DETERMINATION OF ANNUAL OPTIMAL ALTITUDE AND AZIMUTH ANGLES OF FIXED TILT SOLAR COLLECTORS IN THE CONTINENTAL UNITED STATES USING THE NATIONAL SOLAR RADIATION DATABASE

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ABSTRACT

Maps of the continental United States are presented which quantify the spatial variation in annual optimal altitude and azimuth angles of fixed tilt solar collectors. Maps are also presented which show the solar radiation incident upon optimally tilted solar collectors. Incident solar radiation on this optimally tilted surface is compared to a south facing latitude tilted collector. The resultant maps have been generated utilizing meteorological data made available in the National Solar Radiation Database using 758 of the class 1 and class 2 stations. For each of the 758 locations processed in developing these maps, sensitivity plots have also been generated which quantify the variation in average incident solar radiation with respect to solar collector azimuth and altitude angles. A sensitivity plot for the Cincinnati/Northern Kentucky Airport is presented in the written paper and the entire set of 758 sensitivity plots are available for review at the website http://AndySchroder.com.

1. INTRODUCTION

In many installations of solar collectors, it is desired to mount the collector at a fixed orientation, rather than utilizing a tracking mechanism that keeps the collector surface orthogonal to the incident beam radiation. This may be due to architectural integration of solar collectors or due to marginal economic return of a solar collector tracking mechanism in geographic regions where a high percentage of the incident solar radiation may be diffuse radiation.

In the case of architecturally integrated solar collectors, precise determination of annual optimal orientation, and the sensitivity of average incident radiation to this optimal orientation can strongly influence the overall proportions of the building. The complexity of bracketry utilized in mounting solar collectors which are roof mounted, but not necessarily architecturally integrated will depend on the sensitivity to the annual optimum fixed tilt solar collector orientation

The typical rule of thumb indicates that the solar collector should be mounted such that the collector altitude angle is equal to the latitude angle of the installation site and its azimuth angle is south facing. Doing so will place the collector plane parallel to a plane tangent to the point at the equator with the same longitude. Christensen and Barker showed that this rule of thumb is indeed inaccurate due to weather effects[1]. This work also focuses on determining the optimal solar collector orientation of non-concentrating, fixed tilt solar collectors, but with special care taken to incorporate higher spatial and temporal resolution solar radiation data.

2. METHODOLOGY

Total solar radiation on a tilted solar collector surface is comprised of both beam radiation and diffuse radiation. The diffuse radiation incident on the surface can be broken down into two main sources: diffuse radiation from the sky and diffuse radiation reflected from the ground. Liu and Jordan proposed that these two diffuse radiation sources be assumed isotropic and that the total radiation on a tilted surface is the sum of the beam radiation, diffuse radiation from the sky, and the ground reflected diffuse radiation[2]. Approximating the ground as an infinite horizontal plane, view factors for these diffuse radiation sources on the collector from the sky and the ground can be represented by

$$F_{c-s} = \frac{1 + cos(\beta)}{2} \quad (1)$$

and

$$F_{c-g} = \frac{1 - cos(\beta)}{2} \quad (2)$$

respectively, where β represents the collector altitude angle, the slope of the collector surface with respect to the horizontal[3]. Ground reflected diffuse radiation is determined utilizing the total radiation incident upon the ground, and the surface albedo, ρ_g, the diffuse ground reflection coefficient. A relationship for the incidence angle of beam radiation on a tilted surface can be derived utilizing geometric principles.

$$\theta = arccos(cos(\theta_z)cos(\beta) + sin(\theta_z)sin(\beta)cos(\gamma_s - \gamma)) \quad (3)$$

γ_s represents the solar azimuth angle, γ represents the collector azimuth angle, and θ_z represents the solar zenith angle, the incidence angle of beam radiation on a horizontal surface. For further clarification on concepts of solar geometry, the reader is encouraged to review the classic text of Duffie and Beckman entitled *Solar Engineering of Thermal Processes*[4].

