappeenranta, Finland for 10 kilowatts system in first year would be 8.57 MW by fixed 15-degree tilted system. After considering 0.5 percent annual degradation factor, solar energy produced by 10-kWp system would be 164 MWh, 202MWh, and 239 MWh for 20, 25 and 30 years lifetime respectively. Therefore, cost of electricity according to Eq.8.4 would be shown in table 10 for various interest rates and different lifetime scenarios.

Table 7: Levelised cost of electricity with various interest rates for different life time

Interest rates [%]	**0**	**2**	**4**	**6**	**8**	**10**
LCOE for 20 years lifetime [€cent/kWh]	7.34	8.07	8.81	9.54	10.28	11.01
LCOE for 25 years lifetime [€cent/kWh]	5.94	6.54	7.13	7.73	8.32	8.92
LCOE for 30 years lifetime [€cent/kWh]	5.01	5.52	6.02	6.52	7.02	7.52

Levelised cost of electricity '€/kWh' for fixed 15 degree tilted system is taken as reference for each tracking system in order to analysed the cost in €/Wp. Furthermore, cost would be analysed with different interest rate. Table8 shows maximum costs for the different systems for same levelised cost of electricity €/kWh as fixed tilted 15-degree system. Furthermore, additional costs for each system in order to maintain the same levelised cost of electricity €/kWh as fixed tilted with 15-degree system is shown in table9. If additional cost for different tracking systems are more than estimated values as shown in table9, system is considered as too expensive for Lappeenranta, Finland.

Table 8: Cost analysis for different systems compare to fixed tilted 15 degree system.

Costs [€/Wp]						
Different systems	**Interest rates [%]**					
	0	**2**	**4**	**6**	**8**	**10**
Fixed OptAng45	1.48	1.62	1.79	1.96	2.16	2.38
Horiz EW	1.61	1.78	1.95	2.15	2.36	2.60

Horiz NS	1.72	1.89	2.08	2.29	2.52	2.77
Horiz NS OptAng45	2.06	2.26	2.49	2.74	3.01	3.31
Vertical OptAng60	2.02	2.22	2.45	2.69	2.96	3.26
Dual axis	2.10	2.31	2.54	2.80	3.08	3.38

Table 9: Additional costs analysis for different systems on the basic of fixed tilted with 15-degree system

Additions Costs [€]						
	Interest rates [%]					
Different systems	**0**	**2**	**4**	**6**	**8**	**10**
Fixed OptAng45	2758	3034	3458	4044	4808	5769
Horiz EW	4145	4559	5135	5889	6837	8001
Horiz NS	5195	5714	6406	7286	8375	9693
Horiz NS OptAng45	8219	9041	10065	11312	12803	14563
Vertical OptAng60	8569	9426	10489	9289	10578	12116
Dual axis	9018	9919	11031	12374	13972	15849

9 Results and Discussions

This section presents the important result from the simulations. Results of performance analysis for different locations and different weather conditions are summarized in this chapter. Furthermore, important results from solar farm and cost analysis of different tracking system on the basic of fixed tilted with 15 degree system.

9.1 Performance analysis

According to the result achieved from simulation result, incident solar energy depends both in system orientation and installation location. In addition, percentage increase in incident solar energy may not be the same for all the locations. In Lappeenranta, Finland, increase in irradiance with different tracking systems will be high as compare to other locations. Similarly, Kisumu, Kenya has minimum increase in irradiance as compare to other locations. Table10 and 11show annual percentage change in incident solar energy and energy produced respectively.

Table 10: Percentage change in annual incident solar energy for different tracking system compare to fixed tilted system

	Kisumu Kenya [%]	Kathmandu Nepal [%]	Lappeenranta Finland [%]
Horiz_axis_EW	5.87	6.27	8.77
Vertical_axis_OptAng	22.14	22.92	33.69
Horiz_axis_NS	25.64	15.32	15.32
Horiz_axis_NS_OptAng	25.64	22.92	33.44
Dual axis	29.63	28.17	38.08

Table 11: Percentage change in energy produced solar energy for different tracking system compare to fixed tilted system

	Kisumu Kenya [%]	Kathmandu Nepal [%]	Lappeenranta Finland [%]
Horiz_axis_EW	6.32	6.45	9.39
Vertical_axis_OptAng	24.26	24.62	39.37
Horiz_axis_NS	27.7	17.45	16.51
Horiz_axis_NS_OptAng	27.7	26.00	37.00
Dual axis	31.73	29.82	46.39

9.2 Tracking advantage

Tracking advantages for each tracking system is analysed with fixed tilted system. (9.1) shows that tracking advantage versus fixed optimal tilted system.

$$TA = \frac{TS - FTS}{FTS} \tag{9.1}$$

In (9.1), TA symbolizes tracking advantage, tracking systems are represented by TS and FTS denotes fix tilted system.

9.2.1 Monthly tracking advantage

Fig.39 represents the monthly tracking advantages compare to fixed tilted system for Kisumu, Kenya. Dual axis tracking advantage reach up to 36 percentage. Horizontal axis north south system has almost constant tracking advantage. During the month of January, May, June July and December where irradiance are best, tracking advantages are also increase during these months.

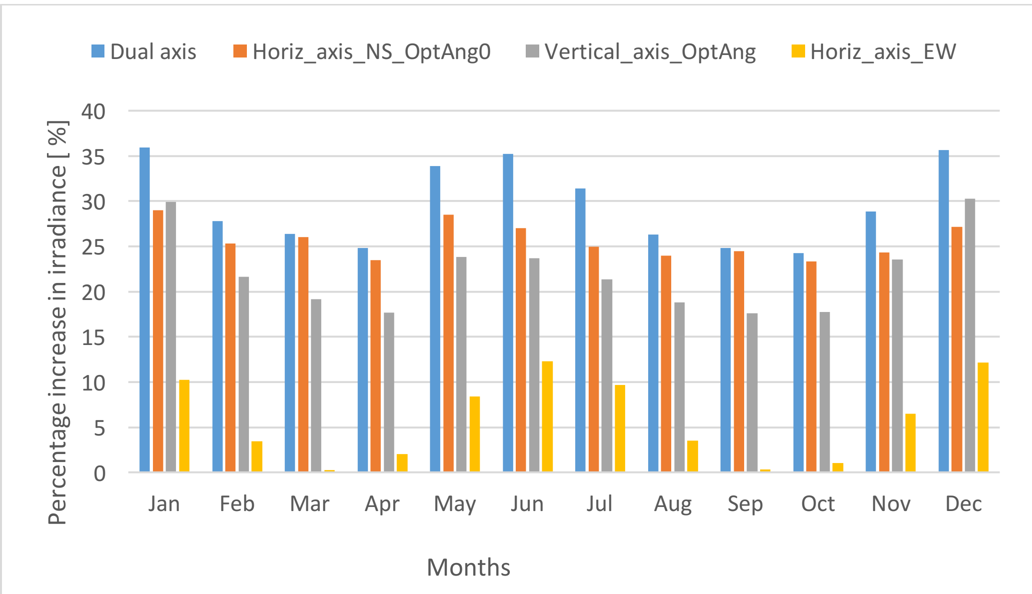

Fig. 39: Irradiance increase percent compare to fixed tilted system in Kisumu, Kenya

Monthly increase in irradiance for different tracking systems compare to fix tilted system are shown in Fig.39. During the winter months tracking advantages are more compare to summer months. During the rainy season June, July and August irradiance decrease. Since, sky is cover by thick cloud for most these months. Thus, tracking advantages are also decrease reduce in these months. Tracking advantages for horizontal axis north south with optimal tilted system has almost same irradiance compare to dual axis system almost whole months.

