



Analysis of a full spectrum hybrid lighting system

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Abstract

Hybrid lighting is a new approach to lighting that integrates light from natural and electric sources. A two-axis tracking concentrator collects beam radiation which is reflected onto a mirror that divides the solar radiation into infrared and visible spectra. The visible light is distributed through optical fibers and combined with fluorescent lighting in specially designed luminaires. The infrared portion of the spectrum is used to generate electricity using a thermal photovoltaic array. A simulation of a hybrid lighting system has been created using the TRNSYS transient simulation program. The simulation incorporates the spectral properties of the hybrid lighting components as well as the spectral distribution of the incoming solar radiation that is based upon output from the SMARTS atmospheric transmittance model. An office building model is coupled with the hybrid lighting simulation to predict the annual energy impact upon lighting, heating, and cooling loads. Simulations were performed in six locations within the United States. Hybrid lighting systems performed best in Honolulu, HI and Tucson, AZ justifying system capital costs of \$2410 and \$1995 per module, respectively, based on a 10 year payback period.

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1. Introduction

Hybrid lighting is a new solar lighting technology that separates collected solar radiation into visible and thermal portions. The visible portion is used to light buildings and the infrared (IR) portion is used to generate electricity with thermal photovoltaic cells. The technology is currently under development in the United States by a design team comprised of members of industry and academia and led by Oak Ridge National Laboratory. The purpose of this particular study is to evaluate the feasibility and economics of the technology.

The hybrid lighting technology consists of a two-axis, concentrating collector that gathers direct normal solar radiation throughout the day. The direct normal solar radiation is reflected onto a secondary element which divides the solar radiation into the visible and infrared spectrums. The visible light is reflected off of the secondary element and focused into large-core optical fibers that transport the light into a space. The infrared energy is transmitted through the secondary element and focused onto a thermal photovoltaic array which uses the energy to generate electricity. There are two major benefits from hybrid lighting. The first benefit is the reduction in purchased electricity needed to light the building, and the second benefit is a reduced cooling load due to the high efficacy of natural light. Another potential benefit of hybrid lighting is the effect of natural lighting but this effect is difficult to quantify.

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A model of a hybrid lighting system was created in TRNSYS (Klein et al., 2000). The model consists of two major components; the building component and the hybrid lighting component. The TRNSYS type 56 building component was configured to simulate a large multi-use environment such as a retail or office space. The hybrid lighting component model uses the incoming beam radiation and spectral properties of the hybrid lighting system to determine the light and electricity benefits produced. The light 'produced' by the hybrid lighting component is fed back into the building model to calculate the impact the hybrid lighting technology has upon building loads.

An economic model is included in the TRNSYS simulation. Local utility rate schedules are used to convert the hybrid lighting impacts upon the building lighting, heating, and cooling loads into dollars. The energy savings predicted by TRNSYS is then used to determine a break-even capital cost for the hybrid lighting system.

2. Hybrid lighting components

The radiation collection system, the light distribution system, the controls, and the luminaires are depicted in Fig. 1. The collection system is composed of a concentrating solar collector that tracks the sun and gathers solar beam radiation. The radiation is filtered into two wavelength ranges; the visible and the IR. The IR radiation could be used for water heating or other purposes but in this system it is used for electricity generation with a thermal photovoltaic array. The visible radiation is channeled through the light transmission system, to specially configured luminaires located in the lighted space.

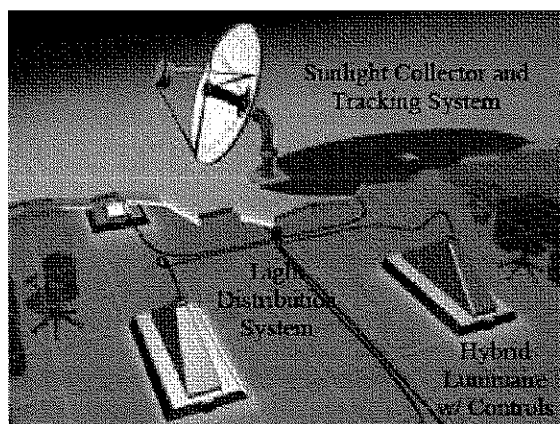


Fig. 1. Hybrid lighting system (<http://www.ornl.gov/hybrid-lighting/techoverview.htm>).

2.1. Concentrating collector

The concentrating collector is in the form of a circular parabolic mirror and a receiver onto which the radiation is focused. The collector gathers the terrestrial radiation and increases the power density of the light by focusing it onto the smaller area of the receiver. Materials used for the concentrator have an average reflectivity of approximately 0.95. Reflection losses and losses due to the secondary element obstruction determine the output of the concentrating collector. A photo of a prototype collector operating at Oak Ridge National Laboratory (ORNL) is shown in Fig. 2.