Assuming that the solar collector surface is unobstructed by any nearby building or building feature, vegetation, geological formation, or a nearby solar collector, the relationships above can be utilized and the total incident solar radiation on a tilted surface can be represented by

$$I_t = I_b cos(\theta) + I_d F_{c-s} + \rho_g (I_b cos(\theta_z) + I_d) F_{c-g} \quad (4)$$

where I_b is the beam radiation and I_d is the diffuse radiation. For a fixed tilt collector, β and γ are constant with time. I_d, I_b, θ_z, γ_s, and ρ_g are a function of time and location. I_d and I_b are highly dependent upon weather conditions.

A computer code utilizing the Octave/MATLAB interpreting language was developed to determine the average total radiation on a tilted surface, I_t. The National Solar Radiation Database (NSRDB) 1991-2005 update was utilized for unknown parameters I_d, I_b, θ_z, γ_s, and ρ_g. The NSRDB is an hourly dataset of solar radiation and climatology data for 1,454 stations throughout the United States of America from 1991 to 2005[5]. Data was processed for 758 class 1 and class 2 stations available in the NSRDB. Data from the remaining 696 stations were either outside of the continental United States or were class 3 stations and were not processed due to the depreciated data quality compared to class 1 and class 2 stations.

It should be noted that the surface albedo is highly spatially and temporally dependent. A nearby lake, green space, blacktop, or concrete can all have varying levels of ground reflectivity. Recent snowfall can also change the surface albedo dramatically within a very short period of time. The temporal and spatial variation in the surface albedo presented in the NSRDB exhibit local spatial and temporal averages (based upon the seasonal and geographic region) and has not rigorously accounted for the true spatial and temporal variation.

For each of the 758 class 1 and class 2 stations processed, solar collector orientation was varied from collector tilts, β, and surface azimuth angles, γ, from $-90°$ to $+90°$ at $5°$ intervals. At each solar collector orientation, total radiation, I_t was calculated for each hour from 1991 to 2005. An average incident solar radiation was computed for each orientation, and the optimal orientation was determined based upon the collector slope and azimuth angle with the highest average incident radiation. The process was then repeated for all 758 locations for collector slopes and azimuth angles ranging from $-10°$ to $+10°$ of the optimal collector orientation, at $1°$ intervals. This was done in order to more precisely determine the optimal azimuth angle and to gain a higher resolution near the optimal collector tilt.

Results were interpolated to fill the entire continental United States and were then were plotted using the software tool gnuplot. State boundary coordinates were utilized from the U.S. Census Bureau Geography Division's cartographic boundary files which are made freely available on the Census Bureau's website[6].

The results assume that future weather conditions will be statistically equivalent to the weather conditions from 1991 to 2005. In reality, there will be some variation in the weather characteristics in the future which may effect the applicability of the results. The results are meant to provide the best information possible in order to influence the design of future solar energy systems, but the results must be interpreted with appropriate engineering judgement.

3. RESULTS AND DISCUSSION

Results are presented in figures 1 thru 6. Figures 1 and 2 present optimal collector altitude and azimuth angles which were determined using the present technique. For a south facing solar collector, a negative azimuth angle indicates an eastern facing orientation and a positive azimuth angle indicates a western facing orientation. Incident solar radiation on the optimally tilted solar collector surface is presented in figure 3. The percentage gained by placing a collector at the optimal tilt, rather than south facing at the latitude tilt (which has been the traditional rule of thumb) is presented in figure 4. Figure 5 shows the difference between the latitude tilt and the optimal tilt. It is evident from these maps that the optimal tilt can be significantly different from the latitude tilt. However, the percentage gained by placing the solar collector at these optimal tilts is very small for most locations.

In all figures, the location of each station processed from the NSRDB is marked with a dot. Some regions do exist with high spatial variation, but the number of stations processed in these regions may be of reduced density. The reader is cautioned when interpreting data which has been interpolated in these locations. Additionally, even when interpreting data directly at one of the stations, it should also be noted that the accuracy of these results depend directly on the quality of the input data that has been provided by the NSRDB.

