ENERGY POSITIVE DAYLIGHTING:
COMBINED DAYLIGHTING AND THERMAL CONTROL IN COMMERCIAL BUILDINGS

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ABSTRACT

Daylighting is an essential element in sustainable commercial building design. However, daily and seasonal variability of the solar resource limits the effectiveness of daylighting for fixed aperture, passive skylight solutions. Beyond a certain point, increases in daylighting fraction can only come at the expense of higher heating and cooling costs. In this paper, a novel approach to integrated daylighting and thermal control will be presented which provides daylight autonomy values higher than standard practice, while reducing building heating and cooling loads. This is accomplished using a new hybrid skylight/solar thermal micro-concentrating module which actively controls the lighting levels in the space while harvesting excess solar energy in the form of high temperature heat which can be used for space heating and solar cooling. The paper will describe the design of both the module and the overall system which is planned for commercial market launch in mid 2013. In addition, the results of a 50 module pilot project on a commercial rooftop in Baltimore completed in early 2012 will be discussed.

1. DAYLIGHTING LIMITED BY HEATING AND COOLING LOADS

Commercial buildings used 18.7 percent of all primary energy consumed in the United States in 2012[1]. Of this total, 20% was used for space heating, 19% for lighting, and 6.0% for cooling, for a total of 8.75 quadrillion BTUs per year, almost ten percent of total US energy consumption. Of all U.S. commercial space, single story buildings comprise 40 percent of the total[2]. Clearly, solutions that address the lighting and space conditioning needs of single story, flat-roofed buildings are an essential part of meeting today's energy challenges. Toplighting is becoming a common energy conservation measure for these building types. Coupled with daylight harvesting systems that dim electric lighting when sunlight is available, skylights have the potential to reduce lighting energy consumption for lighting by 40-60 percent. But because skylights are designed address only one of the building energy needs (lighting), standard fixed-aperture skylights often increase, not decrease, building heating and cooling loads, diminishing the economic returns and limiting the practical skylight to floor ratios to 3-4 percent in most climates.[3]

This can be illustrated by examining the energy savings and losses for lighting, heating, and cooling of a reference building as a function of skylight to floor ratio (SFR). The building, used in each of the analysis cases in this paper, has the characteristics outlined in Table 1 below:

TABLE 1: REFERENCE BUILDING

Climate/TMY File	Baltimore, MD
Building area	40,000 ft^2
Lighting power density	1.25 W/m^2
Lighting efficiency	80 lumens/W
Load profile	Retail
Target illumination level	60 footcandles

The energy savings/losses were calculated using SkyCalc 3.0, a daylighting design tool.[4] SkyCalc default values are used for building characteristics such as building envelope and HVAC parameters.

Figure 1 below shows the contributions of the skylights to the building cooling load. Because natural light has a lower heat content per unit of visible light delivered than artificial lighting (100 lumens/W compared to 80 lumens/W), there is