2.2. Secondary element—cold mirror

The secondary element lies near the focal point of the concentrating collector. It is assumed that all of the solar radiation reflected from the dish strikes the secondary

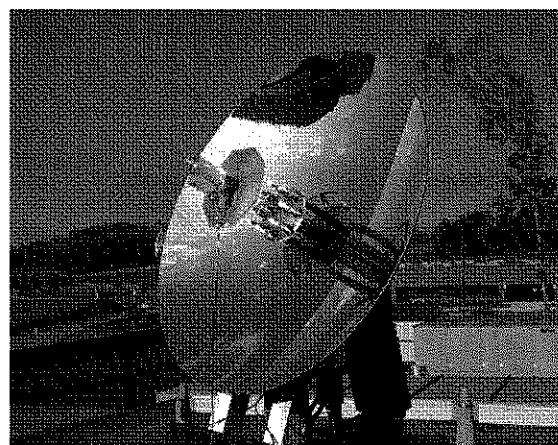


Fig. 2. Hybrid lighting prototype.

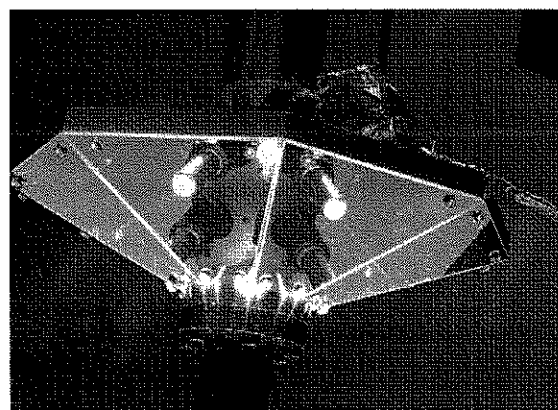


Fig. 3. Secondary element.

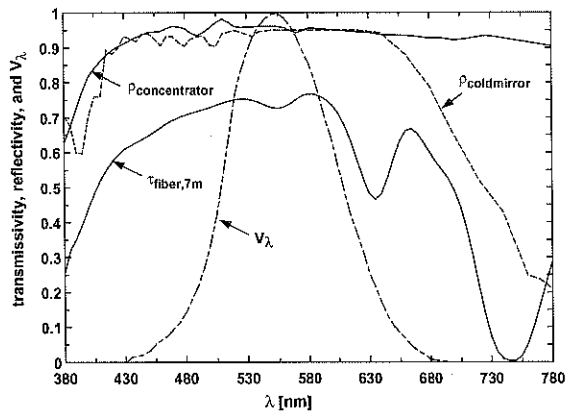


Fig. 4. Hybrid lighting component properties (visible spectrum).

element. The secondary element is comprised of an eight faceted “cold” mirror shown in Figs. 2 and 3. The “cold” mirror allows infrared energy to be transmitted while the visible energy is reflected. Each section of the cold mirror reflects 1/8th of the total visible radiation collected by the concentrator and directs it into one of the light fibers. Fig. 3 shows a picture of the cold mirror with the light fiber shown in the reflection. The spectral properties of the cold mirror are not perfect and some of the solar radiation is lost in the process of being reflected, transmitted, or absorbed. As shown in Fig. 4, the cold mirror is an especially poor reflector at the transition between the visible spectrum and infrared spectrum. However, the low reflectance in the transition region is relatively insignificant due to the spectral sensitivity of the human eye (IESNA, 2000). The eye does not respond very well to wavelengths approaching 0.78 μm , so the reflectance losses at long visible wavelengths are not as significant as they appear to be. The average reflectance of the cold mirror in the visible spectrum is 93% while the average transmittance in the IR spectrum is 96%.

