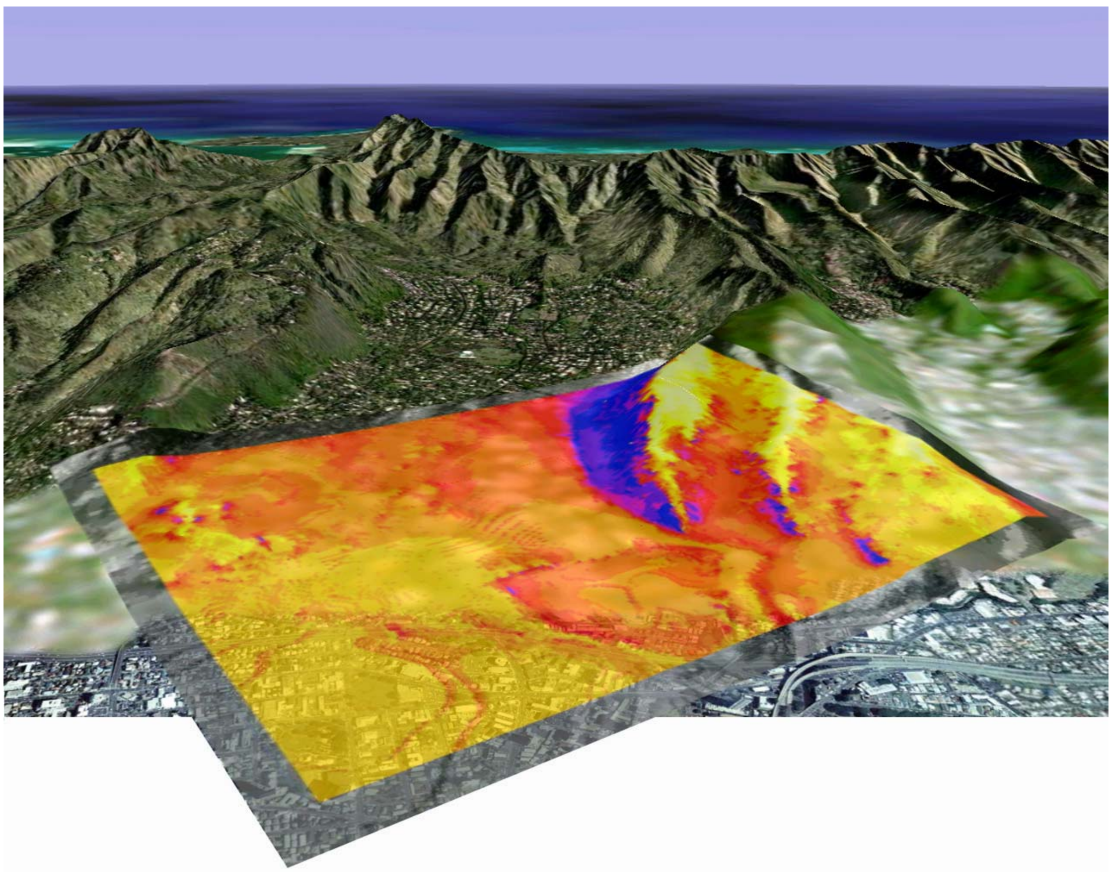
INSOLATION ASSESSMENT ON THE ROOFTOPS OF THE UNIVERSITY OF HAWAII CAMPUS AT MANOA

Solar Energy Program at the University of Hawaii
School of Architecture

FINAL REPORT
December 2004



Report prepared by the
Environmental Research & Design Laboratory
School of Architecture
University of Hawaii at Manoa

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I. Scope and Objectives

The objective of the study is to assess the solar radiation incident upon the rooftop surfaces of the University of Hawaii campus at Manoa, the neighboring residences, and to evaluate the insolation levels striking the research facility rooftops on the Coconut Island campus. This investigation allowed the research team at the Environmental Research and Design Laboratory at the School of Architecture at Manoa to expand their applied knowledge and develop additional confidence in the solar design and analysis methods developed by them in the past two years. This method involves the use of Geographic Information System (GIS) software and aerial photographs to assess rooftop insolation, taking the site's topography into consideration. This study investigated the cooling load impacts of incident radiation and provides estimates on the solar energy generating potential from the campus rooftops if they were fitted with solar energy systems such as photovoltaic or other solar collectors.

Additionally, one of the study's objectives is to estimate the effects of building self-shading. A parapets, an extension of the wall above the roof, creates shading on the roof surface. Establishing a formula for the quantification of parapet shading was accomplished through this research.