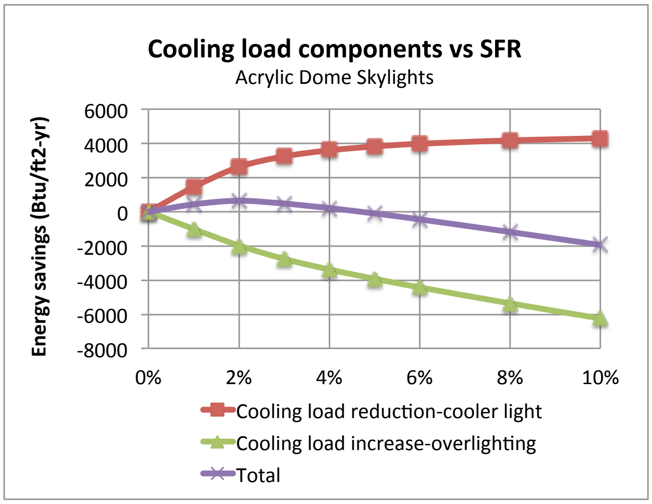

Fig. 1: Cooling load components for dome skylight

	Hour of the day														
	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
January	0	0	4	18	41	58	73	75	69	52	31	9	1	0	0
February	0	0	9	33	58	85	98	93	93	74	47	24	6	0	0
March	0	5	23	54	81	100	117	120	115	97	72	40	12	1	0
April	3	17	48	78	107	126	136	135	129	109	88	56	22	5	0
May	8	31	63	90	118	145	159	151	148	119	97	65	34	10	1
June	12	37	75	107	137	160	170	170	162	142	112	77	43	15	2
July	7	30	65	100	125	147	170	170	159	141	120	84	46	16	2
August	4	21	51	88	118	140	149	144	142	124	100	73	35	9	0
September	1	11	37	68	96	122	128	135	124	99	73	41	13	1	0
October	0	5	24	55	79	101	114	113	101	77	47	19	3	0	0
November	0	1	10	30	53	70	78	80	67	48	24	6	0	0	0
December	0	0	4	18	37	53	62	63	55	38	19	5	0	0	0

Fig. 2: Average daylight footcandles from SkyCalc

a cooling load reduction for increasing contributions of natural light. However, since the lighting levels are not controlled, the actual illumination levels far exceed the required levels during most of the cooling season (see Figure 2). This causes a cooling load increase that, above an SFR of 4%, more than outweighs the cooling effect, resulting in a net increase in the building cooling load.

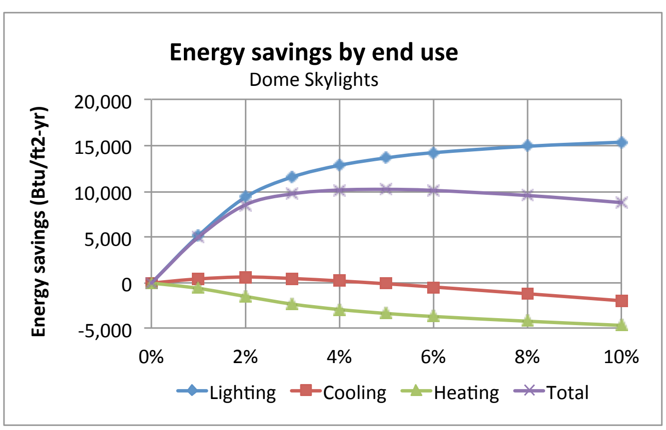

Fig. 3: Energy savings by end use for reference building

Heating loads are also negatively impacted, in two ways. First, the reduced heat content of the light reduces the heat input to the air in the space. Second, increasing skylight area raises the convection heat losses through the skylights to the outside.

The increasing heating and cooling loads combined with the diminishing marginal effectiveness of additional skylight area cause the total energy savings to reach a maximum of about 10 kBtu/ft^2-yr at SFR levels between 3% and 4%. (See Figure 3.) The economic optimum SFR levels are typically below the point of zero marginal savings.[5]

2. INTEGRATED DAYLIGHTING AND THERMAL SOLUTION

In this section an integrated approach is described which also uses sunlight to illuminate the interior space but which collects useful heat while simultaneously reducing both heating and cooling loads. This approach eliminates the fundamental upper limit on the skylight density, allowing higher SFRs and much higher energy savings than the baseline case.

The energy positive daylighting system employs a customized skylight made of multiwall polycarbonate with curved polycarbonate glazing sheet that houses an array of reflecting louvers (Fig. 4). The layered design of the multiwall construction reduces the U-value of the skylight to about half that of a double glazed skylight. The louvers concentrate the sun's direct rays onto receivers that can either transmit the energy as lighting into the space below or capture the light as high grade heat (Fig. 5). As shown in Fig. 6, small changes in the angle of the mirror cause the focal point of the light to strike the thermal absorbing surface, a reflector that directs the light to the space below, or some combination of the two. Glycol is circulated directly through the absorbing surface to capture the heat. During periods of low direct sunlight, the louvers are