2.3. Thermal photovoltaic array

The thermal photovoltaic (TPV) array is a gallium antimonide (GaSb) device which is sensitive in the near infrared spectrum. The overall benefit of including the TPV array in the system is that energy in the near infrared spectrum, which would otherwise be wasted, can be used to generate electricity. A typical silicon (Si) photovoltaic cell would not be effective in this application since its sensitivity is very low in the IR spectrum. The thermal photovoltaic array is made up of 100 cells wired in series over an area of approximately 180 cm^2 . Due to the series configuration of the TPV array, the array performance will be limited by the cell which receives the least amount of radiation. A non-imaging

optical device is being developed to provide a uniform level of radiation incident on the surface of the array. Current simulations performed at the University of Nevada-Reno indicate that a rectangular tube with a wall reflectance of 95% can increase the uniformity of the radiation incident upon the surface of the TPV array (Dye et al., 2003). The study indicates the flux variation to be +7.9%, to –10.8% when using a rectangular tube approximately 25 in. in length. Additional losses will occur due to geometric differences between the array and the optical device. The model used in the simulations includes a uniform 95% reflection loss from the walls of the optical device and an additional 20% loss due to differences in the geometry of the optical device and the TPV array. The non-uniform flux distribution limits the output of the array so an additional 10.8% reduction in incident IR radiation is included in the model to account for the variation predicted by Dye et al. (2003).

2.4. Light distribution system

The light transmission system is composed of flexible, large-core optical fibers. Visible light reflected from the secondary element is focused into these fibers and transmitted to locations in the building where it is needed. The current material being evaluated is a high-luminance light fiber. The light fiber is made of polymethacrylate which is flexible and resistant to fatigue, elongation, and vibration. The spectral attenuation of the fiber is very low except for an absorption band near 635 nm. In the simulations, the optical fiber length is assumed to be 7 m per module. The average transmittance of a 7 m length of fiber for visible light was 75% as seen in Fig. 4. The spectral transmittance and additional details related to the attenuation of the fibers are reported by Schlegel (2003).

The optical fiber temperature will reach a critical point at the fiber inlet unless some type of IR filtering is used. Tekelioglu and Wood (2003) evaluated a number of different filtering and cooling methods and concluded that two techniques could be economical and effective. One technique involves the use of an additional IR filter to reflect any IR radiation before it enters the light fiber. However, the filter transmittance of 90% adds significant losses to the light production of the hybrid lighting system. The second technique uses 14 mm thick fused quartz glass to filter out any undesirable IR radiation. The fused quartz glass method offers an economical and effective solution to overheating at the fiber entrance. Losses due to the coupling of the quartz and optical fiber are estimated at 3% and visible transmission losses through the quartz are estimated at 2% (Maxey et al., 2003).

Another important aspect of the transmission system is the effect the light fiber has upon the color of the light output from the fiber. In a typical installation the light

fibers are run through ceilings and walls to get to the appropriate location. The route will undoubtedly contain many bends. Bending the light fiber causes increased attenuation and a shift in the color of the light. ORNL has developed a chromaticity model to predict the color change of the light depending on the length of light fiber, number of bends, and bend radius (Earl and Muhs, 2003). The effect of additional attenuation losses due to bending has not been included in the model presented here. This hybrid lighting model uses fiber and mirror spectral attenuation data, a uniform entrance loss, and average fiber length to model the transmission losses.

2.5. Luminaires and controls

Control systems will have to be created to ensure that the combination of hybrid solar and electrical lighting maintains a uniform lighting level. A control system consisting of light sensors coupled with dimmable electronic ballasts can adjust the artificial illumination levels within the building during the presence of natural light. Unfortunately the efficacy of dimmable fluorescent lighting decreases with decreasing load fraction (NLPIP, 1999). Another control scenario involves using constant efficacy fluorescent lighting and controlling the illumination by turning the lights on and off in stages. Problems with the staging control strategy include lighting uniformity and illumination level variation. A control system combining the dimmable fluorescent lighting with a staging control strategy may be the best solution.

The hybrid lighting systems have a combination of electrical and natural light sources in each luminaire. Each luminaire needs to be able to produce a uniform source of light using electrical light, natural light, or both. Two designs have been developed that can be integrated into existing or new construction. An end light design 'plugs' the light fiber into a hemispherical diffuser much like recessed incandescent light fixtures. A side-light design utilizes a cylindrical diffuser, similar in shape to a fluorescent light bulb, to distribute the light evenly. Both designs are currently being developed to improve the light distribution and efficiency. Sufficient spectral data are not currently available to predict the efficiency of the different luminaire designs. Preliminary experimental data from ORNL reported a 58.4% efficiency of the side emitting rod luminaires (Earl et al., 2003). It is estimated that nearly 20% of the losses are due to optical fiber coupling losses which have since been addressed by Maxey et al. (2003).