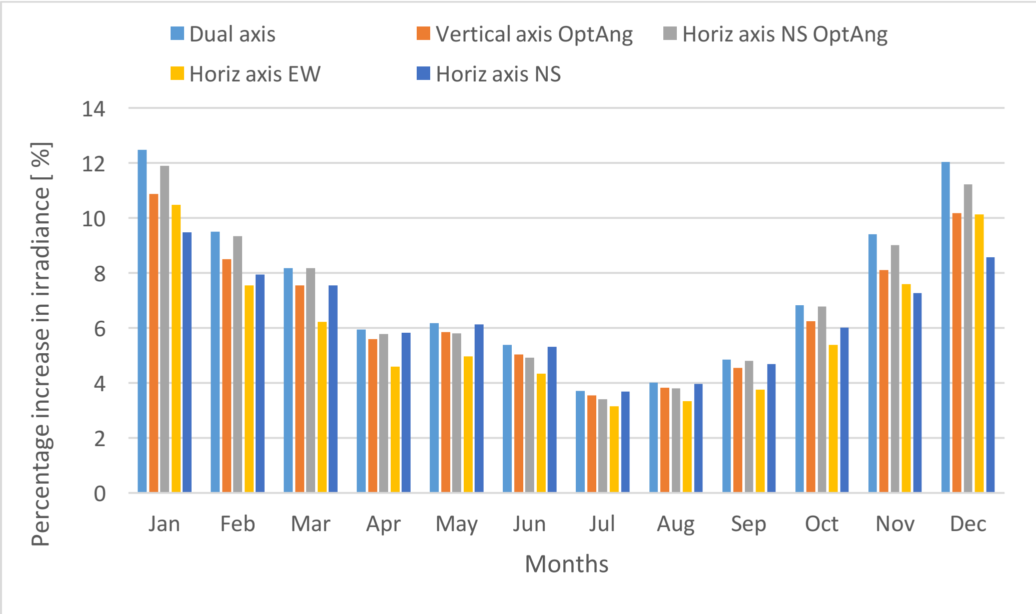

Fig. 40: Monthly increase in irradiance for different tracking system compare to fixed tilted system in Kathmandu, Nepal

Monthly tracking advantages are different system compare to fixed tilted system for Lappeenranta, Finland is shown in Fig.41. Although the horizontal axis north-south system has positive advantages with overall year analysis, there will be negative change in irradiance from September to March. Tracking advantages rises during summer months. During summer months tracking advantages rise almost 50 percent for dual axis system, vertical axis with optimal tilted system and horizontal axis north-south tilted system. There are slightly difference between horizontal axis north-south system and its tilted system during summer months. However, for other season there will be large difference in irradiance. According to incident solar energy and energy produced, single axis vertical tilted system would be better than horizontal axis north-south tilted system for those location with high latitude.

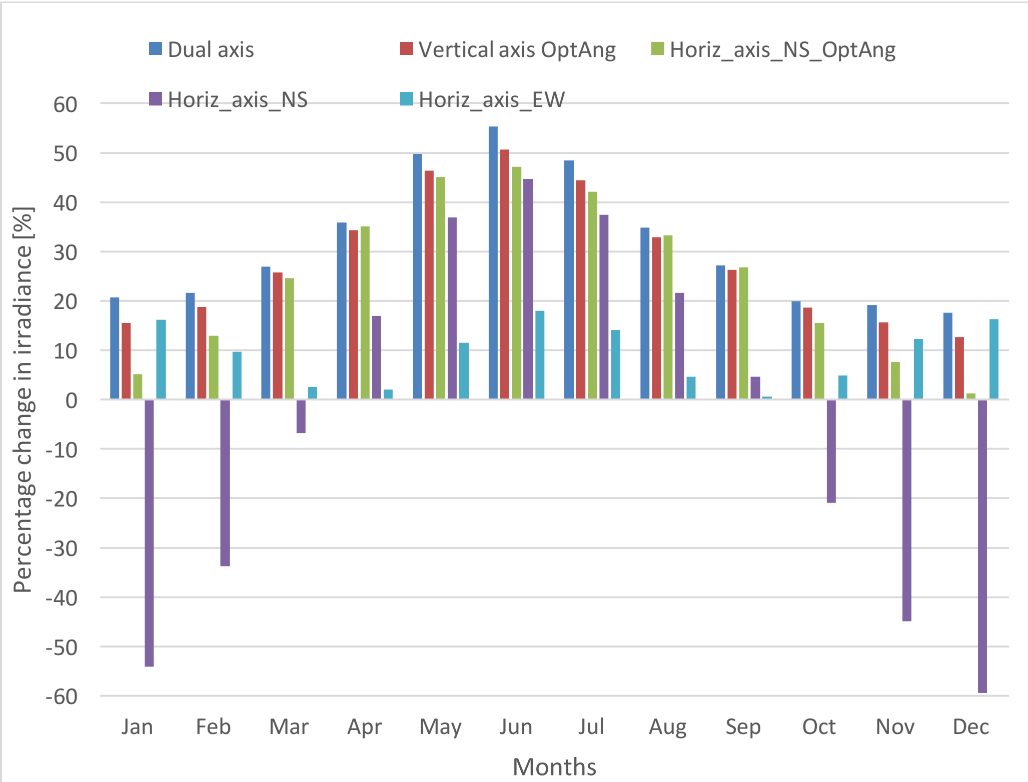

Fig. 41: Monthly percentage change in irradiance for different tracking system compare to fixed tilted system for Lappeenranta, Finland

9.2.2 *Daily tracking advantage*

According to Fig.42 shows that daily percentage change in irradiance for clear winter days. Result shows that during the noon where, there is maximum irradiance have positive change in irradiance compare to Fix tilted system. Horizontal axis north-south system has worst performance for clear winter days also during noon. Horizontal axis east-west system is good at least for clear winter days.