Further spatial resolution could have been gained using the 10km gridded SUNY dataset available in the NSRDB, however, this approach was avoided due to the significantly increased computational resources required, and the lack of additional meteorological data included with the 10km gridded SUNY dataset. Additional meteorological data is desired for future studies which will incorporate the temperature dependency of the efficiency of solar thermal collectors and photovoltaic solar collectors into the sensitivity plots determined at each location.

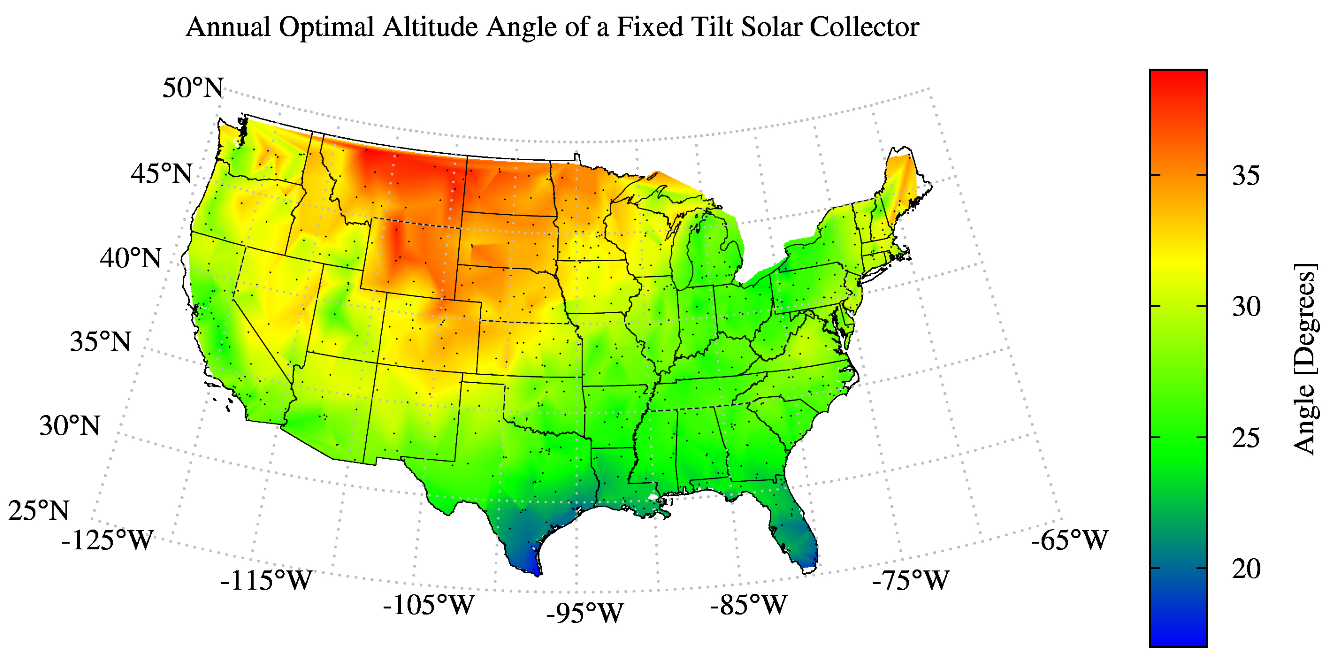

Fig. 1: Spatial Variation in Annual Optimal Altitude Angle of a Fixed Tilt Solar Collector