3. The hybrid lighting model

The hybrid lighting simulation was developed to utilize either spectral (narrow-band) or average (wide-

band) data to model radiation and hybrid lighting component properties. The TRNSYS model consists of one new subroutine, type 292, that models the performance of both the narrow-band and wide-band hybrid lighting models. The wide-band model simulates a hybrid lighting system using average spectral properties of the components, while the narrow-band model uses spectral properties input at 5 nm bandwidths. The narrow-band model utilizes spectral data for the concentrator, the secondary element, the TPV, the optical fibers, and the human eye. The solar irradiance model embedded within the narrow-band subroutine predicts the spectral distribution of direct normal solar radiation at 5 nm bandwidths based upon the output of SMARTS, version 2.91 (Gueymard, 2000). Both the wide-band and the narrow-band models predict the potential savings of a hybrid lighting system in terms of energy and dollars.

3.1. The building model

The building component is modeled using the TRNSYS type 56 multi-zone building model. Type 56 is designed to provide detailed thermal models of buildings. The model consists of two windowless 2500 m² zones. One zone uses standard fluorescent lighting and the other zone uses a hybrid lighting system. Schedules in the two zones simulate the heating, cooling, and ventilation of a typical mixed use environment. Additional gains in the model account for the people, computers, and lights in the building. Cooling in the building is supplied using a chiller and heating loads are met through the combustion of natural gas. Using time-of-day rate schedules, energy costs can be calculated for the two zones of the building model with the difference representing the energy savings due to the hybrid lighting system.

4. Simulation results

Annual simulations were run to evaluate a hybrid lighting system in six different climate regions within the United States (US). Reno, NV and Tucson, AZ, were used to represent mountain and desert climates. Seattle, WA, was chosen to show the effectiveness of the technology in the Pacific Northwest. Madison, WI was chosen to represent the Midwestern US, and Atlanta, GA was used to represent the Eastern US. An additional simulation was run for Honolulu, HI due to the large amount of sunshine and high electricity prices in Hawaii. The results of the simulation include lighting, heating, and cooling load estimates for the building with and without the hybrid lighting system. The annual energy savings due to the hybrid lighting system can be calcu-

lated from the difference in energy loads and the generation from the TPV array.

The simulations were run using the type 56 building model, the narrow-band hybrid lighting model, and TMY2 weather data for each location. The concentrator surface consisted of a highly reflective enhanced aluminum coating with an active area of 1.7 m². The optical fibers averaged 7 m in length with an 8% fiber entrance loss included to account for additional IR filtering and reflective losses. Illuminance levels in the building were set to 500 lux from 8 am to 5 pm 7 days a week, and the luminaire efficiency, based upon the light input to the luminaire and the useful light output, was assumed to be 83%. Simulations were performed using both high-efficacy and low-efficacy auxiliary lighting to show the effect of building lighting upon the hybrid lighting system performance.

4.1. Lighting

The lighting loads of the building with increasing numbers of hybrid lighting modules and perfect controls are shown in Fig. 5. The lighting load decreases linearly with increasing number of modules until the lighting system begins to saturate. At the saturation point, the hybrid lighting system produces more light than is needed on some days and thus displaces less energy per additional module. The system in Tucson, AZ performed the best and the system in Seattle, WA showed the worst performance. Although the system in Hawaii is closer to the equator the high amounts of moisture in the Hawaiian climate lead to smaller amounts of annual beam radiation than dry climates like Reno, NV and Tucson, AZ.

The system in Hawaii saturates at a higher number of modules than the other locations because the lower latitude resulted in daylight hours more in phase with the building lighting hours. The fluorescent lighting in

the building is operational from 8 am to 5 pm. In Hawaii the sun always rises by 8 am and sets after 5 pm, but in Reno for 2–3 months of the year the sun sets before 5 pm. During this time the hybrid lighting system cannot be used in Reno but it still can be used in Hawaii. Longer useful daylight hours in Hawaii lead to a larger number of modules before saturation when compared to an identical system located in Reno.

The lighting load with no hybrid lighting modules is higher when using a low efficiency light bulb as shown in Fig. 6 for Tucson, AZ. When the number of hybrid lighting systems is increased the energy savings is greater for the set of simulations using low-efficacy lighting. Although low-efficacy lighting makes the hybrid lighting systems more attractive this study uses high-efficacy lighting; if the system is attractive with high-efficacy lighting then it is even more attractive with low-efficacy lighting (such as halogen lighting used in jewelry stores).

Realistic controls contribute additional losses to the hybrid lighting system. The control system simulated consisted of 85 lm/W electronic dimmable ballasts and bulbs, photosensors, and a four-stage control strategy. By dividing the lights into equal stages, the lights can be maintained at full operational levels and turned off or on to reduce or increase the lighting load as needed. In a two-stage system the lights are divided into two groups. Both groups remain on until the hybrid lighting system provides 50% of the lighting load. At this point one stage, or in this case, half, of the lights are turned off while the remaining lights stay on. The remaining half of the lights stay on until the entire load is met by the hybrid lighting system. Staging systems with more than two stages are designed in the same manner with each stage designed to meet an equal fraction of the lighting load.