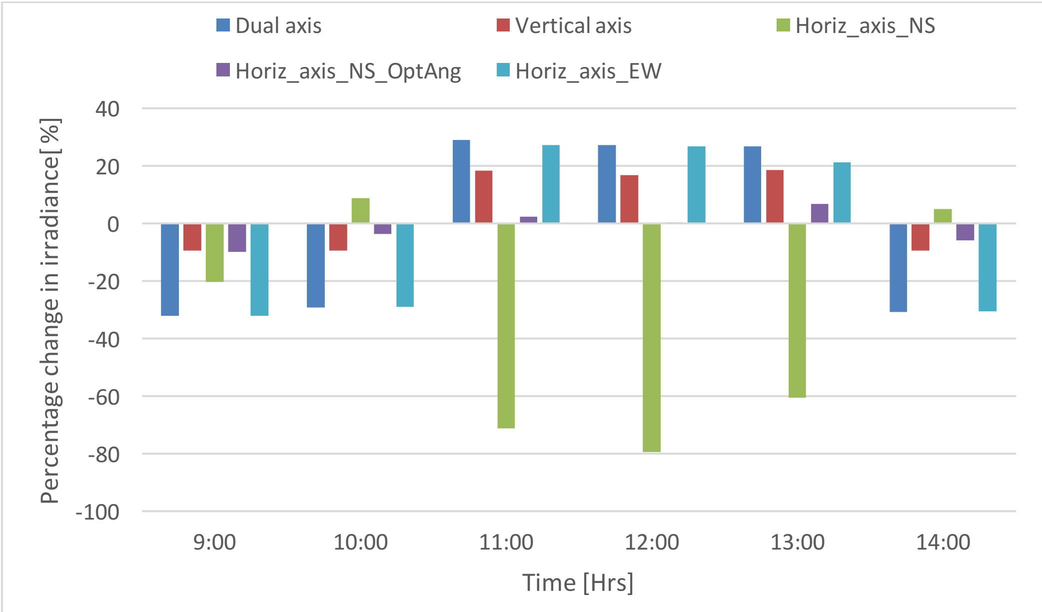

Fig. 42: Percentage change in irradiance for clear winter days in January compare to fixed tilted system in Lappeenranta, Finland

The result from Fig.43 shows that percentage change in irradiance for clear summer days for different tracking systems compare to fixed tilted system. During early morning and evening tracking advantages are extremely high 1200 to 2300 percentage. Nevertheless, during mid-day increases in irradiance are almost constant below 100 percentages. This is due to fact that, during daytime fixed tilted panel will also get enough direct radiation.

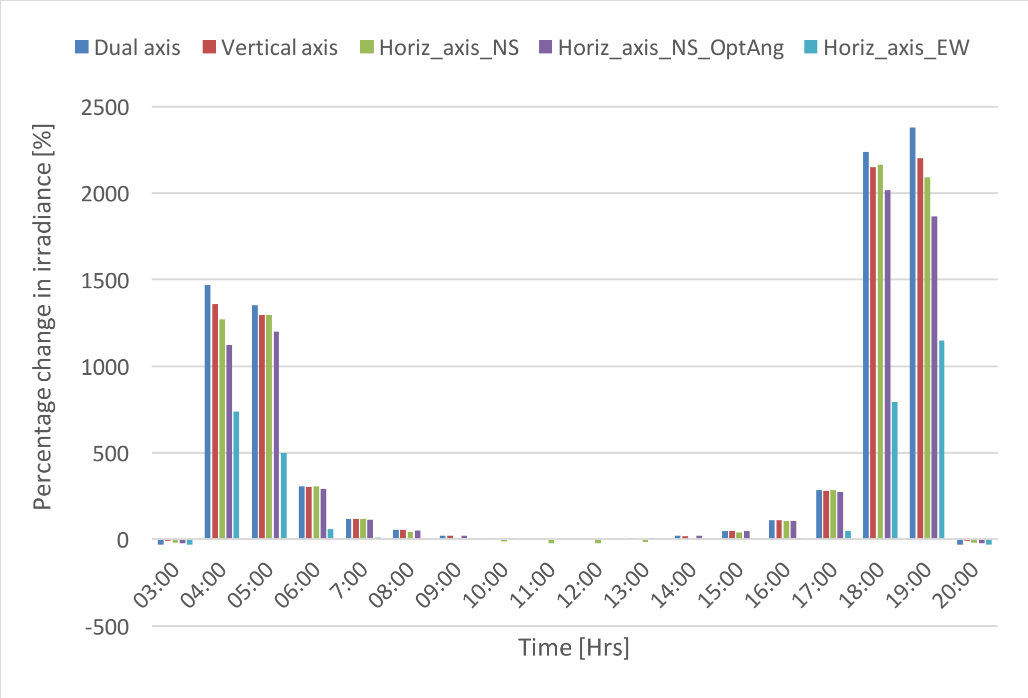

Fig. 43: Percentage change in irradiance for clear summer day in May as compare to fixed tilted system in Lappeenranta, Finland

9.3 Result from solar farm

For clear summer days, analysis show that peak power production will be in morning for panel facing east. This peak power production will shift towards early in the morning with the increase in tilted angle. Similarly, for panel facing west peak power production shift towards late evening with increase in tilted angle.

During the fully overcast days, power production will not depend upon direction of panel facing. Nevertheless, power production will strongly depend on tilted angle. Therefore, panel facing horizontally towards sky has highest power production and vertical wall has lowest.

9.4 Cost Analysis results

On the basic of 1.2€/watt for fixed tilted with 15-degree system, installation of various tracking systems cost was analysed. According to results total installation cost for fixed optimally tilted system would be 1.48€/Wp. For the various horizontal axis systems cost will varies from 1.61€/Wp to 2.10€/Wp. Costs for single axis vertical optimally tilted system and dual axis would be 2.06€/Wp and 2.1€/Wp respectively. Furthermore, these costs will increase with increase in interest rate. After considering 10 percentage interest rate for 5 years, levelised cost of electricity increased to 2.3€/Wp for fixed 45 degree tilted system.

In order to maintained same levelised cost of electricity LCOE for each systems, additional cost must be increase in the same ratio with energy production. The particular tracking systems would be too expensive if additional cost is greater than calculated cost as shown in Table9.

9.5 Recommendation for suitable tracking system

Since, tracking advantages depend up on the amount of solar irradiation and system location. According to incident solar energy and energy produced, vertical axis tilted system would be better compare to horizontal system for the location with higher latitude angle. Horizontal axis north-south system must be tilted with optimal angle for the location far from equator. For the location near to equator such as Kenya, horizontal axis north-south system would be the best both performance and financially points of view.

Similarly, PV modules can be oriented according to energy consumption habits that is peak energy demands. If the peak energy demand is in the morning, panel facing east would be best option. Similarly, panel facing west is selected for evening peak demands response. Various tilted angles can be adjusted according to demand response.

According to financial point of view, dual axis system is too expensive. Thus, horizontal axis north south optimally tilted system would be best choice followed with single axis vertical optimally tilted system. Additional cost of each tracking systems must correspond to additional energy produced by each tracking systems, in order to obtain same levelised cost of electricity for each system.

10 Conclusions

Installation of solar photovoltaic system is growing with a decreasing the cost of solar panels and batteries. Solar tracking system capture 5 to 50 percentage more solar radiation compare to fixed tilted systems. This increase percentage depend upon the type of solar tracking systems and geographical location where it installed.

In case of high latitude angle similar to Finland, single tracking system: vertical axis optimally tilted and horizontal axis north-south optimally tilted would be the best. Although horizontal axis north-south system has clear positive advantage with overall year analysis, there will be negative change in irradiance from September to March. Conversely, during these winter months irradiance itself is low. Daily tracking advantage shows that during clear summer days tracking advantage is extremely higher during early morning and late evening. However, during the noon tracking advantage is almost constant. For the location near equator, fixed system and horizontal axis system need not to be tilted. Furthermore, dual axis system would be best for all locations. Nevertheless, for economically dual axis system is too expensive.