II. Insolation assessment on the rooftops of the University of Hawaii at Manoa

Method:

All the components necessary to the computation of the solar radiation assessment were gathered: digital topographic maps of Honolulu [Fig. 1] (7.5 minutes Digital Raster Graphic), Digital Elevation Model (DEM) of the Island of Oahu [Fig. 2], digitized aerial photography of the University of Hawaii at Manoa and close surroundings [Fig. 3], GIS shapefile of the streets of Oahu [Fig. 4]. Software equipment includes ArcView GIS, coupled with various software extensions: Spatial Analyst[1], Solar Analysis[2], and Image Analysis[3]. Ecotect environmental analysis software was also used to model the effects of parapet shading on the building rooftops.

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[1] ESRI software
[2] HEMI, Pinde Fu and Paul M. Rich
[3] ESRI software

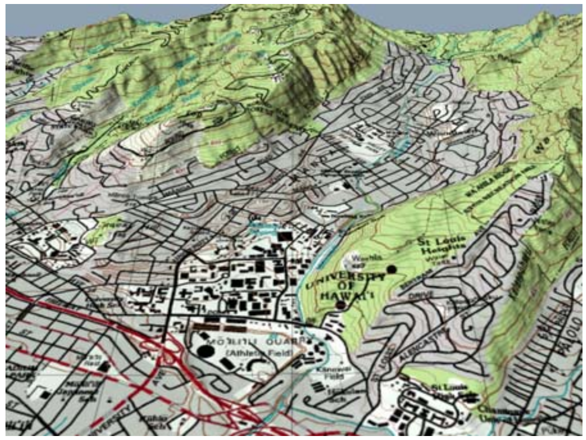

Figure 1 - Digital Raster Graphic of Manoa Valley

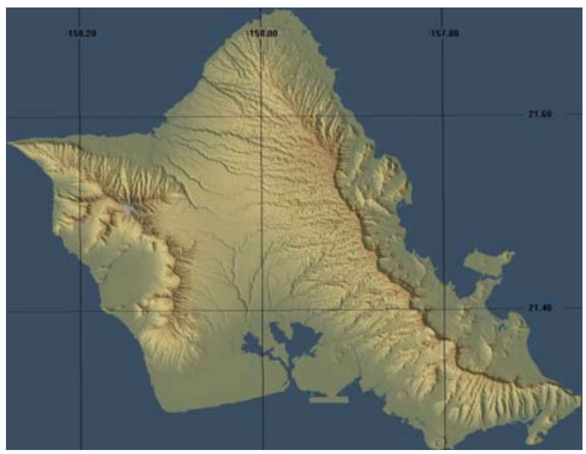

Figure 2 - Digital Elevation Model of Oahu

Figure 3 - Aerial Photograph Sample of the University of Hawaii

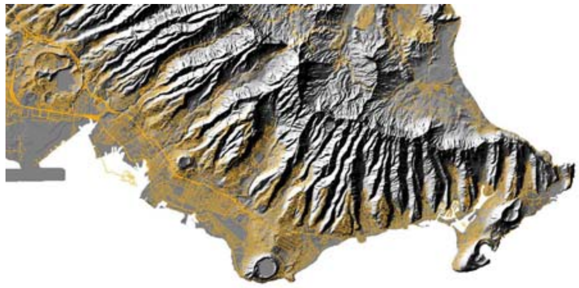

Figure 4 - GIS Shape file of the Streets of Oahu

Solar radiation on flat surfaces was calculated using the Solar Analyst and the DEM. Such calculation takes into account the topographic properties of the surrounding terrain. Thus surface insolation can be affected by the shading caused by hills and mountain ranges. This method is unique to most insolation assessments in regard to this accounting of orographic shading.

The aerial photograph was imported into the GIS platform and georeferenced so as to match the scale and orientation of the existing DEM. This georeferencing allows the accurate sizing of features measured on the aerial photograph. The Image Analysis was used to identify the rooftops of the Manoa Campus. For the purpose of this investigation, the study ignored most non-flat rooftop surfaces, which represent a minority, and present different structural and economical requirements to bear solar energy systems.

The Image Analysis can identify and associate similar hues, picked off the various rooftops surfaces of the campus. It can therefore recognize a more or less homogeneous rooftop surface, delineate its geometric boundaries and calculate its surface area with a satisfactory level of accuracy.

Analysis:

During the analysis, the software identified 135,972 m^2, or 1,463,591 ft^2 (roughly 1.5 million square feet) of flat rooftop surfaces [Fig. 5].

It must be noted that the surface area of the two parking structures located on the lower campus was included into the matrix. The reason for such assumption is obvious when considering that the surface area offered by the two parking structures accounts for 31% of the total campus' flat rooftops area, and that a simple structure could suffice to shade the cars parked on the top level while possibly collecting power from the sun.