The simulation results shown in Fig. 5 assume perfect control. An available control system using 85 lm/W

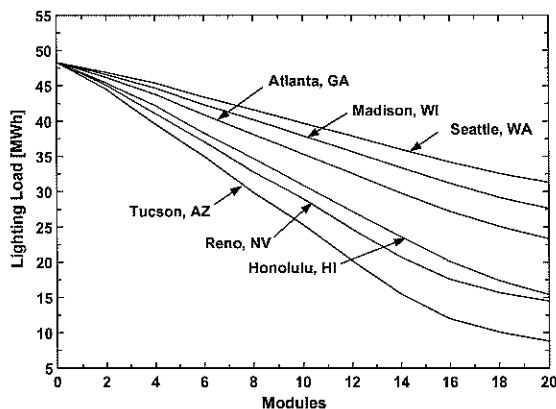


Fig. 5. Lighting load with a lamp efficacy of 85 lm/W.

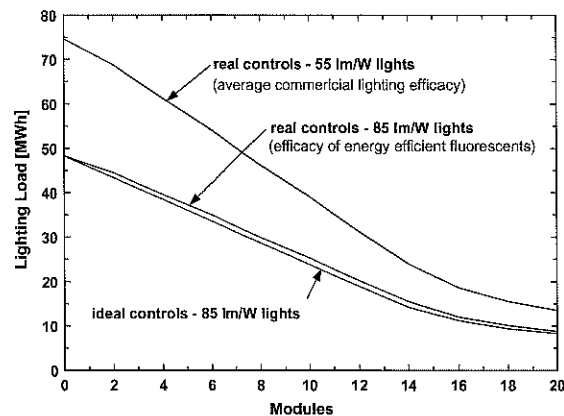


Fig. 6. Annual lighting load with a hybrid lighting system, Tucson, AZ, USA.

electronic dimmable ballasts and bulbs, photosensors, and a four-stage control strategy was implemented in the model. In this control system, the photosensors provide feedback to continuously adjust the lighting level in the building. The auxiliary fluorescent lighting system is dimmable, but part-load operation results in lower efficiency lamp performance. Staging controls were introduced to minimize the dimmable lamp and ballast inefficiencies at part-load. By dividing the lights into equal stages, the lights can be maintained at high load levels and turned off or on to reduce or increase the lighting output as needed. Using a staging control strategy allows the auxiliary lighting to operate at higher load fractions resulting in more efficient performance.

Simulations using the same physical parameters as used to generate Fig. 5 but with realistic controls rather than perfect controls were performed and the results are included in Fig. 6. A comparison of the results included in Fig. 6 indicates that a well-designed control system can have very little impact upon system performance. For the six locations simulated, the losses due to the controls were responsible for approximately a 5–10% increase in lighting load per system module. A poorly designed control system results in increased lighting loads and decreased benefits from the hybrid lighting system. The control system also impacts the building heating and cooling loads. Cooling energy savings decreased by roughly 5% for all locations while changes in heating energy savings were negligible.

4.2. Cooling

Simulations run in warmer climates such as Honolulu and Tucson tended to have higher annual building cooling loads than cooler climates in Seattle and Reno. Madison which has the coldest climate of the selected locations surprisingly has a higher cooling load than Reno or Seattle due to the latent cooling load in the summer. In all of the locations, the cooling load decreased with increasing hybrid lighting modules and then began to increase again as excess light was introduced into the building.

Since filtered natural light has an efficacy of approximately 200 lm/W, increasing the amount of natural light that displaces artificial light in the building should result in a reduced cooling load. Fig. 7 shows the change in cooling load with additional hybrid lighting modules for the simulation using 85 lm/W fluorescent lamps. As with the lighting load, the cooling load decreases linearly with additional systems until the building begins to saturate. As the building saturates, more light is brought into the building than is needed, thereby increasing the cooling load. From Fig. 7 it is clear that sunny locations like Tucson, AZ, Reno, NV, and Honolulu, HI which already benefit from an abundance of natural daylight also have large reductions in cooling

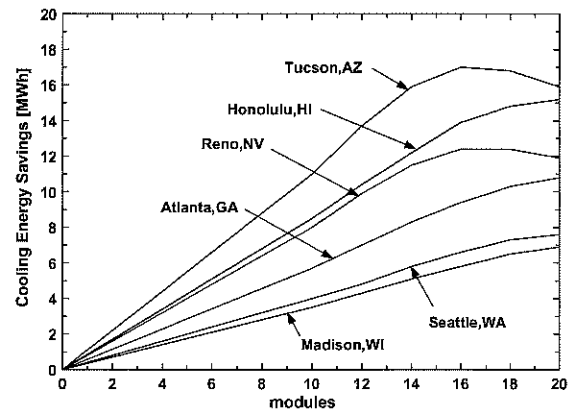


Fig. 7. Cooling energy savings with 85 lm/W lighting.

load making them ideal places for a hybrid lighting system.