Fig. 4. Energy positive skylight with daylighting and thermal control

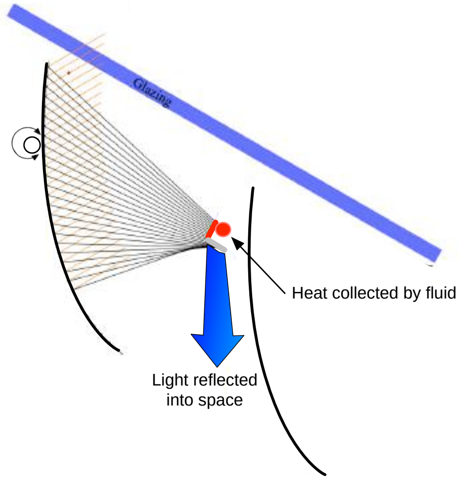

Fig. 5: Louver movement to split energy flow

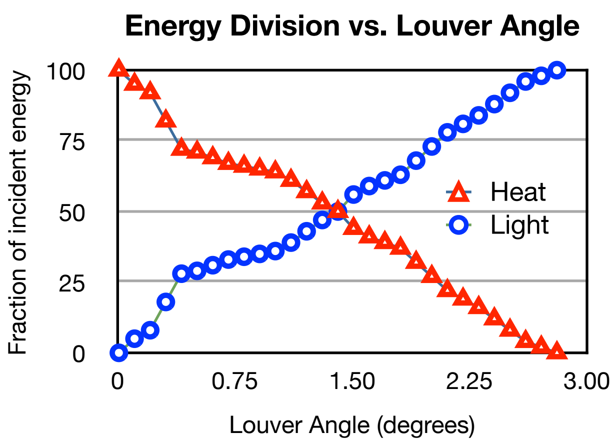

Fig. 6: Energy division as function of louver mirror angle

opened fully to allow all available diffuse light to penetrate into the building space.

The louver angle is controlled by a small motor powered by a control board that is also connected to an array of light sensors installed in the light well of the skylight (Fig. 7). The controller continuously seeks to maintain a desired lighting output from the module. The louver angle is thus continually adjusted to maintain the lighting output in the presence of changes in the sky conditions and desired light setpoint. As the fraction of lighting varies in response to conditions, the fraction of energy going into thermal heat changes in inverse proportion.

The close control of the light output from the module has several direct benefits. First, it allows the daylight illumination levels to be changed in real time time to satisfy varying lighting requirements. For example, light output can be tied to an occupancy sensor to allow 100% thermal energy capture when no lighting is needed. This also frees the system designer from having to match the density of skylight spacing to the lighting requirements of the space below. Skylights can be evenly spaced, and the light output adjusted dynamically.

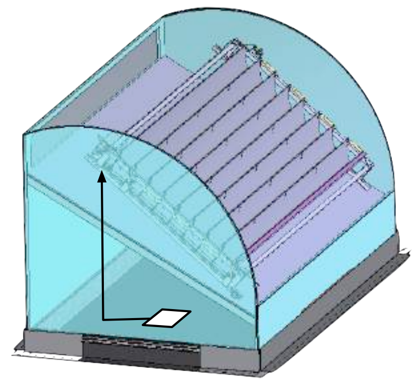

Fig. 7: Feedback light sensor location

Second, the excess lighting effect that negates the potential cooling load savings in standard skylights as seen in Figure 2 is greatly reduced, allowing the cooling benefits of high efficacy sunlight to be realized. This is illustrated in Figure 8, which shows a direct comparison of the average daylight illumination levels. Since the light output of each skylight in summer is reduced by more than half, the glare that is typically emitted from skylights in midsummer is greatly reduced.