In case of clear sky condition, it is wise to track the solar radiation. Nevertheless, during cloudy condition fixed horizontal system has highest yield. The ground reflected radiation increase according to increase in tilted angle. For northern countries during three-spring months reflection from snow increase the irradiation from 4 to 8 percentage

During clear summer days, for fixed panel facing east, peak power production would be in the morning. The peak production shift early in the morning with the increase in tilted angle. Similarly, for panel facing west, peak power production shift towards late evening with increase in tilted angle. During the fully overcast days, power production will not depend upon direction of panel facing. Nevertheless, power production will strongly depend on tilted angle. Therefore, panel facing horizontally towards sky has highest power production and vertical wall has lowest. Nevertheless, ground reflection would be maximum for vertical wall.

The installation cost of each solar tracking system is higher than fixed system. Furthermore, operating and maintenance cost would be higher due to moving parts like bearing and motors. The cost of each tracking system is analyzed with 1.2€/Wp for fixed 15 degree tilted system.

Levelised cost of electricity was analyzed for 20, 25 and 30 years lifetime with interest rates upto 10-percent. Additional cost of each tracking system was calculated in order to maintain same levelised cost of electricity as fixed 15 degree tilted system. The particular tracking systems would be too expensive if additional cost is greater than calculated results.

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Appendix I. Cost calculation of fixed 15 degree tilted system

System Inputs	
System Size [kWp]	10
1st-Year Production [kWh]	8 570
Annual Degradation	0,50 %
Total loan period [year]	5
Cost (€/Wp)	1,20

Fixed with tilted with 15 degree

Year	Energy production [kWh]	Total cost (without interest)	Total cost including interest					
			Interest rate	2 %	4 %	6 %	8 %	10 %
1	8570,00	12 000 €		13 200 €	14 400 €	15 600 €	16 800 €	18 000 €
2	8527,15							
3	8484,51	12000						
4	8442,09							
5	8399,88							
6	8357,88							
7	8316,09							
8	8274,51							
9	8233,14							
10	8191,97							
11	8151,01							
12	8110,26							
13	8069,71							
14	8029,36							
15	7989,21							
16	7949,27							
17	7909,52							
18	7869,97							
19	7830,62							
20	7791,47							
21	7752,51							
22	7713,75							
23	7675,18							
24	7636,80							
25	7598,62							
26	7560,63							
27	7522,82							
28	7485,21							
29	7447,78							
30	7410,55							
Total for 20 years lifetime	163497,64							
Total for 25 years lifetime	201874,50							
Total for 30 years lifetime	239301,50		LCOE [€cent/kWh] 20 yrs lifetime					
			7,34	8,07 €	8,81 €	9,54 €	10,28 €	11,01 €
			LCOE [€cent/kWh] 25 yrs lifetime					
			5,944	6,539	7,133	7,728	8,322	8,916
			LCOE [€cent/kWh] for 30 yrs lifetime					
			5,01	5,52	6,02	6,52	7,02	7,52

Appendix II. Cost calculation of fixed optimally 45 tilted system

System Inputs	
System Size [kWp]	10
1st-Year Production [kWh]	10 540
Annual Degradation	0,50 %
Cost for 25 years lifetime [€/kWh]	0,059
Cost for 30 years lifetime [€/kWh]	0,050

Fixed with optimal tilted angle 45 degree

Year	Energy production [kWh]	Total cost for 25 years lifetime (without interest)	Total costs for 25 years lifetime including interest					Total cost for 30 years lifetime (without interest)	Total costs for 25 years lifetime including interest				
		Interest rate	2 %	4 %	6 %	8 %	10 %		2 %	4 %	6 %	8 %	10 %
1	10540,00	627 €	689 €	758 €	834 €	917 €	1 009 €	529 €	581 €	640 €	703 €	774 €	851 €
2	10487,30	623 €	686 €	754 €	830 €	913 €	1 004 €	526 €	578 €	636 €	700 €	770 €	847 €
3	10434,86	620 €	682 €	751 €	826 €	908 €	999 €	523 €	576 €	633 €	696 €	766 €	843 €
4	10382,69	617 €	679 €	747 €	821 €	904 €	994 €	521 €	573 €	630 €	693 €	762 €	839 €
5	10330,78	614 €	676 €	743 €	817 €	899 €	989 €	518 €	570 €	627 €	690 €	758 €	834 €
6	10279,12	611 €	672 €	739 €	813 €	895 €	984 €	515 €	567 €	624 €	686 €	755 €	830 €
7	10227,73	608 €	669 €	736 €	809 €	890 €	979 €	513 €	564 €	621 €	683 €	751 €	826 €
8	10176,59	605 €	665 €	732 €	805 €	886 €	974 €	510 €	561 €	617 €	679 €	747 €	822 €
9	10125,70	602 €	662 €	728 €	801 €	881 €	969 €	508 €	559 €	614 €	676 €	743 €	818 €
10	10075,08	599 €	659 €	725 €	797 €	877 €	965 €	505 €	556 €	611 €	672 €	740 €	814 €
11	10024,70	596 €	655 €	721 €	793 €	872 €	960 €	503 €	553 €	608 €	669 €	736 €	810 €
12	9974,58	593 €	652 €	717 €	789 €	868 €	955 €	500 €	550 €	605 €	666 €	732 €	806 €
13	9924,70	590 €	649 €	714 €	785 €	864 €	950 €	498 €	547 €	602 €	662 €	729 €	802 €
14	9875,08	587 €	646 €	710 €	781 €	859 €	945 €	495 €	545 €	599 €	659 €	725 €	798 €
15	9825,71	584 €	642 €	707 €	777 €	855 €	941 €	493 €	542 €	596 €	656 €	721 €	794 €
16	9776,58	581 €	639 €	703 €	774 €	851 €	936 €	490 €	539 €	593 €	653 €	718 €	790 €
17	9727,69	578 €	636 €	700 €	770 €	847 €	931 €	488 €	537 €	590 €	649 €	714 €	786 €
18	9679,06	575 €	633 €	696 €	766 €	842 €	927 €	485 €	534 €	587 €	646 €	711 €	782 €
19	9630,66	572 €	630 €	693 €	762 €	838 €	922 €	483 €	531 €	584 €	643 €	707 €	778 €
20	9582,51	570 €	627 €	689 €	758 €	834 €	917 €	481 €	529 €	581 €	640 €	704 €	774 €
21	9534,59	567 €	623 €	686 €	754 €	830 €	913 €	478 €	526 €	579 €	636 €	700 €	770 €
22	9486,92	564 €	620 €	682 €	751 €	826 €	908 €	476 €	523 €	576 €	633 €	697 €	766 €
23	9439,49	561 €	617 €	679 €	747 €	822 €	904 €	473 €	521 €	573 €	630 €	693 €	762 €
24	9392,29	558 €	614 €	676 €	743 €	817 €	899 €	471 €	518 €	570 €	627 €	690 €	759 €
25	9345,33	556 €	611 €	672 €	739 €	813 €	895 €	469 €	515 €	567 €	624 €	686 €	755 €
26	9298,60							466 €	513 €	564 €	621 €	683 €	751 €
27	9252,11							464 €	510 €	561 €	618 €	679 €	747 €
28	9205,85							462 €	508 €	559 €	614 €	676 €	743 €
29	9159,82							459 €	505 €	556 €	611 €	673 €	740 €
30	9114,02							457 €	503 €	553 €	608 €	669 €	736 €
Total for 25 years lifetime	**248279,73**	**14758,46**	**16234,31**	**17857,74**	**19643,51**	**21607,86**	**23768,65**						
Total for 30 years lifetime	**294310,12**	**14758,46**						**14758,46**	**16234,31**	**17857,74**	**19643,51**	**21607,86**	**23768,65**
		Cost [€/Wp] 25 yrs lifetime						Cost [€/Wp] for 30 yrs lifetime					
		1,476	1,623	1,786	1,964	2,161	2,377	1,476	1,623	1,786	1,964	2,161	2,377