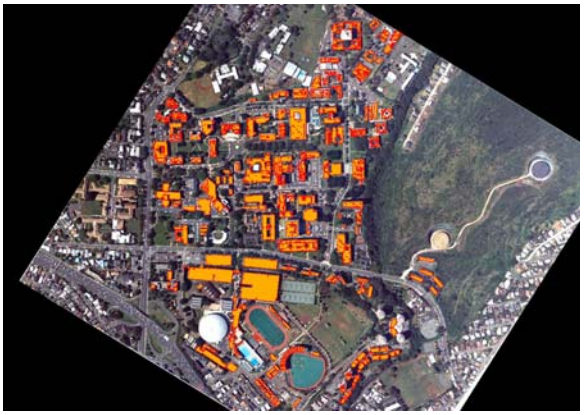

Figure 5 - Identified Rooftops of the University of Hawaii

The Solar Analyst GIS extension was used on a surface area extending 1.79 square miles around the University of Hawaii Campus [Fig. 6]. A solar transmission of 0.57 was used for the calculation, as published by NREL[4]. This clearness index factor is the official annual average solar transmission factor for the Honolulu area, as recorded from the Honolulu International Airport. The simulation engine was set up to compute annual daily average insolation on horizontal surfaces only. The values obtained are thus representative of the daily average amount of solar radiation incident on horizontal surfaces throughout a calendar year. Summer values will usually be higher, while winter values will be lower.

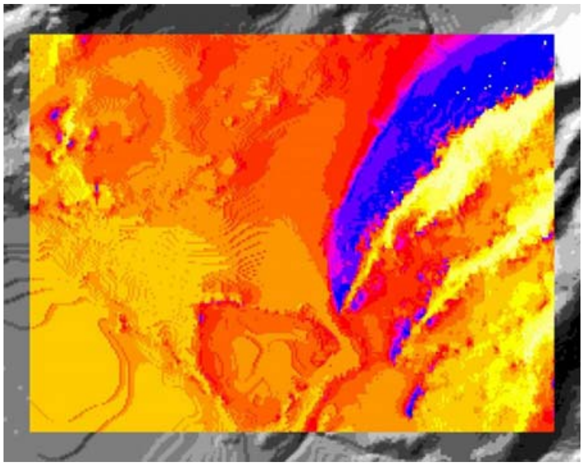

Figure 6 - Solar Mapping of Manoa Valley

[4] National Renewable Energy Laboratory (1995). *Solar Radiation Data Manual for Buildings*. Golden, Colorado.

The resultant “solar map” was then “fitted” to the identified campus rooftop surface areas [Fig. 7]. Doing so enables a range of insolation restricted solely to the surfaces under study.

The range of insolation falling on the campus rooftop surfaces is between 5,077 Wh / m^2 per day on and about Hale Kuahine building on the Northeastern part of the campus, to 5,259 Wh / m^2 per day on and about Orvis auditorium on the Southwestern part of the campus. The mean insolation value throughout the campus rooftops is 5,206 Wh / m^2 per day. This value was chosen to calculate a mean total insolation value for the entire campus identified rooftop surface areas. The mean total annual daily solar radiation incident on the University's flat rooftops is thus 5,206 Wh / m^2 x 135,972 m^2 = 707,870,232 Wh, or 707,870 kWh per day.

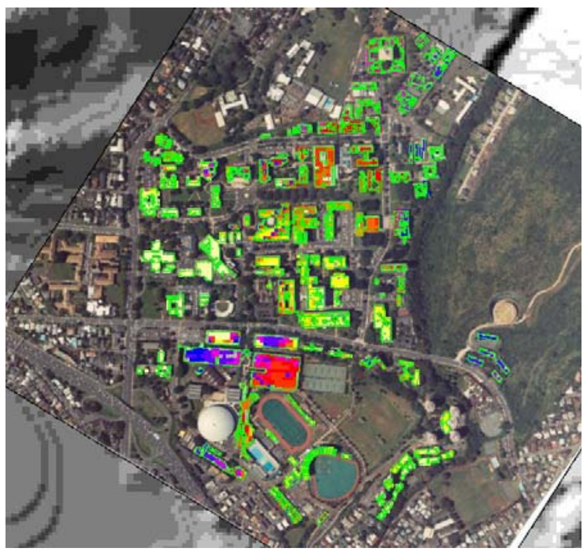

Figure 7 - Solar mapping of the University's Rooftops

Overshading modeling:

The effect of shading by rooftop features such as parapets and elevator or ventilation towers need to be assessed in order to present relatively accurate data.

Such assessment is very difficult to perform, as every rooftop features different solar obstructions of various heights.