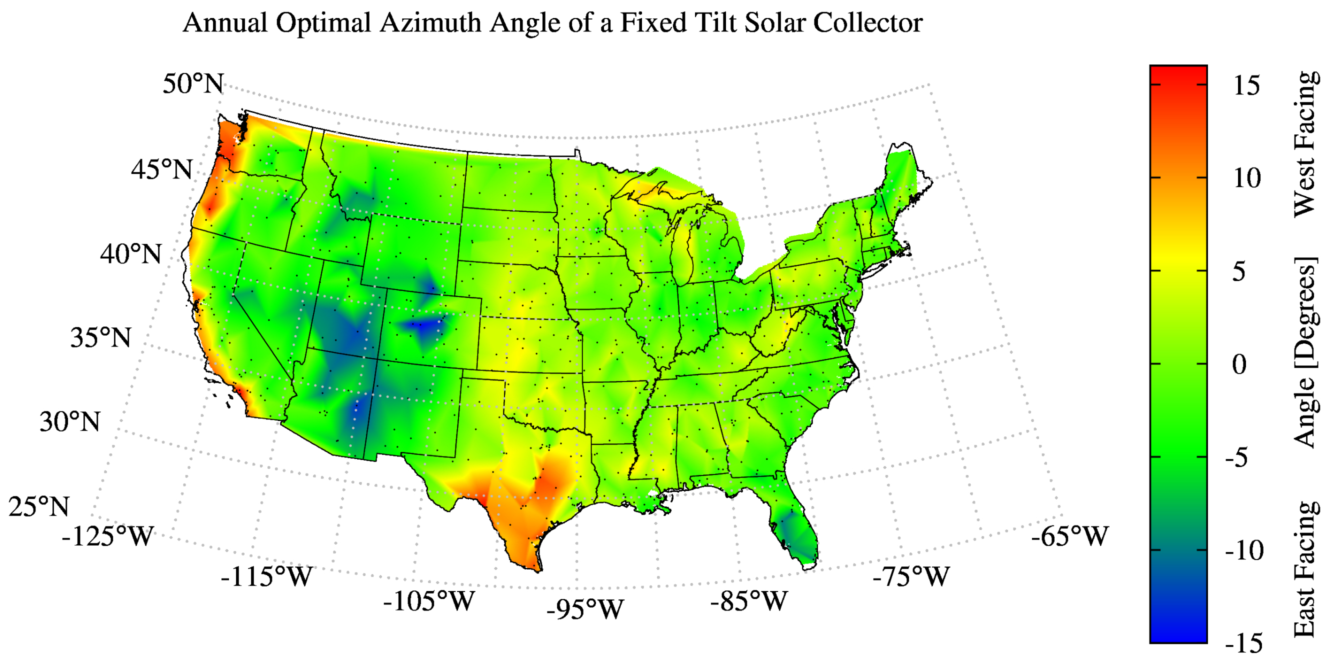

Fig. 2: Spatial Variation in Annual Optimal Azimuth Angle of a Fixed Tilt Solar Collector