Appendix III. Cost calculation of horizontal axis east-west system

System Inputs	
System Size [kWp]	10
1st-Year Production [kWh]	11 530
Annual Degradation	0,50 %
Cost for 25 years lifetime [€/kWh]	0,059
Cost for 30 years lifetime [€/kWh]	0,050

Horizontal axis east west system

Year	Energy production [kWh]	Total cost for 25 years lifetime (without interest)	Total costs for 25 years lifetime including interest					Total cost for 30 years lifetime (without interest)	Total costs for 30 years lifetime including interest				
0			2 %	4 %	6 %	8 %	10 %		2 %	4 %	6 %	8 %	10 %
1	11530,00	685 €	754 €	829 €	912 €	1 003 €	1 104 €	578 €	636 €	700 €	770 €	847 €	931 €
2	11472,35	682 €	750 €	825 €	908 €	998 €	1 098 €	575 €	633 €	696 €	766 €	842 €	927 €
3	11414,99	679 €	746 €	821 €	903 €	993 €	1 093 €	572 €	630 €	693 €	762 €	838 €	922 €
4	11357,91	675 €	743 €	817 €	899 €	988 €	1 087 €	570 €	627 €	689 €	758 €	834 €	917 €
5	11301,12	672 €	739 €	813 €	894 €	984 €	1 082 €	567 €	623 €	686 €	754 €	830 €	913 €
6	11244,62	668 €	735 €	809 €	890 €	979 €	1 076 €	564 €	620 €	682 €	751 €	826 €	908 €
7	11188,40	665 €	732 €	805 €	885 €	974 €	1 071 €	561 €	617 €	679 €	747 €	821 €	904 €
8	11132,45	662 €	728 €	801 €	881 €	969 €	1 066 €	558 €	614 €	675 €	743 €	817 €	899 €
9	11076,79	658 €	724 €	797 €	876 €	964 €	1 060 €	555 €	611 €	672 €	739 €	813 €	895 €
10	11021,41	655 €	721 €	793 €	872 €	959 €	1 055 €	553 €	608 €	669 €	736 €	809 €	890 €
11	10966,30	652 €	717 €	789 €	868 €	954 €	1 050 €	550 €	605 €	665 €	732 €	805 €	886 €
12	10911,47	649 €	713 €	785 €	863 €	950 €	1 045 €	547 €	602 €	662 €	728 €	801 €	881 €
13	10856,91	645 €	710 €	781 €	859 €	945 €	1 039 €	544 €	599 €	659 €	725 €	797 €	877 €
14	10802,63	642 €	706 €	777 €	855 €	940 €	1 034 €	542 €	596 €	655 €	721 €	793 €	872 €
15	10748,61	639 €	703 €	773 €	850 €	935 €	1 029 €	539 €	593 €	652 €	717 €	789 €	868 €
16	10694,87	636 €	699 €	769 €	846 €	931 €	1 024 €	536 €	590 €	649 €	714 €	785 €	864 €
17	10641,40	633 €	696 €	765 €	842 €	926 €	1 019 €	534 €	587 €	646 €	710 €	781 €	859 €
18	10588,19	629 €	692 €	762 €	838 €	921 €	1 014 €	531 €	584 €	642 €	707 €	777 €	855 €
19	10535,25	626 €	689 €	758 €	834 €	917 €	1 009 €	528 €	581 €	639 €	703 €	773 €	851 €
20	10482,57	623 €	685 €	754 €	829 €	912 €	1 004 €	526 €	578 €	636 €	700 €	770 €	847 €
21	10430,16	620 €	682 €	750 €	825 €	908 €	999 €	523 €	575 €	633 €	696 €	766 €	842 €
22	10378,01	617 €	679 €	746 €	821 €	903 €	994 €	520 €	572 €	630 €	693 €	762 €	838 €
23	10326,12	614 €	675 €	743 €	817 €	899 €	989 €	518 €	570 €	627 €	689 €	758 €	834 €
24	10274,49	611 €	672 €	739 €	813 €	894 €	984 €	515 €	567 €	623 €	686 €	754 €	830 €
25	10223,11	608 €	668 €	735 €	809 €	890 €	979 €	513 €	564 €	620 €	682 €	751 €	826 €
26	10172,00							510 €	561 €	617 €	679 €	747 €	821 €
27	10121,14							508 €	558 €	614 €	676 €	743 €	817 €
28	10070,53							505 €	555 €	611 €	672 €	739 €	813 €
29	10020,18							502 €	553 €	608 €	669 €	736 €	809 €
30	9970,08							500 €	550 €	605 €	665 €	732 €	805 €
Total for 25 years lifetime	271600,12	16144,69	17759,16	19535,08	21488,58	23637,44	26001,19						
Total for 30 years lifetime	321954,05							16144,69	17759,16	19535,08	21488,58	23637,44	26001,19
		Cost [€/WP] 25 yrs lifetime						Cost[€/Wp] for 30 yrs lifetime					
		1,61446908	1,775916	1,953508	2,148858	2,363744	2,600119	1,61446908	1,775916	1,953508	2,148858	2,363744	2,600119

Appendix IV. Cost calculation of horizontal axis North- south system

System Inputs	
System Size [kWp]	10
1st-Year Production [kWh]	12 280
Annual Degradation	0,50 %
Cost for 25 years lifetime [€/kWh]	0,059
Cost for 30 years lifetime [€/kWh]	0,050