4.3. Heating

As expected, the locations with colder climates have a higher heating load than locations with warmer climates. All of the chosen locations need some type of heating except for Hawaii. The change in lighting gains has less of an effect on the heating load because the much of the heating load occurs at night when the lights are off. This result is in contrast to the cooling load which typically occurs during the day when building gains and ambient temperatures are high.

Due to the range of heating loads in the various locations, Fig. 8 was included to show the effect of increasing numbers of hybrid lighting modules upon the building heating load. The buildings in Madison, WI and Atlanta, GA behave as expected with a linear increase in heating load with increasing number of hybrid

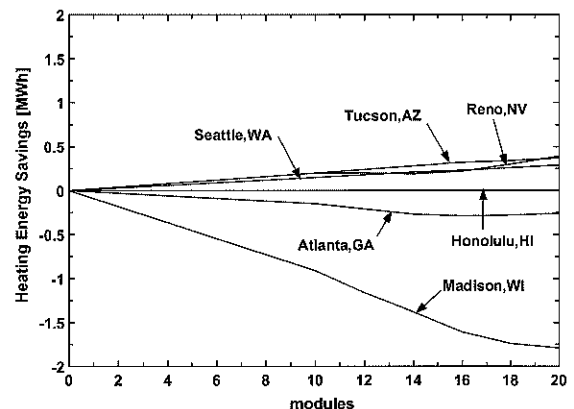


Fig. 8. Heating energy savings with 85 lm/W lighting.

lighting modules. The unexpected decrease in heating load in Seattle and Tucson is due to the low annual heating demands which are dominated by night-time heating. The hybrid lighting system is only effective during daylight hours and most of the heating in these locations occurs just before sunrise. From further analysis it was found that the change in heating load was directly due to the hybrid lighting system's impact upon the cooling load during the day. The decreased cooling load from the hybrid lighting system resulted in a higher average zone temperature. As heating becomes necessary the higher zone temperature due to the hybrid lighting system results in a lower heating load.

The climate in Reno results in both heating and cooling during the same day for much of the year. Up until about 10 modules, the building in Reno experiences a decreased heating load much like Tucson and Seattle. From 10 to 15 modules, the heating load begins to increase slightly due to an increased heating load during the day caused by the hybrid lighting system. At approximately 16 modules, the building begins to saturate with light and the heating load decreases due to the heat associated with the excess light.

4.4. TPV

The electricity produced by the TPV array is directly proportional to system size and annual beam radiation. The array in Tucson, AZ receives the most beam radiation and produces the most electricity while the array in Seattle, WA receives the least amount of beam radiation and produces the least amount of electricity. The revenue produced by the TPV array, shown in Fig. 9, is a function of the annual energy production as well as the local utility rate. All energy produced by the array is assumed to be sold back to the utility at the rate the utility charges less metering, distribution, and demand fees. Electricity in Hawaii is the most expensive at an

average cost of \$0.184/kWh while the average cost of electricity in Atlanta is only \$0.062/kWh.

4.5. Annual savings

The annual energy savings of each system is due to the reduction in lighting and cooling loads, the heating load impact, and the electrical energy produced by the TPV array. The energy savings is converted into dollars using rate schedules from utilities near the simulated locations. Time-of-use commercial rates were used for electricity costs and natural gas costs were based on fixed commercial rates. Fig. 10 shows the simulated annual savings for the hybrid lighting system. Due to the high cost of energy, a hybrid lighting system saved the most money in Honolulu, while inexpensive energy in Atlanta resulted in the lowest savings. The lighting controls introduce inefficiencies in the auxiliary lighting system at part-load. These inefficiencies cause the savings, shown in Fig. 10, to increase with increasing system size until each hybrid lighting system begins to saturate the building with light. Once the building has more light than is needed the savings due to the hybrid lighting system decreases.