The study discounted the overshading effects of large rooftop towers as these cast large shadows which surface area was deducted from the overall rooftop surface area while using the Image Analysis. Since the software recognizes homogeneous colors, most large shadows were not calculated in the total rooftop surface area.

Parapet shading was in some case also discounted while identifying rooftop area. Further simulation was nonetheless performed to assess the effect of such overshadowing.

Three building models were constructed within the Ecotect environmental building analysis software[5] [Fig. 8]. Each buildings presented different rooftop surface areas: 10,000 m^2, 1,000 m^2 and 100 m^2. Each roofs featured a 1-meter high parapet, somewhat representative of the average roof parapet.

The simulation showed that on the largest roof surface, the parapet affected the incident solar radiation by only 0.7%, while on the 1,000 square meter roof the annual insolation was decreased by 3.4%. The insolation on the 100 square meter rooftop was decreased by 11.4%. The values follow an inverse logarithmic equation of the form $y = 1.8404x{\wedge}^{0.5919}$, enabling the approximation of a shading coefficient on various roof surface areas.

The mean surface area of the university's flat roofs was calculated to be around 850 m^2.

With this surface area, the shading coefficient is very close to 3.5%.

This coefficient can be taken into account when assessing total solar energy potential on the roof surfaces. In doing so, the mean total annual daily solar radiation incident on the University's flat rooftops thus becomes 707,870,232 - (707,870,232 x 0.035) = 683,094,774 Wh.

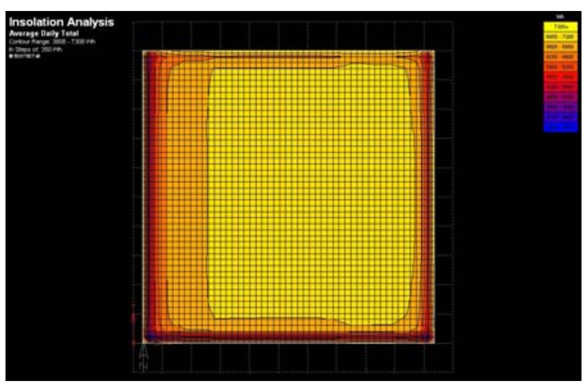

Figure 8 - Modeling of Parapet Shading on Rooftop

III. Insolation assessment on surrounding residential rooftops:

Assessment of solar radiation incident on multiple residential rooftop surfaces is a challenging task due to the various geometry, orientation, slope and size of any given residential roof.

[5] Square One Research PTY LTD

It can be confidently said, however, than the rooftop typology - geometry, orientation, size and slope type – of a neighborhood is relatively homogeneous, because of zoning and planning regulations [Fig. 9]. The size and geometry of a residential roof, for example, is dependent on the parcel of the house, itself dependent, and maximizing the given property lot. These lots are often equally sized subdivisions of larger parcels. Common building construction practices and codes also narrow down the range of roof slopes angles. Orientation of the roof surfaces is perhaps the most varied feature of any rooftop typology within a neighborhood.

Figure 9 - Typical Residential Rooftop Typology around UH

Since the amount of solar radiation received on a surface is affected by its slope and orientation, it is essential to first assess their respective importance.

An aerial photograph of the campus' neighborhoods confirms the uniformity of the residential roof typology. The roofs are mostly hip roofs, allowing adequate overhang to surround the houses. The average roof slope (pitch) can be estimated to be between 4/12 and 5/12, or 20º for most hip roofs. Although the geometry of the roofs appears very varied, they are for the most part rectangular in nature. This brings the rooftop vocabulary to two general shapes. One of which is a long, rectangular gable roof featuring two sides of equal area facing opposite directions. The other is a square hip roof, having four sides equal in area and facing opposite directions. The range of rooftop typology found in the neighborhood of the campus spans between these two general morphologies, some more rectangular than others, making their typology most similar with the gable roof, while others approaches the square hip roof shape and surfaces configuration. As the building elongates in one axis, two of its roof surfaces increase in area while the other two decreases.

Research and modeling show, however, a trivial difference in insolation potential between the two different roof typologies, given a similar roof pitch, for any orientation[6].

Calculations performed on the Helianthus surface insolation simulator show a range of annual insolation potential from 91.85% (East-West gable roof) to 92.55% (North-South gable roof) of the optimum surface configuration (a South facing shed roof tilted 20º) for a 20ºslope angle [Table 1]. This 0.7% maximum difference in insolation potential demonstrates the small impact the overall shape and orientation has on incident solar radiation on such low-pitch surfaces. It is important to note that this small difference is partly caused by the location of the area of study, i.e., within the tropics, where solar radiation can be received from all direction during the period of a year. In Hawaii, insolation can be received on north-facing surfaces during the radiation-intensive summer months.