Horizontal axis North South system

Year	Energy production [kWh]	Total cost for 25 years lifetime (without interest)	Total costs for 25 years lifetime including interest					Total cost for 30 years lifetime (without interest)	Total costs for 30 years lifetime including interest				
0			2 %	4 %	6 %	8 %	10 %		2 %	4 %	6 %	8 %	10 %
1	12280,00	730 €	803 €	883 €	972 €	1 069 €	1 176 €	616 €	677 €	745 €	820 €	902 €	992 €
2	12218,60	726 €	799 €	879 €	967 €	1 063 €	1 170 €	613 €	674 €	741 €	816 €	897 €	987 €
3	12157,51	723 €	795 €	874 €	962 €	1 058 €	1 164 €	610 €	671 €	738 €	811 €	893 €	982 €
4	12096,72	719 €	791 €	870 €	957 €	1 053 €	1 158 €	607 €	667 €	734 €	807 €	888 €	977 €
5	12036,24	715 €	787 €	866 €	952 €	1 048 €	1 152 €	604 €	664 €	730 €	803 €	884 €	972 €
6	11976,05	712 €	783 €	861 €	948 €	1 042 €	1 147 €	601 €	661 €	727 €	799 €	879 €	967 €
7	11916,17	708 €	779 €	857 €	943 €	1 037 €	1 141 €	598 €	657 €	723 €	795 €	875 €	962 €
8	11856,59	705 €	775 €	853 €	938 €	1 032 €	1 135 €	595 €	654 €	719 €	791 €	870 €	958 €
9	11797,31	701 €	771 €	849 €	933 €	1 027 €	1 129 €	592 €	651 €	716 €	787 €	866 €	953 €
10	11738,32	698 €	768 €	844 €	929 €	1 022 €	1 124 €	589 €	647 €	712 €	783 €	862 €	948 €
11	11679,63	694 €	764 €	840 €	924 €	1 016 €	1 118 €	586 €	644 €	709 €	780 €	858 €	943 €
12	11621,23	691 €	760 €	836 €	919 €	1 011 €	1 113 €	583 €	641 €	705 €	776 €	853 €	939 €
13	11563,13	687 €	756 €	832 €	915 €	1 006 €	1 107 €	580 €	638 €	702 €	772 €	849 €	934 €
14	11505,31	684 €	752 €	828 €	910 €	1 001 €	1 101 €	577 €	635 €	698 €	768 €	845 €	929 €
15	11447,79	680 €	749 €	823 €	906 €	996 €	1 096 €	574 €	631 €	695 €	764 €	840 €	925 €
16	11390,55	677 €	745 €	819 €	901 €	991 €	1 090 €	571 €	628 €	691 €	760 €	836 €	920 €
17	11333,59	674 €	741 €	815 €	897 €	986 €	1 085 €	568 €	625 €	688 €	756 €	832 €	915 €
18	11276,93	670 €	737 €	811 €	892 €	981 €	1 080 €	565 €	622 €	684 €	753 €	828 €	911 €
19	11220,54	667 €	734 €	807 €	888 €	977 €	1 074 €	563 €	619 €	681 €	749 €	824 €	906 €
20	11164,44	664 €	730 €	803 €	883 €	972 €	1 069 €	560 €	616 €	677 €	745 €	820 €	902 €
21	11108,62	660 €	726 €	799 €	879 €	967 €	1 063 €	557 €	613 €	674 €	741 €	816 €	897 €
22	11053,07	657 €	723 €	795 €	875 €	962 €	1 058 €	554 €	610 €	671 €	738 €	812 €	893 €
23	10997,81	654 €	719 €	791 €	870 €	957 €	1 053 €	551 €	607 €	667 €	734 €	807 €	888 €
24	10942,82	650 €	716 €	787 €	866 €	952 €	1 048 €	549 €	604 €	664 €	730 €	803 €	884 €
25	10888,11	647 €	712 €	783 €	861 €	948 €	1 042 €	546 €	601 €	661 €	727 €	799 €	879 €
26	10833,66							543 €	598 €	657 €	723 €	795 €	875 €
27	10779,50							541 €	595 €	654 €	719 €	791 €	871 €
28	10725,60							538 €	592 €	651 €	716 €	787 €	866 €
29	10671,97							535 €	589 €	648 €	712 €	784 €	862 €
30	10618,61							532 €	586 €	644 €	709 €	780 €	858 €
Total for 25 years lifetime	**289267,08**	**17194,87**	**18914,35**	**20805,79**	**22886,37**	**25175,00**	**27692,50**						
Total for 30 years lifetime	**342896,42**							**17194,87**	**18914,35**	**20805,79**	**22886,37**	**25175,00**	**27692,50**
		Cost[€/Wp] for 30 yrs lifetime						Cost[€/Wp] for 30 yrs lifetime					
		1,719486581	1,891435	2,080579	2,288637	2,5175	2,76925	1,719486581	1,891435	2,080579	2,288637	2,5175	2,76925

Appendix V. Cost calculation of horizontal axis north-south optimally 45 tilted system

System Inputs	
System Size [kWp]	10
1st-Year Production [kWh]	14 440
Annual Degradation	0,50 %
Cost for 25 years lifetime [€/kWh]	0,059
Cost for 30 years lifetime [€/kWh]	0,050