Finally, the direct control of lighting levels enables a different type of space heating: direct radiant heating. In winter, the high profile of the skylight and the angle of the louvered concentrator enable the capture of far more solar energy than is needed for illumination during periods of direct solar flux. While this excess energy could be directed to the thermal absorbing surface for storage and use as space heating or process heat, it is more efficient from a thermal standpoint to direct the light down into the space to

Hour of the day

	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
January	0	0	4	18	41	58	73	75	69	52	31	9	1	0	0
February	0	0	9	33	58	85	98	93	93	74	47	24	6	0	0
March	0	5	23	54	81	100	117	120	115	97	72	40	12	1	0
April	3	17	48	78	107	126	136	135	129	109	88	56	22	5	0
May	8	31	63	90	118	145	159	151	148	119	97	65	34	10	1
June	12	37	75	107	137	160	170	170	162	142	112	77	43	15	2
July	7	30	65	100	125	147	170	170	159	141	120	84	46	16	2
August	4	21	51	88	118	140	149	144	142	124	100	73	35	9	0
September	1	11	37	68	96	122	128	135	124	99	73	41	13	1	0
October	0	5	24	55	79	101	114	113	101	77	47	19	3	0	0
November	0	1	10	30	53	70	78	80	67	48	24	6	0	0	0
December	0	0	4	18	37	53	62	63	55	38	19	5	0	0	0

Hour of the day

	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
January	0	0	4	42	44	52	53	52	54	52	46	17	0	0	0
February	0	0	9	44	51	53	55	58	58	58	58	49	21	2	0
March	0	0	5	26	43	55	59	60	60	60	59	46	29	9	0
April	0	13	31	47	53	57	61	61	61	61	58	55	41	12	1
May	3	22	53	56	60	64	68	68	66	67	65	60	57	34	8
June	5	37	51	61	65	68	71	72	69	63	59	52	42	19	3
July	5	29	50	57	63	67	74	76	75	75	68	61	51	35	12
August	0	6	36	57	60	67	69	75	78	79	70	62	56	39	13
September	0	14	54	59	61	63	69	72	69	64	59	58	44	11	1
October	0	2	23	45	54	57	59	61	60	58	58	54	38	5	0
November	0	0	23	36	49	51	56	57	52	50	41	26	2	0	0
December	0	0	6	33	45	50	53	53	54	53	51	32	4	0	0

Fig. 8: Daylighting footcandles with active control (right) compared to baseline uncontrolled case

Hour of the day	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
January	0	0	4	62	93	139	143	157	154	130	73	16	0	0	0
February	0	0	9	54	114	143	154	157	154	148	106	62	20	2	0
March	0	0	5	25	50	86	101	124	112	83	75	54	27	9	0
April	0	13	43	81	112	133	131	122	115	94	89	70	40	12	1
May	3	22	72	95	95	82	77	79	67	76	67	66	58	34	8
June	5	37	51	61	65	68	71	72	69	63	59	52	42	19	3
July	5	29	50	57	63	67	74	76	75	75	68	61	51	35	12
August	0	6	36	57	60	67	69	75	78	79	70	62	56	39	13
September	0	14	54	59	61	63	69	72	69	64	59	58	44	11	1
October	0	2	23	64	74	57	59	61	60	58	58	54	38	5	0
November	0	0	24	61	120	115	126	111	92	90	52	25	2	0	0
December	0	0	6	37	87	126	144	147	155	147	91	31	4	0	0

Fig. 9: Daylight illumination levels using radiant heating

intentionally exceed the minimum lighting levels to provide direct radiant heat. (See Fig. 9) The direct heating is delivered at a higher efficiency than if the heat were captured since the losses in the thermal absorber and in the transport and storage of the thermal fluid and heat are avoided.

Direct heating has other advantages as well. The radiant energy is absorbed by the floor, ceiling, walls, and other surfaces in the space, offsetting the heat load increases of the cooler sunlight. The radiant energy also raises the temperature of these surfaces and so that the mean radiant temperature experienced by the occupants is elevated. This higher radiant environment enhances the thermal comfort of the occupants and also allows the setpoint of the forced air heating system to be reduced while providing the same level of comfort, which saves an additional amount of heating energy[6]. Finally, good daylighting is particularly important during the heating season to counter seasonal affective disorder (SAD), a mild depression that has been linked to low sunlight levels in the winter months in temperate climates. Not all types of buildings would be able to make use of these high lighting levels. Grocery stores, for example, often have tighter illumination requirements that, if exceeded, would cause adverse effects on merchandise such as produce or open refrigerated cases.[7]