Table 1 - Insolation Potentials for Various Rooftop Typologies

ρg = 0.2 95% - 100% 90% - 95% 85% - 90% 0% - 85%									
0	95.54%	95.54%	95.54%	95.54%	95.54%	95.54%	95.54%	95.54%	95.54%
5	95.31%	95.31%	95.33%	95.34%	95.34%	95.33%	95.33%	95.33%	95.33%
10	94.61%	94.63%	94.69%	94.74%	94.76%	94.69%	94.69%	94.69%	94.69%
15	93.46%	93.51%	93.64%	93.77%	93.82%	93.64%	93.64%	93.64%	93.64%
20	91.85%	91.95%	92.19%	92.44%	92.55%	92.20%	92.20%	92.19%	92.20%
25	89.81%	89.97%	90.38%	90.79%	90.95%	90.38%	90.38%	90.38%	90.38%
30	87.35%	87.61%	88.23%	88.83%	89.07%	88.21%	88.22%	88.23%	88.22%
35	84.48%	84.87%	85.76%	86.59%	86.92%	85.70%	85.73%	85.76%	85.73%
40	81.24%	81.81%	83.03%	84.11%	84.53%	82.88%	82.96%	83.03%	82.96%
45	77.64%	78.47%	80.07%	81.42%	81.93%	79.78%	79.94%	80.07%	79.94%
50	73.72%	74.91%	76.93%	78.54%	79.14%	76.43%	76.73%	76.93%	76.73%
55	69.52%	71.23%	73.65%	75.50%	76.18%	72.85%	73.36%	73.65%	73.36%
60	65.12%	67.51%	70.27%	72.33%	73.09%	69.11%	69.92%	70.27%	69.92%
65	61.21%	63.85%	66.83%	69.07%	69.90%	65.55%	66.46%	66.83%	66.46%
70	58.53%	59.89%	63.36%	65.73%	66.61%	62.57%	62.81%	63.36%	62.81%
75	55.67%	56.86%	59.89%	62.35%	63.28%	59.47%	59.61%	59.89%	59.61%
80	52.65%	53.49%	56.43%	58.95%	59.91%	56.28%	56.22%	56.43%	56.22%
85	49.49%	50.14%	53.00%	55.57%	56.54%	53.01%	52.85%	53.00%	52.85%
90	46.21%	46.80%	49.64%	52.21%	53.19%	49.70%	49.51%	49.64%	49.51%

To evaluate the average residential rooftop surface area, the Image Analysis GIS extension was used on the aerial photograph of the University of Hawaii at Manoa campus and its neighborhood. It identified one hundred residential rooftops and calculated an average surface area for each of 140 m^2, or roughly 1,500 square feet [Fig. 10]. Because the surface identification is performed in 2 dimensions, a corrective multiplier, dependant on the roof pitch, must be used to provide a more accurate surface area. Since the roof slope angles were estimated at 20º, the corrective multiplier is 6.42%, derived from the equation: (1/(cos (pitch)))-1. Thus the identified average rooftop surface area is 140 + (140 x 6.42%) = 149 m^2, or 1,500 + (1,500 x 6.42%) = 1,596 square feet.

[6] Environmental Research & Design Laboratory (2004). *Assessment of Solar Energy Potential on Existing Buildings.* Palo Alto, CA: EPRI

Figure 10 - Identified Residential Rooftop Surfaces

Using the similar annual daily average insolation value of 5,206 W/h/m^2 on a horizontal surface as that computed for the campus buildings, the surface insolation simulator computed a maximum insolation potential of 5,400 Wh/m^2 on a surface tilted 20º and facing south. From the calculation previously performed, the annual daily average incident solar radiation on the residential rooftops can be estimated at being between (5,400 x 0.9185) and (5,400 x 0.9255) or 4,959.9 Wh/m^2 and 4,997.7 Wh/m^2. With an average roof surface area of 149 m^2, one can expect a total annual daily average insolation ranging between (149 x 4,959.9) = 739,025 Wh, or 739 kWh and (149 x 4,997.7) = 744,657 Wh, or 745 kWh per residence.

IV. Assessment of solar radiation on the rooftops of Coconut Island:

Clearness Index:

Coconut Island, a research facility belonging to the University of Hawaii, was incorporated into the study’s scope of work. The island is located just off the northeastern coast of the Oahu. This location makes the solar radiation more susceptible to cloud cover, typical of the northern coastal regions of the Hawaiian Islands.

Although the method to assess insolation is similar in every ways to that followed for the University of Hawaii campus, an extra step was needed to interpolate the sky transmission (also known as clearness index) within this region of Oahu.