Horizontal axis North South with Optimal tilted angle 45 degree

Year	Energy production [kWh]	Total cost for 25 years lifetime (without interest)	Total costs for 25 years lifetime including interest					Total cost for 30 years lifetime (without interest)	Total costs for 30 years lifetime including interest				
0			2 %	4 %	6 %	8 %	10 %		2 %	4 %	6 %	8 %	10 %
1	14440,00	858 €	944 €	1 039 €	1 142 €	1 257 €	1 382 €	724 €	797 €	876 €	964 €	1 060 €	1 166 €
2	14367,80	854 €	939 €	1 033 €	1 137 €	1 250 €	1 375 €	720 €	793 €	872 €	959 €	1 055 €	1 160 €
3	14295,96	850 €	935 €	1 028 €	1 131 €	1 244 €	1 369 €	717 €	789 €	867 €	954 €	1 050 €	1 155 €
4	14224,48	846 €	930 €	1 023 €	1 125 €	1 238 €	1 362 €	713 €	785 €	863 €	949 €	1 044 €	1 149 €
5	14153,36	841 €	925 €	1 018 €	1 120 €	1 232 €	1 355 €	710 €	781 €	859 €	945 €	1 039 €	1 143 €
6	14082,59	837 €	921 €	1 013 €	1 114 €	1 226 €	1 348 €	706 €	777 €	854 €	940 €	1 034 €	1 137 €
7	14012,18	833 €	916 €	1 008 €	1 109 €	1 219 €	1 341 €	703 €	773 €	850 €	935 €	1 029 €	1 132 €
8	13942,12	829 €	912 €	1 003 €	1 103 €	1 213 €	1 335 €	699 €	769 €	846 €	931 €	1 024 €	1 126 €
9	13872,41	825 €	907 €	998 €	1 098 €	1 207 €	1 328 €	696 €	765 €	842 €	926 €	1 018 €	1 120 €
10	13803,05	820 €	903 €	993 €	1 092 €	1 201 €	1 321 €	692 €	761 €	838 €	921 €	1 013 €	1 115 €
11	13734,03	816 €	898 €	988 €	1 087 €	1 195 €	1 315 €	689 €	758 €	833 €	917 €	1 008 €	1 109 €
12	13665,36	812 €	894 €	983 €	1 081 €	1 189 €	1 308 €	685 €	754 €	829 €	912 €	1 003 €	1 104 €
13	13597,03	808 €	889 €	978 €	1 076 €	1 183 €	1 302 €	682 €	750 €	825 €	908 €	998 €	1 098 €
14	13529,05	804 €	885 €	973 €	1 070 €	1 177 €	1 295 €	678 €	746 €	821 €	903 €	993 €	1 093 €
15	13461,40	800 €	880 €	968 €	1 065 €	1 172 €	1 289 €	675 €	743 €	817 €	898 €	988 €	1 087 €
16	13394,10	796 €	876 €	963 €	1 060 €	1 166 €	1 282 €	672 €	739 €	813 €	894 €	983 €	1 082 €
17	13327,13	792 €	871 €	959 €	1 054 €	1 160 €	1 276 €	668 €	735 €	809 €	890 €	978 €	1 076 €
18	13260,49	788 €	867 €	954 €	1 049 €	1 154 €	1 269 €	665 €	731 €	805 €	885 €	974 €	1 071 €
19	13194,19	784 €	863 €	949 €	1 044 €	1 148 €	1 263 €	662 €	728 €	801 €	881 €	969 €	1 066 €
20	13128,22	780 €	858 €	944 €	1 039 €	1 143 €	1 257 €	658 €	724 €	797 €	876 €	964 €	1 060 €
21	13062,58	776 €	854 €	940 €	1 033 €	1 137 €	1 251 €	655 €	721 €	793 €	872 €	959 €	1 055 €
22	12997,26	773 €	850 €	935 €	1 028 €	1 131 €	1 244 €	652 €	717 €	789 €	867 €	954 €	1 050 €
23	12932,28	769 €	846 €	930 €	1 023 €	1 125 €	1 238 €	649 €	713 €	785 €	863 €	949 €	1 044 €
24	12867,61	765 €	841 €	926 €	1 018 €	1 120 €	1 232 €	645 €	710 €	781 €	859 €	945 €	1 039 €
25	12803,28	761 €	837 €	921 €	1 013 €	1 114 €	1 226 €	642 €	706 €	777 €	855 €	940 €	1 034 €
26	12739,26							639 €	703 €	773 €	850 €	935 €	1 029 €
27	12675,56							636 €	699 €	769 €	846 €	931 €	1 024 €
28	12612,19							632 €	696 €	765 €	842 €	926 €	1 019 €
29	12549,13							629 €	692 €	761 €	838 €	921 €	1 013 €
30	12486,38							626 €	689 €	758 €	833 €	917 €	1 008 €
Total for 25 years lifetime	**340147,94**	**20219,37**	**22241,31**	**24465,44**	**26911,98**	**29603,18**	**32563,50**						
Total for 30 years lifetime	**403210,45**							**20219,37**	**22241,31**	**24465,44**	**26911,98**	**29603,18**	**32563,50**
		Cost[€/Wp] for 30 yrs lifetime						Cost[€/Wp] for 30 yrs lifetime					
		2,021936989	2,224131	2,446544	2,691198	2,960318	3,25635	2,02193699	2,224131	2,4465438	2,691198	2,960318	3,25635

Appendix VI. Cost calculation of vertical axis optimally tilted system

System Inputs	
System Size [kWp]	10
1st-Year Production [kWh]	14 690
Annual Degradation	0,50 %
Cost for 25 years lifetime [€/kWh]	0,059
Cost for 30 years lifetime [€/kWh]	0,050

Vertical axis with optimal tilted angle 60 degree

Year	Energy production [kWh]	Total cost for 25 years lifetime (without interest)	Total costs for 25 years lifetime including interest					Total cost for 30 years lifetime (without interest)	Total costs for 30 years lifetime including interest				
0			2 %	4 %	6 %	8 %	10 %		2 %	4 %	6 %	8 %	10 %
1	14 690	873 €	961 €	1 057 €	1 162 €	1 278 €	1 406 €	737 €	810 €	891 €	980 €	1 079 €	1 186 €
2	14616,55	869 €	956 €	1 051 €	1 156 €	1 272 €	1 399 €	733 €	806 €	887 €	976 €	1 073 €	1 180 €
3	14543,47	865 €	951 €	1 046 €	1 151 €	1 266 €	1 392 €	729 €	802 €	882 €	971 €	1 068 €	1 175 €
4	14470,75	860 €	946 €	1 041 €	1 145 €	1 259 €	1 385 €	726 €	798 €	878 €	966 €	1 062 €	1 169 €
5	14398,40	856 €	941 €	1 036 €	1 139 €	1 253 €	1 378 €	722 €	794 €	874 €	961 €	1 057 €	1 163 €
6	14326,40	852 €	937 €	1 030 €	1 133 €	1 247 €	1 372 €	718 €	790 €	869 €	956 €	1 052 €	1 157 €
7	14254,77	847 €	932 €	1 025 €	1 128 €	1 241 €	1 365 €	715 €	786 €	865 €	951 €	1 047 €	1 151 €
8	14183,50	843 €	927 €	1 020 €	1 122 €	1 234 €	1 358 €	711 €	782 €	861 €	947 €	1 041 €	1 145 €
9	14112,58	839 €	923 €	1 015 €	1 117 €	1 228 €	1 351 €	708 €	778 €	856 €	942 €	1 036 €	1 140 €
10	14042,02	835 €	918 €	1 010 €	1 111 €	1 222 €	1 344 €	704 €	775 €	852 €	937 €	1 031 €	1 134 €
11	13971,81	831 €	914 €	1 005 €	1 105 €	1 216 €	1 338 €	701 €	771 €	848 €	933 €	1 026 €	1 128 €
12	13901,95	826 €	909 €	1 000 €	1 100 €	1 210 €	1 331 €	697 €	767 €	844 €	928 €	1 021 €	1 123 €
13	13832,44	822 €	904 €	995 €	1 094 €	1 204 €	1 324 €	694 €	763 €	839 €	923 €	1 016 €	1 117 €
14	13763,28	818 €	900 €	990 €	1 089 €	1 198 €	1 318 €	690 €	759 €	835 €	919 €	1 010 €	1 112 €
15	13694,46	814 €	895 €	985 €	1 083 €	1 192 €	1 311 €	687 €	755 €	831 €	914 €	1 005 €	1 106 €
16	13625,99	810 €	891 €	980 €	1 078 €	1 186 €	1 304 €	683 €	752 €	827 €	909 €	1 000 €	1 100 €
17	13557,86	806 €	887 €	975 €	1 073 €	1 180 €	1 298 €	680 €	748 €	823 €	905 €	995 €	1 095 €
18	13490,07	802 €	882 €	970 €	1 067 €	1 174 €	1 291 €	676 €	744 €	819 €	900 €	990 €	1 089 €
19	13422,62	798 €	878 €	965 €	1 062 €	1 168 €	1 285 €	673 €	740 €	814 €	896 €	985 €	1 084 €
20	13355,51	794 €	873 €	961 €	1 057 €	1 162 €	1 279 €	670 €	737 €	810 €	891 €	981 €	1 079 €
21	13288,73	790 €	869 €	956 €	1 051 €	1 157 €	1 272 €	666 €	733 €	806 €	887 €	976 €	1 073 €
22	13222,28	786 €	865 €	951 €	1 046 €	1 151 €	1 266 €	663 €	729 €	802 €	883 €	971 €	1 068 €
23	13156,17	782 €	860 €	946 €	1 041 €	1 145 €	1 259 €	660 €	726 €	798 €	878 €	966 €	1 062 €
24	13090,39	778 €	856 €	942 €	1 036 €	1 139 €	1 253 €	656 €	722 €	794 €	874 €	961 €	1 057 €
25	13024,94	774 €	852 €	937 €	1 031 €	1 134 €	1 247 €	653 €	718 €	790 €	869 €	956 €	1 052 €
26	12959,82							650 €	715 €	786 €	865 €	951 €	1 047 €
27	12895,02							647 €	711 €	782 €	861 €	947 €	1 041 €
28	12830,54							643 €	708 €	779 €	856 €	942 €	1 036 €
29	12766,39							640 €	704 €	775 €	852 €	937 €	1 031 €
30	12702,56							637 €	701 €	771 €	848 €	933 €	1 026 €
Total for 25 years lifetime	**346036,93**	**20569,43**	**22626,37**	**24889,01**	**27377,91**	**30115,70**	**33127,27**						
Total for 30 years lifetime	**410191,24**							**20569,43**	**22626,37**	**24889,01**	**27377,91**	**30115,70**	**33127,27**
		Cost[€/Wp] for 30 yrs lifetime						Cost[€/Wp] for 30 yrs lifetime					
		2,056942824	2,262637	2,488901	2,737791	3,01157	3,312727	2,05694282	2,262637	2,488901	2,737791	3,01157	3,312727