The collection of heat using an optical concentrator system has higher thermal efficiency compared to flat plate and evacuated tube collectors and also maintains high collection efficiency at temperatures above 200 F. Single effect absorption chillers require heat in the range of 160 F to 200 F, and so these systems provide an additional opportunity to offset cooling loads in the summer months. The chilled water produced by these systems driven by heat from an array of modules described here can be used for supplementing the air conditioning system cooling, or for refrigeration subcooling in grocery stores or other industrial buildings that require low temperature refrigeration.

3. SYSTEM DESIGN USING ENERGY POSITIVE SKYLIGHTS

An example of a system design making use of each of the energy streams that can be provided by the system described is shown in Figure 10 below. A problem that arises when operating a system with one input and multiple outputs is how to prioritize among the possible choices to maximize the value of the system. Table 2 may be used as a guide, which shows the energy effectiveness of each output stream. The energy effectiveness is defined as the primary energy displaced for each unit of incident solar energy. Primary energy is defined as the raw fuel energy that has not been subjected to any conversion or transformation process. It is a useful metric when comparing energy streams of varying quality (or exergy), such when comparing electrical and

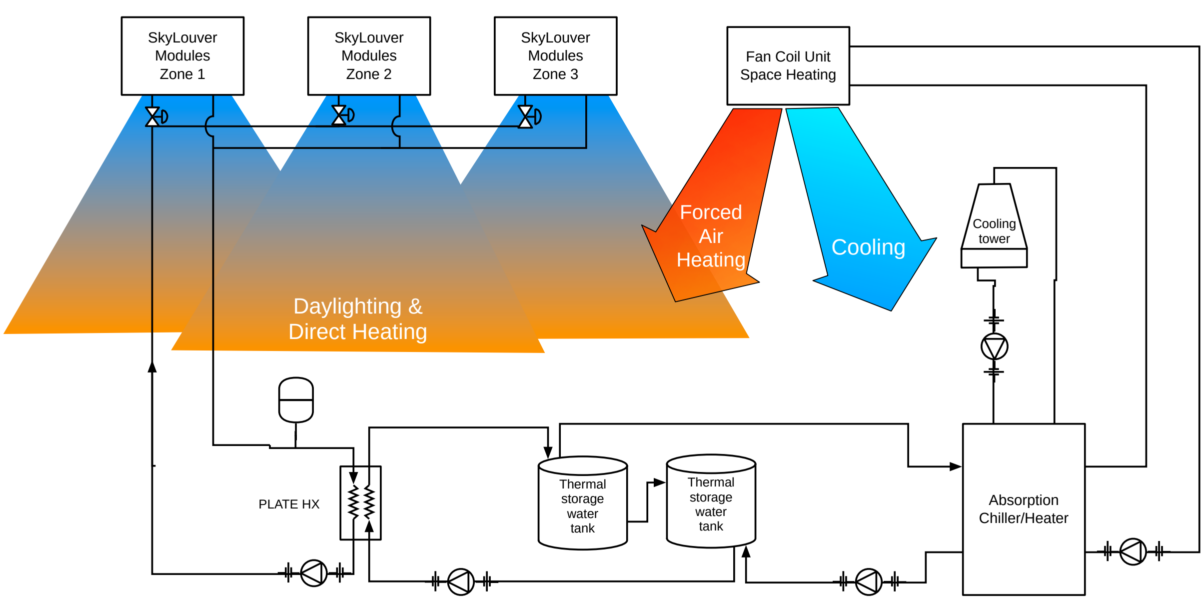

Fig. 10: Example building energy system design using an energy positive daylighting system

TABLE 2: RELATIVE VALUE OF ENERGY STREAMS

Energy Use	Average solar collection efficiency	Displaced load	Energy effectiveness (Primary energy displaced/incident solar energy)
Daylighting	61%	Lighting at 80 lumens/Watt	2.28
Radiant heating	61%	Furnace at 85% efficiency	0.71
Refrigeration subcooling	45%	Chiller at 1.8 kWe/ton subcooling	0.50
Air conditioning	45%	Packaged AC at COP=2.8	0.34
Hot water & space heating	55%	Boiler/furnace at 85% efficiency	0.24

thermal energy savings. For calculation purposes, electrical energy is multiplied by a factor of three to obtain the primary (fossil) energy source that is required to generate it, which is equivalent to an electrical generation and distribution efficiency of 33%.