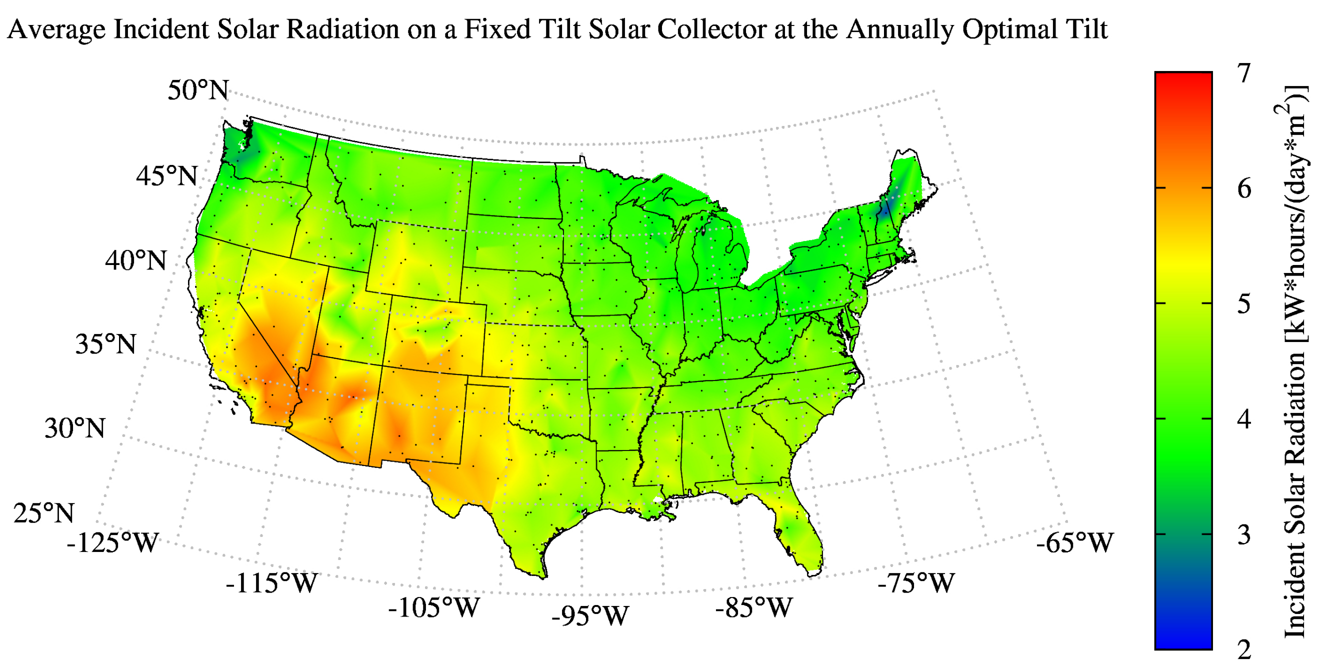

Fig. 3: Spatial Variation in Average Incident Solar Radiation on a Fixed Tilt Solar Collector Mounted at the Annual Optimal Azimuth and Altitude Angle