The clearness index is a reduction multiplier accounting for cloudiness and atmospheric particulates. An index of 1.0 means a perfectly clear sky, while 0 represents an entirely obstructed sky. Clearness index are generally calculated by dividing the amount of solar radiation received on a flat surface to the hypothetical amount received at the top of the atmosphere for an identical location. Where such data are recorded, clearness index are available or easily calculated. This index is needed for the insolation computation of the Solar Analyst. Honolulu, for example, has a yearly average clearness index (labeled kt) of 0.57[7]. For regions where global solar radiation on horizontal surface are not accessible or non-existent, the clearness index needs to be extrapolated. Since cloudiness is often accompanied by rainfall, and rainfall is more commonly available than insolation data, a proportional relationship and equation can be derived from any precipitation data available within a particular location. It is important to note here that such correlations were only found adequate within close geographical regions. No satisfactory correlation could be established between precipitation and clearness index when done on a country-broad base.

Using four known clearness index within various regions of the Hawaiian Islands, and matching them with their respective precipitation data, an equation of the form y = 0.7668x-0.0972 was derived, with a R2 value (representing how well the data correlate) of 0.9937 [Fig. 11]. Using the precipitation data recorded in Kaneohe, the nearest city by Coconut Island, a clearness index of 0.50 was interpolated.

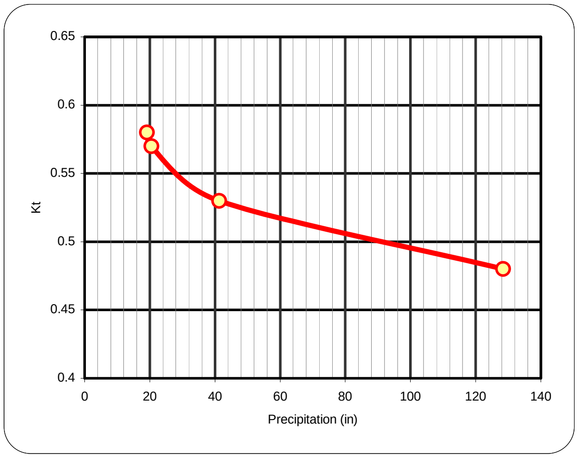

Figure 11 - Clearness Index Extrapolation Curve

[7] National Renewable Energy Laboratory (1995). *Solar Radiation Data Manual for Buildings*. Golden, Colorado.

Digital Elevation Model:

As discussed in the interim report, the DEM of Oahu did not include Coconut Island. Thus, since such data is required, a DEM was created manually and merged into the existing Oahu DEM [Fig. 12]. The process was successful. A default elevation value of 1 meter (3 feet) was selected for the entire island. Although the topography of the island is known to vary from 0 to 9 meters throughout, the discrepancy is insignificant for this study.

Figure 12 - DEM of Coconut Island

Rooftop area:

The rooftop surface areas of the Coconut Island facilities were identified within the GIS platform [Fig. 13]. The total area was estimated at 6,543 m^2, or 70,428 ft^2. The roof typology of the Coconut Island building is quite homogeneous in geometry and orientation. Most roofs tend to follow a northwest-southeast axis and are elongated gable. Their slope can be estimated at 20º, making the identified surface area larger by a factor of 6.42%, or 6,963m^2 (74,950 square feet).

Figure 13 - Identified Rooftops of Coconut Island

Solar Insolation:

After using the Solar Analyst, the solar radiation annual daily average for Coconut Island was computed to be 4,495 Wh/m^2 on a horizontal surface [Fig. 14].

The Helianthus insolation simulation program calculated a range between 94% and 94.26% of maximum potential surface insolation (shed roof tilted 15º and facing due south) for gable or hip roofs tilted 20º. Since the optimum surface incident solar radiation was calculated (also with Helianthus) to be 4.58 kWh/m^2, the annual daily average surface insolation on the roofs of Coconut Island facilities can be assessed to be between (4,580 x 0.94) and (4,580 x 0.9426), or 4,305 Wh/m^2 and 4,317 Wh/m^2.

The total amount of daily solar radiation received on Coconut Island can thus be assessed at 4,305 Wh/m^2 x 6,963 m^2 = 29,975,715 Wh = 29,975.7 kWh or roughly 30,000 kWh.