Each of the end uses of the solar energy shown has a different efficiency for collection and distribution. Daylighting and radiant heating have an efficiency of 61% which is the value of transmittance of visible light for the optical portion of the module. The other three energy streams have a thermal collection efficiency that is a function of the average collection temperature. Since the absorption chiller requires a higher temperature than hot water and space heating, the collection efficiency for subcooling and air conditioning is lower.

Each energy stream also has a different conversion factor depending on the efficiency of the energy conversion equipment that is displaced by the solar resource. Daylighting has the highest energy effectiveness (greater than one) because it directly displaces electrical energy that requires three units of primary energy to generate. It is for this reason that the module controller is designed to achieve a desired lighting output first before other loads are satisfied. Radiant heating is has the next highest effectiveness due to the direct delivery of the energy to the point of need without thermal conversion losses in the collector, storage and delivery. Applications which make use of the absorption chiller have lower effectiveness due to the high collection temperatures and the fact that the COP of absorption chillers is less than unity (0.7). Hot water and space heating have the lowest effectiveness because they are displacing heat loads, not higher value electrical loads. This does not imply that the energy streams with lower energy effectiveness are not desirable per se, but only that in a relative sense the applications with a higher effectiveness are generally preferable at any given time. This relative ranking of energy value is independent of capital costs, and is meant to inform operational decisions and not necessarily design. Other factors, such as renewable energy credits, rebates, subsidies and fossil/electrical energy ratios will also affect the cost effectiveness of the energy streams and are not considered here. Another important factor, also out of the scope of this paper, is the degree to which a value stream can be relied upon for reducing the peak electrical demand for the building. Demand reduction increases the financial value of the displaced energy due to reduced demand charges or time of day billing. For further information on this, see Ref. (8).

4. ANALYSIS RESULTS

The system shown in Figure 10 was modeled to determine the overall energy savings that can be achieved as a function of skylight to floor ratio (SFR). The model considers each surface of the energy positive skylight shown in Figures 4 and 7, its orientation, and the direct and diffuse solar flux that is incident on it on a hourly basis throughout the year, both from the sky and reflected from the roof. A performance model of the concentrating louver element was developed from measured performance data for the thermal efficiency and light transmission characteristics. An array of these hybrid skylights was then combined with a simple building energy balance model driven by TMY2 weather data that was benchmarked to an eQuest model with the same building parameter inputs. The building parameters were the same as those in Table 1 to enable direct comparison with SkyCalc results. Finally, the solar thermal collection, storage, and distribution were modeled and run through the hourly simulation using the priority ranking in Table 2.

The effect of the energy positive daylighting system on the building cooling loads is shown in Figure 11. There is a residual amount of cooling load increase due to overlighting