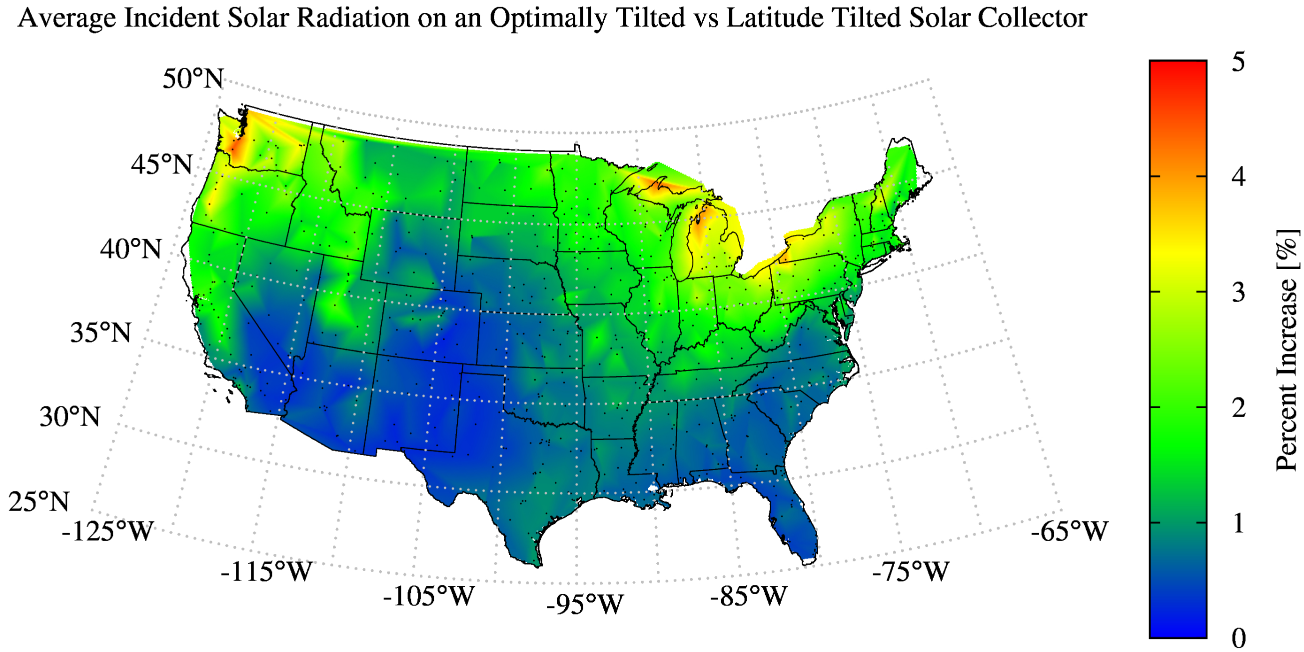

Fig. 4: Spatial Variation in Percent Increase in Average Incident Solar Radiation on a Fixed Tilt Solar Collector Mounted at the Annual Optimal Azimuth and Altitude Angle vs a South Facing Latitude Tilted Collector

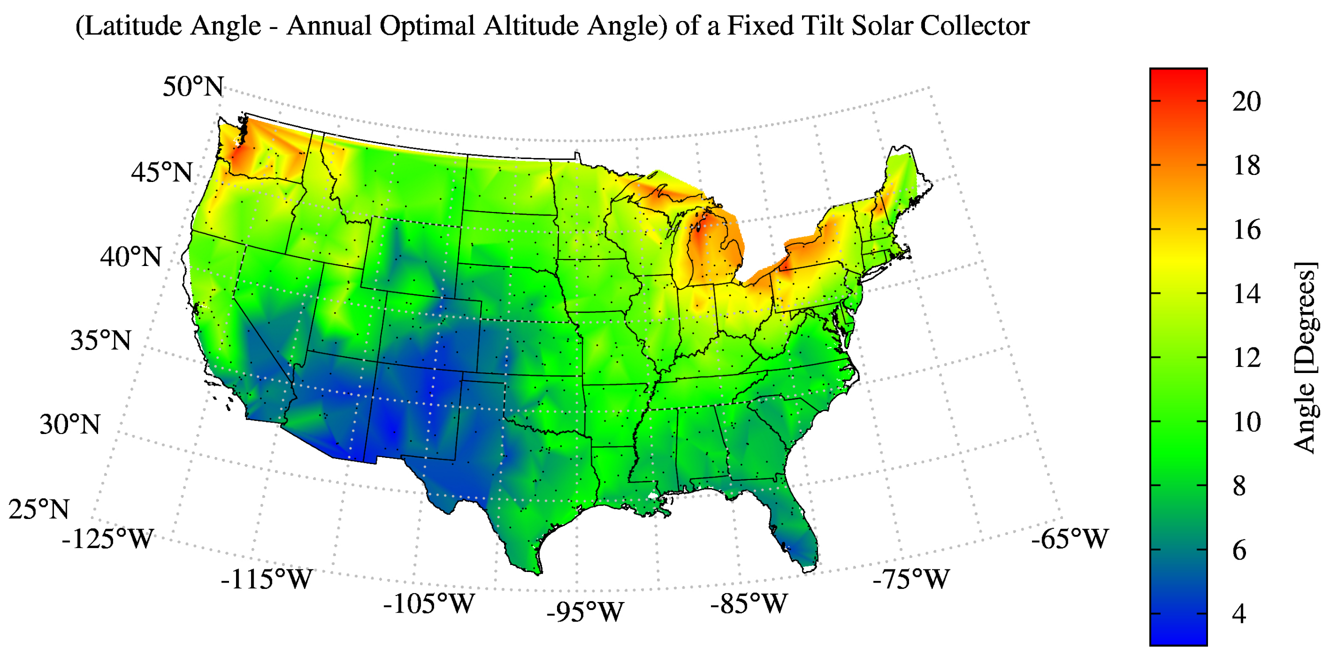

Fig. 5: Spatial Variation in Latitude Angle - Annual Optimal Altitude Angle of a Fixed Tilt Solar Collector