Appendix VII. Cost calculation of dual axis system

System Inputs	
System Size [kWp]	10
1st-Year Production [kWh]	15 010
Annual Degradation	0,50 %
Cost for 25 years lifetime [€/kWh]	0,059
Cost for 30 years lifetime [€/kWh]	0,050

Dual axis system

Year	Energy production [kWh]	Total cost for 25 years lifetime (without interest)	Total costs for 25 years lifetime including interest					Total cost for 30 years lifetime (without interest)	Total costs for 30 years lifetime including interest				
0			2 %	4 %	6 %	8 %	10 %		2 %	4 %	6 %	8 %	10 %
1	15 010	892 €	981 €	1 080 €	1 188 €	1 306 €	1 437 €	753 €	828 €	911 €	1 002 €	1 102 €	1 212 €
2	14934,95	888 €	977 €	1 074 €	1 182 €	1 300 €	1 430 €	749 €	824 €	906 €	997 €	1 097 €	1 206 €
3	14860,28	883 €	972 €	1 069 €	1 176 €	1 293 €	1 423 €	745 €	820 €	902 €	992 €	1 091 €	1 200 €
4	14785,97	879 €	967 €	1 063 €	1 170 €	1 287 €	1 416 €	741 €	816 €	897 €	987 €	1 086 €	1 194 €
5	14712,04	875 €	962 €	1 058 €	1 164 €	1 280 €	1 408 €	738 €	812 €	893 €	982 €	1 080 €	1 188 €
6	14638,48	870 €	957 €	1 053 €	1 158 €	1 274 €	1 401 €	734 €	807 €	888 €	977 €	1 075 €	1 182 €
7	14565,29	866 €	952 €	1 048 €	1 152 €	1 268 €	1 394 €	730 €	803 €	884 €	972 €	1 069 €	1 176 €
8	14492,46	861 €	948 €	1 042 €	1 147 €	1 261 €	1 387 €	727 €	799 €	879 €	967 €	1 064 €	1 170 €
9	14420,00	857 €	943 €	1 037 €	1 141 €	1 255 €	1 380 €	723 €	795 €	875 €	962 €	1 059 €	1 165 €
10	14347,90	853 €	938 €	1 032 €	1 135 €	1 249 €	1 374 €	719 €	791 €	871 €	958 €	1 053 €	1 159 €
11	14276,16	849 €	933 €	1 027 €	1 130 €	1 242 €	1 367 €	716 €	787 €	866 €	953 €	1 048 €	1 153 €
12	14204,78	844 €	929 €	1 022 €	1 124 €	1 236 €	1 360 €	712 €	784 €	862 €	948 €	1 043 €	1 147 €
13	14133,76	840 €	924 €	1 017 €	1 118 €	1 230 €	1 353 €	709 €	780 €	858 €	943 €	1 038 €	1 141 €
14	14063,09	836 €	920 €	1 011 €	1 113 €	1 224 €	1 346 €	705 €	776 €	853 €	939 €	1 032 €	1 136 €
15	13992,77	832 €	915 €	1 006 €	1 107 €	1 218 €	1 340 €	702 €	772 €	849 €	934 €	1 027 €	1 130 €
16	13922,81	828 €	910 €	1 001 €	1 102 €	1 212 €	1 333 €	698 €	768 €	845 €	929 €	1 022 €	1 124 €
17	13853,20	823 €	906 €	996 €	1 096 €	1 206 €	1 326 €	695 €	764 €	841 €	925 €	1 017 €	1 119 €
18	13783,93	819 €	901 €	991 €	1 091 €	1 200 €	1 320 €	691 €	760 €	836 €	920 €	1 012 €	1 113 €
19	13715,01	815 €	897 €	986 €	1 085 €	1 194 €	1 313 €	688 €	757 €	832 €	915 €	1 007 €	1 108 €
20	13646,44	811 €	892 €	982 €	1 080 €	1 188 €	1 306 €	684 €	753 €	828 €	911 €	1 002 €	1 102 €
21	13578,20	807 €	888 €	977 €	1 074 €	1 182 €	1 300 €	681 €	749 €	824 €	906 €	997 €	1 097 €
22	13510,31	803 €	883 €	972 €	1 069 €	1 176 €	1 293 €	677 €	745 €	820 €	902 €	992 €	1 091 €
23	13442,76	799 €	879 €	967 €	1 064 €	1 170 €	1 287 €	674 €	742 €	816 €	897 €	987 €	1 086 €
24	13375,55	795 €	875 €	962 €	1 058 €	1 164 €	1 280 €	671 €	738 €	812 €	893 €	982 €	1 080 €
25	13308,67	791 €	870 €	957 €	1 053 €	1 158 €	1 274 €	667 €	734 €	808 €	888 €	977 €	1 075 €
26	13242,13							664 €	730 €	803 €	884 €	972 €	1 069 €
27	13175,92							661 €	727 €	799 €	879 €	967 €	1 064 €
28	13110,04							657 €	723 €	795 €	875 €	963 €	1 059 €
29	13044,49							654 €	720 €	791 €	871 €	958 €	1 053 €
30	12979,26							651 €	716 €	788 €	866 €	953 €	1 048 €
Total for 25 years lifetime	**353574,83**	**21017,50**	**23119,25**	**25431,18**	**27974,30**	**30771,73**	**33848,90**						
Total for 30 years lifetime	**419126,66**							**21017,50**	**23119,25**	**25431,18**	**27974,30**	**30771,73**	**33848,90**
		Cost[€/Wp] for 30 yrs lifetime						Cost[€/Wp] for 30 yrs lifetime					
		2,10175029	2,311925	2,543118	2,79743	3,077173	3,38489	2,101750292	2,311925321	2,543118	2,79743	3,077173	3,38489