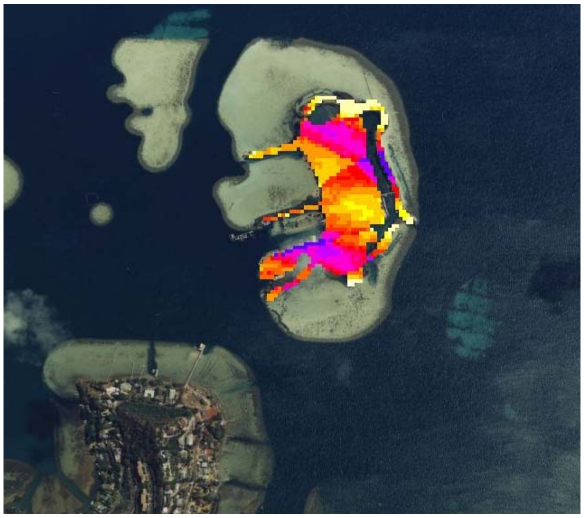

Figure 14 - Solar Mapping of Coconut Island

V. Photovoltaic potential outputs:

One of this study's goals is to assess how much electricity photovoltaic systems equal in area to those identified rooftop surfaces could produce. A conservative photovoltaic system efficiency of 10% can be used to estimate the annual daily average amount of electrical energy that such systems could output[8]. This 10% is for the overall efficiency of the system, including photovoltaic panel, converter (from DC to AC) and other wire losses.

Photovoltaic panels laid flat on the identified flat roofs of the University of Hawaii at Manoa could therefore potentially output a yearly daily average of (683,094,774 x 0.10) = 68,309,477 Wh or 68,309 kWh. As computed by Helianthus, this output represent 95.6% of the optimum potential that would be achieved by titling the photovoltaic panels 20º and facing them due south.

Similarly, photovoltaic panels placed on the tilted roof surfaces of the identified Coconut Island's rooftops could potential output a yearly daily average of (29,975 x 0.10) = 2,997 kWh, or roughly 3,000kWh.

[8] Sandia National Laboratories (1991). *Maintenance and Operation of Stand-Alone Photovoltaic Systems*. Albuquerque, NM.

VI. Thermal Sol-Air gains:

There are two major forms of heat flow processes that occur through the opaque building envelope itself, also called fabric thermal gains. One of them, referred to as conduction gains, is caused by the difference in temperature between the outside and the inside of the building. As heat flows from hot to cold, any exterior temperature in excess of that inside the building will create a thermal differential flowing from the inside to the inside going through the building fabric, in order to create a thermal equilibrium.

The rate of this heat flow is proportional to the difference in temperature between the exterior air temperature and the interior air temperature. The larger the thermal differential, the faster the heat flow.

The other form of heat flow is indirectly related to the first one. It is called indirect solar heat gains or Sol-Air gain. Sol-air gains are those conduction gains through the building fabric that are caused solely by solar radiation. Because the solar rays do not go through a glazing material (direct solar gains) but rather hit the surface of the building's envelope, their accompanied heat gains are termed indirect solar gains.

In receiving solar radiations, the building fabric heats up. This added fabric heat is combined to the outdoor air temperature to create the Sol-Air temperature, which is defined as the equivalent outdoor air temperature that will cause the same rate of heat flow as the current air temperature and solar radiation incident on the building. This increase temperature raises the rate of heat flow between the outdoor and indoor of the building[9].

As the Sol-air gains are caused by incident solar radiation, it is highly affected by the reflectivity of the building envelope. Dark surfaces will absorb more radiation, thus increasing the heat flow. The opposite will occur with light-color surfaces. It is therefore very important, in hot climate receiving considerable solar radiation, to choose adequate building surfaces reflectivity. Under the Hawaiian latitude, it becomes crucial to select light-color surfaces for the roof surfaces as those receive more solar radiation than any other building surfaces.

For this study, an estimation of the Sol-air gain impact was done for the rooftop surfaces identified on the University of Hawaii campus. This assessment, done with the Ecotect software, assumed a default roof element made of 6" concrete and 3" insulation foam for all buildings. Various surface

[9] Steven Szokolay (2004). *Introduction to Architectural Science: the Basis of Sustainable Design*. Architectural Press

reflectivities were used and total annual sol-air gains were computed. The interior space was assigned an air conditioning system working from 7:00 am to 10:00 pm, and a thermostat setting of 77º F (air conditioning turns on above this indoor temperature). The following table summarizes the results:

Table 2 - Sol-Air Gains for Various Rooftop Reflectivities

Surface Reflectivity	Total annual sol-air gains
20%	5,197 W/m^2
40%	4,016 W/m^2
60%	2,880 W/m^2
80%	1,744 W/m^2

These gains can also be thought of the extra heat energy that any air conditioning system must work at eradicating every year in order to maintain the maximum room air temperature of 77º F, due solely to the incident solar radiation on the rooftop and the roofing material chosen. Sol-air gains analysis can also identify the time of the day the thermal gain caused by the solar radiation actually affect the interior space. In this case, the heat caused by the sun tends to affect the interior space in the evenings, due to the thermal lag effect of the ceiling's concrete mass [Fig. 15].