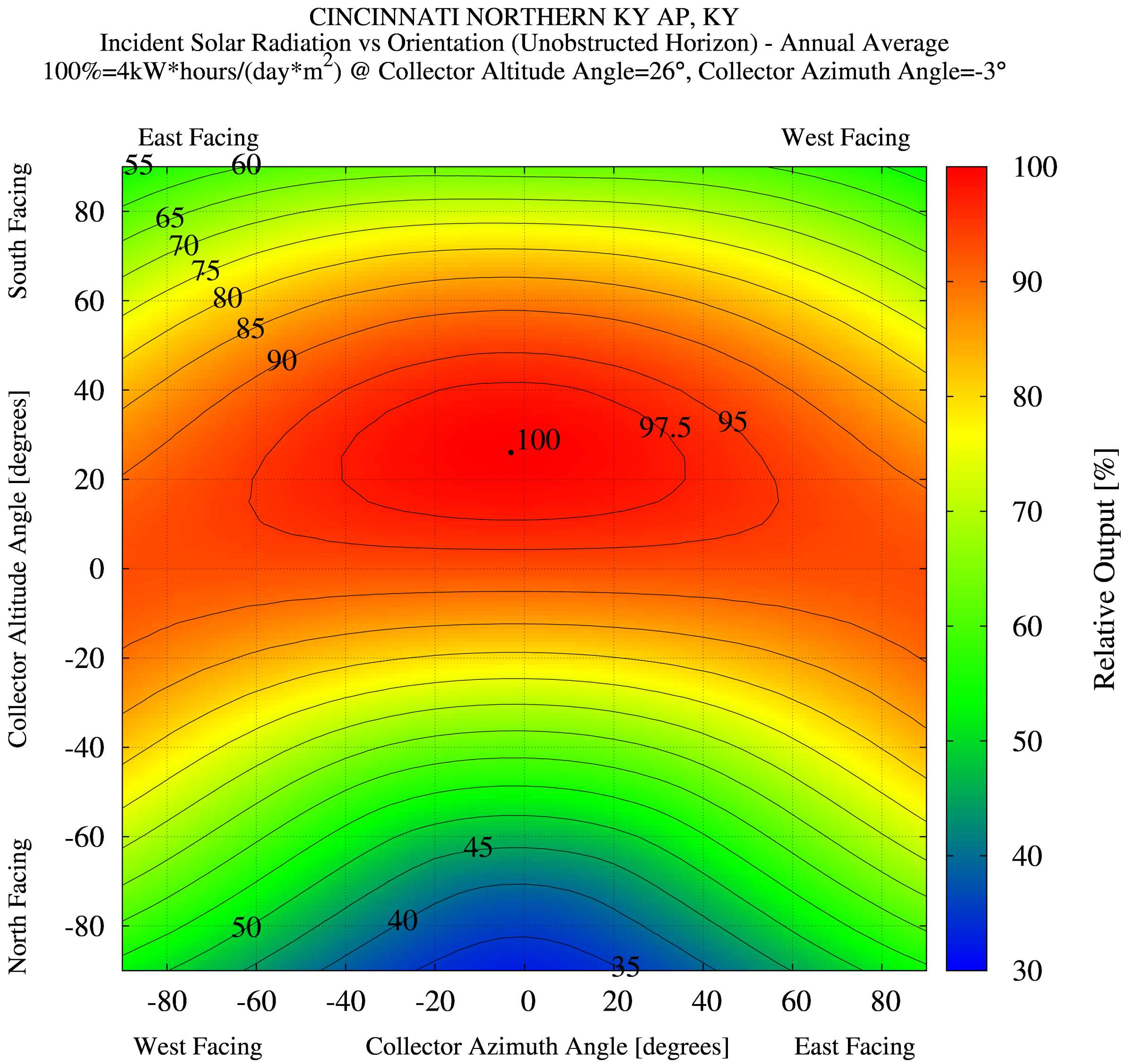

Fig. 6: Angular Sensitivity of Average Incident Solar Radiation of a Fixed Tilt Solar Collector for Cincinnati/Northern Kentucky Airport