4.6. Economic analysis

Using the annual savings, the break-even capital cost of a hybrid lighting system can be determined for a particular location. The hybrid lighting model uses the P_1 , P_2 economic method to calculate the break-even capital cost (BECC) (Duffie and Beckman, 1991). The BECC method is chosen due to the nature of the economic indicator. At this point in the design stage, realistic component prices are not available for determining economic parameters such as years to payback, life-cycle savings, or return on investment. Instead the BECC is

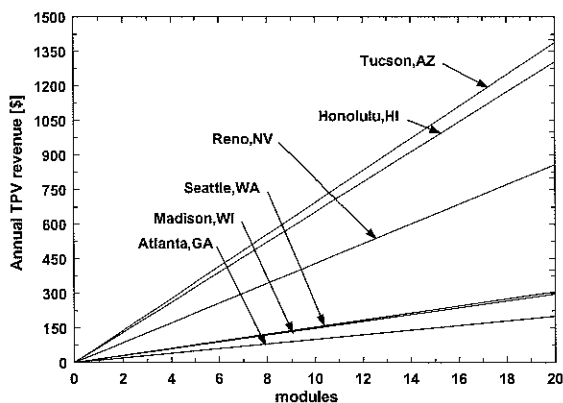


Fig. 9. Annual TPV revenue.

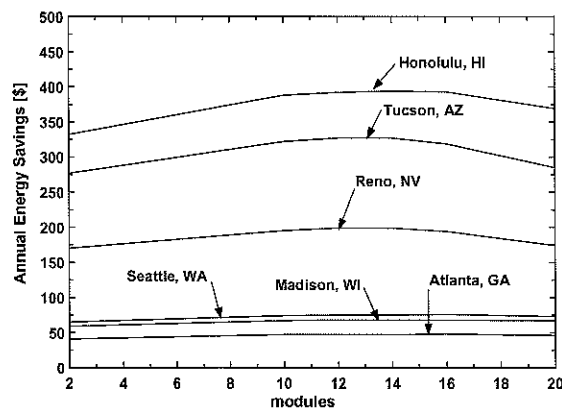


Fig. 10. Annual savings 85 lm/W dimmable bulbs and ballasts, four-stage controls.

calculated as a price target where the energy savings predicted by the TRNSYS model will economically compensate for the cost of the hybrid lighting system. The BECC, based on the P_1 , P_2 economic method, condenses 14 economic parameters into one which simplifies any additional economic analyses. P_1 is the ratio of the life-cycle fuel cost to the first year fuel costs, and P_2 is the ratio of equipment life-cycle owning and operating cost to initial equipment cost. The parameters P_1 and P_2 can be used in Eq. (1) to calculate the life-cycle savings (LCS) of a piece of equipment. Setting the LCS to zero Eq. (1) can be re-arranged to give Eq. (2), the BECC in terms of the ratio P_1 to P_2 and the annual energy savings in dollars from a hybrid lighting system. Using a P_1/P_2 ratio based upon the economic parameters contained in Table 1, the break-even capital cost of a complete hybrid lighting system can be calculated using the annual savings predicted by the TRNSYS model.

$$\text{LCS} = P_1(\text{First Year Fuel Costs}) - P_2(\text{Equipment Cost}) \quad (1)$$

$$\text{BECC} = P_1/P_2(\text{First Year Fuel Cost}) \quad (2)$$

Table 2 shows the break-even capital cost of a hybrid lighting system for the various locations simulated. The break-even capital costs are calculated based on the maximum annual savings for each system over a 10, 20, or 30 year analysis period. For a 10 year analysis period Honolulu, HI and Tucson, AZ offer the highest break-

Table 1
 P_1/P_2 economic parameters

Economic parameters	Values		
Years of analysis (n)	10	20	30
Discount rate (dis)	6%	6%	6%
Fuel inflation rate (inf _f)	2%	2%	2%
General inflation rate (inf)	3%	3%	3%
Initial down payment (down)	20%	20%	20%
Mortgage rate (m)	6%	6%	6%
Years of loan (Y_L)	10	20	30
Years of depreciation (Y_D)	10	20	30
Incoming producing ($C = 1$), or non-income producing ($C = 0$)	1	1	1
Income tax rate (t bar)	40%	40%	40%
Ratio of first year miscellaneous costs to initial cost (M_s)	3%	3%	3%
Ratio of resale value at the end of the analysis to initial cost (R_v)	0.3	0.3	0.3
Ratio of initial valuation to initial cost (Val)	1	1	1
Property tax rate (PR _{tx})	3%	3%	3%
P_1/P_2	6.1	7.7	8.5

even capital costs of and \$2410 and \$1995, respectively. In Madison, WI and Atlanta, GA the break-even capital costs were much less due to inexpensive electricity and lower amounts sunshine.