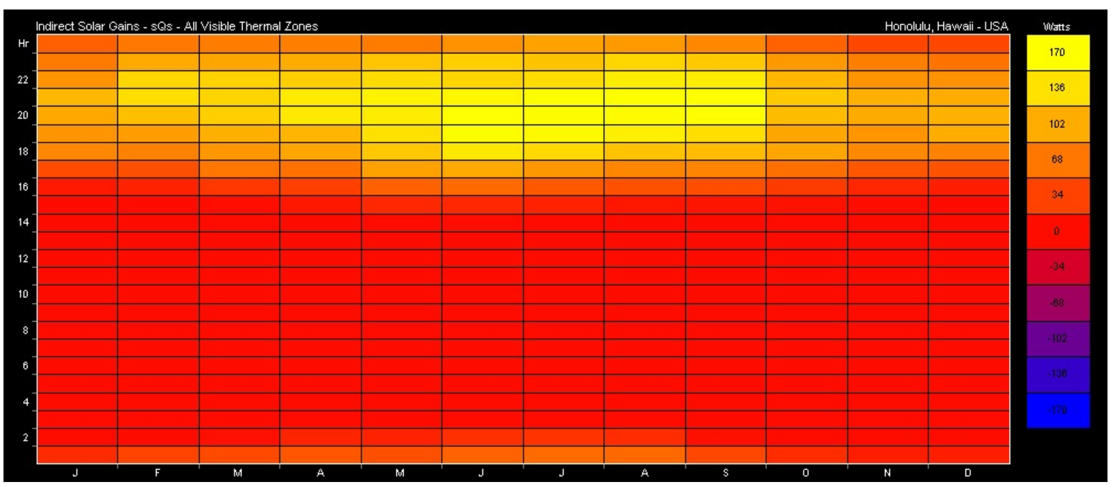

Figure 15 - Annual Average Sol-Air Thermal Gains

It is worth noting that any surface placed between the incident solar radiations and the roof of the building will absorb or reflect solar radiation, increasing or reducing the thermal load on the building. Photovoltaic system or other solar energy collectors lend themselves perfectly to such use, as they can fully benefit from the insolation while shading the building rooftop from the sol-air thermal gains.

VII. Summary:

This study assessed the amount of solar energy incident to the flat rooftops of the University of Hawaii at Manoa, using geographic information System software and aerial photographs. The topography of the area of study, including valley and hillside effects on insolation, were calculated as part of the solar formula. The annual daily average insolation on these surfaces was computed to be 5,206 Wh / m^2.

The surface area of the rooftops was also computed using Image Analysis GIS add-in extension. The identified surface area, including the uppermost parking lot structure surface area, totaled 135,972 m^2, or roughly 1.5 million square feet. Thus, the annual average insolation on the campus's flat rooftops can be calculated at 707,870 kWh per day.

Further modeling of roof parapets overshading showed an average 3.5% decrease in incident solar radiation, lowering the total annual daily average insolation to 683,095 kWh. Assuming 10% efficiency in energy conversion, where these flat rooftop surfaces fitted with photovoltaic systems, they could output, on a yearly average, over 68,000 kWh per day.

The study also evaluated the amount of solar energy potential incident on the residential rooftops neighboring the University of Hawaii. An annual daily average insolation of 739 kWh per residence was estimated, resulting in an annual average energy output of 74kWh per day per residence if the residences roofs were fitted with photovoltaic systems.

In addition, a similar study was performed for the rooftops of the buildings located on Coconut Island, on the north side of Oahu. An annual daily average insolation was computed at 4,495 kWh/m^2. The surface area of the facilities rooftop was identified to be 6,963m^2 or 74,950 square feet, making the total annual daily average solar radiation roughly 30,000 kWh. Photovoltaic systems could supply about 3,000 kWh of electrical energy per day on a yearly average.

Lastly, a thermal analysis was done to assess the amount of heat gained through the rooftops of the University, caused solely by solar radiation. This amount is greatly affected by the reflectivity of the roof surfaces and can range from above 5 kW/m^2 for dark roofs, to under 2 kW/m^2 for brighter roof surfaces.

The overall results of the study demonstrates the significant amount of solar energy striking the rooftops of buildings on Oahu and the potential exploitation of these under-utilized surfaces for energy production. The development of hybrid systems serving both as energy collector and shading devices would certainly prove to be an appropriate measure, not only producing electric power, but also reducing the overall cooling load campus wide.

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ESRI software – www.esri.com

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Square One Research PTY LTD – www.squ1.com

Steven Szokolay (2004). Introduction to Architectural Science: the Basis of Sustainable Design. Architectural Press