Figure 6 presents a sensitivity plot for the Greater Cincinniati/Northern Kentucky Airport. As can be seen, the optimal solar collector tilt is located at an azimuth angle of -3° and an altitude angle of 26°. At altitude angles of approximately +/- 15° and azimuth angles of +/-37.5° within the optimal tilt, the average incident solar radiation is still within 97.5% of that of the optimal tilt. This large range with minimal reduction in average incident solar radiation from the optimal further explains the minimal percent increase in average incident solar radiation seen for the Greater Cincinnati/Northern Kentucky area in Figure 4.

With changes in location, the optimal orientation will change, as was shown in the Figures 1 and 5. The sensitivity to the optimal orientation will also change. Christensen and Barker proposed a correlation based approach for determining the annual optimal orientation of a solar collector, and the sensitivity of the incident solar radiation to that optimal orientation[1]. This work makes no attempt at such a process, but rather, the entire set of 758 sensitivity plots have been made available on the website http://AndySchroder.com. The reader is encouraged to use this resource in order to obtain results from a station nearest to their geographic region of interest.

4. CONCLUSIONS AND FUTURE WORK

Results have been presented for annual optimal solar collector orientation and have been compared to a south facing solar collector at a latitude tilt. It is evident that there is a significant difference between the optimal solar collector orientation and a solar collector oriented south facing with a latitude tilt. Although the orientation of south facing solar collectors with a latitude tilt are different than the optimal orientation, the sensitivity of the average incident radiation is fairly low within a wide range of the optimal solar collector orientation.

The results presented in figures 1 thru 6 assumed a solar collector efficiency of 100%. In reality, both solar electric and solar thermal collectors do indeed have significantly lower efficiencies which may due to optical losses, thermal losses, or photovoltaic cell inefficiencies. Due to the significant variation in component and system configuration efficiencies from application to application, no attempt was made to incorporate the efficiency of any system or component in this study. The present results are meant to be a guide during the system design process. Modeling of specific components should always be conducted when designing any solar energy system.

This study can be expanded in several areas. First, the assumption was made that the solar collector is not obstructed by any neighboring structures or building features. In reality, the solar collector may be shaded due to a nearby building or building feature, vegetation, geological formation, or a nearby solar collector. Determination of optimal solar collector orientation, incident solar radiation, and the sensitivity of the incident solar radiation to the optimal solar collector orientation with respect to shading levels can be useful in the system design process. This information can help to influence the spacing and tilt of staggered arrays of solar collectors which may be placed upon the roof of a building or ground mounted. It can also influence the relative placement of buildings and vegetation with respect to a solar collector installation. In cases such as solar thermal systems and off grid solar electric systems where the collected solar energy is unable to be transported and must be stored on site, or when the utility grid reaches a state where a high fraction of energy production is from renewable energy sources (which are variable), the system designer may not necessarily be interested in an annually optimal solar collector orientation, but rather, an optimal orientation at a specific time period where there is an energy production deficit. This study can be expanded to determine optimal collector orientations for specific time periods of the day and season.

5. NOMENCLATURE

β	Collector altitude angle, the slope of the collector surface with respect to the horizontal
γ	Collector azimuth angle
γ_s	Solar azimuth angle
ρ_g	Surface Albedo, diffuse ground reflection coefficient
θ	Angle of incidence, the angle between the beam radiation on a surface and the normal to that surface
θ_z	Zenith angle, the angle of incidence of beam radiation on a horizontal surface
F_{c-g}	View factor from the solar collector to the ground
F_{c-s}	View factor from the solar collector to the sky
I_b	Beam radiation
I_d	Diffuse radiation on a horizontal surface
I_t	Total incident radiation on a tilted surface

6. ACKNOWLEDGEMENTS

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7. REFERENCES

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