Table 3 contains a further economic break-down of the hybrid lighting system in Honolulu. Applying the P_1 ,

Table 2
Break-even capital cost

Location	Annual Savings [\$/module]	P_1/P_2	Average energy rate, 8 am–5 pm, summer [\$/kWh]	BECC [\$/module]
Honolulu, HI	\$395	6.1	0.165	\$2410
		7.7		\$3042
		8.5		\$3358
Tucson, AZ	\$327	6.1	0.137	\$1885
		7.7		\$2518
		8.5		\$2780
Reno, NV	\$199	6.1	0.083	\$1214
		7.7		\$1532
		8.5		\$1692
Seattle, WA	\$76	6.1	0.059	\$464
		7.7		\$585
		8.5		\$646
Madison, WI	\$68	6.1	0.056	\$415
		7.7		\$524
		8.5		\$578
Atlanta, GA	\$48	6.1	0.055	\$293
		7.7		\$370
		8.5		\$408

Table 3
Break-even capital costs, Honolulu, HI

Simulation type	Annual savings [\$/module]	Analysis period [yrs]	P1/P2	BECC [\$/module]
Average commercial efficacy (55 lm/W)	\$597	10	6.1	\$3642
		20	7.7	\$4597
		30	8.5	\$5075
Base with 95% luminaire efficiency	\$435	10	6.1	\$2654
		20	7.7	\$3350
		30	8.5	\$3698
Base with ideal controls	\$413	10	6.1	\$2519
		20	7.7	\$3180
		30	8.5	\$3511
Base: (85 lm/W) with real controls	\$395	10	6.1	\$2410
		20	7.7	\$3042
		30	8.5	\$3358
Base without TPV	\$329	10	6.1	\$2007
		20	7.7	\$2533
		30	8.5	\$2797

P_2 , economic analysis to the annual savings, the BECC can be calculated for different hybrid lighting system technologies. From this analysis the incremental BECC of the various technologies can be established and analyzed. Larger annual energy savings (AES) occur when the average luminous efficacy of lights inside the building is less than that of energy efficient fluorescents (85 lm/W). Because commercial buildings employ a variety of lighting sources—incandescent, halogen, fluorescent—the average luminous efficacy of commercial buildings is 55 lm/W. When the HLS is simulated with lighting at this efficacy the AES increases to \$597 with a corresponding BECC of \$3642. Better luminaire design would also increase the AES and BECC. As discussed previously, ideal controls would marginally increase the BECC. The TPV on the Honolulu system is responsible for approximately \$66 of the \$395 per year in annual energy savings. Installing a system without TPV would decrease the AES and BECC by a small amount. Considering the potential cost and added technical difficulty of adding the TPV to the system, the rationale for continued inclusion of the TPV in the design should be considered carefully.

5. Conclusions

Of the locations investigated, the most economic location to install a hybrid lighting system was Honolulu, HI with Tucson, AZ being the best location within the continental United States. Using the predicted annual savings over a ten year analysis period, the break-even capital cost of hybrid lighting modules in these

locations are \$2410 and \$1995. Using longer economic analysis periods results in higher break-even capital costs of \$3042 and \$2518 for a 20 year period and \$3358 and \$2780 for a 30 year period. These costs represent the maximum total cost that could be invested in a hybrid lighting module without having a negative life-cycle cost over the economic period. The hybrid lighting module includes these major components: concentrating collector (active collecting area of 1.7 m²), two-axis tracking equipment, secondary element, TPV assembly, optical fibers (~7 m per module), luminaires, and controls. To manufacture, ship, and install a hybrid lighting module for less than \$2410 per module will be challenging.

Another factor that must be considered in these systems is the value of natural light. Studies have indicated that the benefits of natural light may include personal well-being and productivity (Fay, 2003). If the presence of natural light could be attributed to one less sick day a year, a slight improvement in employee productivity, or a higher probability that people would visit your store, then the break-even capital costs of a hybrid lighting system would increase tremendously. For instance, if the average employee with a salary of \$30,000/year is responsible for \$60,000 of revenue each year, and this employee's productivity increases by just 1% annually due to daylighting, then the additional revenue that the natural light indirectly provides would be \$600 per employee per year. Assume that this occurs in an office environment like the office modeled, with about 150 employees, and the annual savings and additional revenues due to the daylighting increase to \$90,000. If the physiological benefits of natural light could be included

in the overall benefits received from a hybrid lighting system, the break-even capital cost of the technology would increase making it easier to economically justify.

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