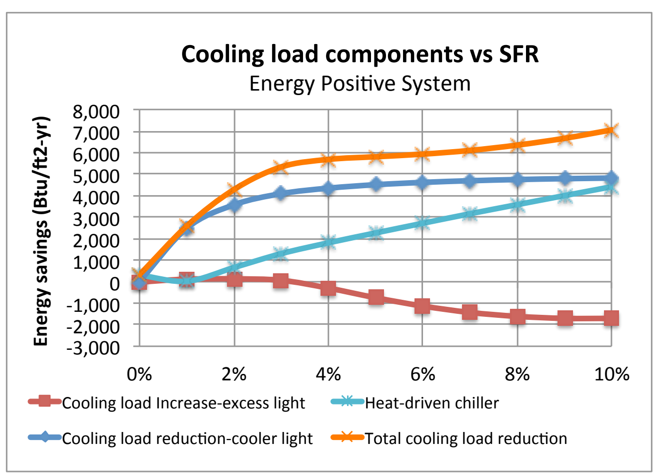

Fig. 11: Cooling load components with integrated system

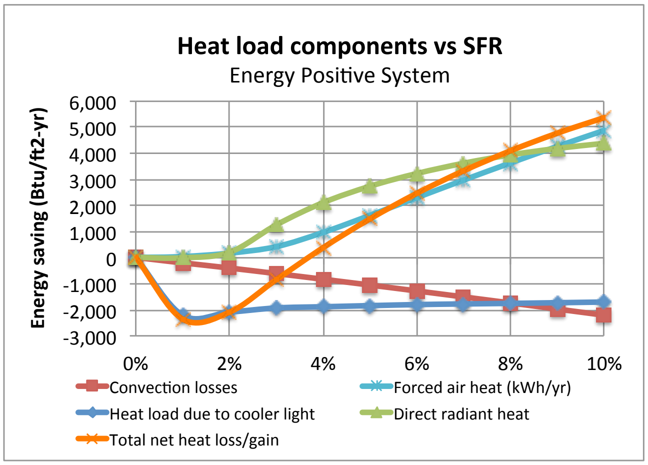

Fig. 12: Heating load components with integrated system

at SFR ratios greater than 4%. The cooling load reduction due to the higher luminous efficacy of sunlight grows rapidly then levels off as the lighting load is satisfied. The other contribution to reducing the cooling load is the output of the heat driven chiller, which grows linearly with SFR at levels above 1%. The convection heat gains through the module are relatively small and so are not shown separately for clarity, but are included in the totals shown. The combined effect on the building cooling load of these energy flows is positive and monotonically increasing.

The heating load summary is shown in Figure 12. The increase in heat load due to the cooler light source levels off at about 2 kBtu/ft^2-yr. The convection losses, more significant for heating load than cooling, increase linearly to 2200 Btu/ft^2-yr at 10% SFR. The two factors that reduce the heat load to save energy are the direct radiant heating and the forced air heating. These values are very small at low SFR levels (below 2%) because the simulated control algorithm prioritizes daylight and there is little excess energy for heating. At SFR levels above 2%, these heat contributions grow to bring the net heat load effect to break even at about 3.5% SFR and to increase the heat savings above that level.

The total energy savings for the energy positive daylighting system and the dome skylights and the are shown in Figures 13 and 14, respectively, which have been given the same y-axis for ease of comparison. The energy positive system has about 30 percent greater lighting savings than the dome skylight due to the higher profile of the rooftop unit which capture more direct sunlight when the sun angle is low in morning, afternoon, and winter periods. The positive contributions to the energy savings for heating and cooling loads cause the total energy savings for the energy positive system to continue to increase monotonically to a savings level of twice that achieved by the dome skylights at 4 % SFR.

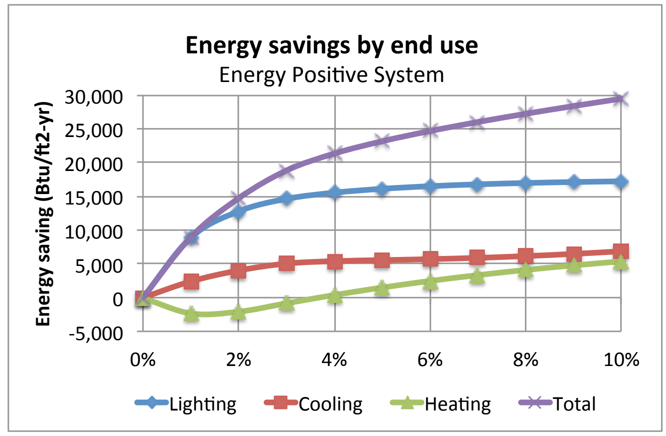

Fig. 13: Total energy savings by end use, integrated system

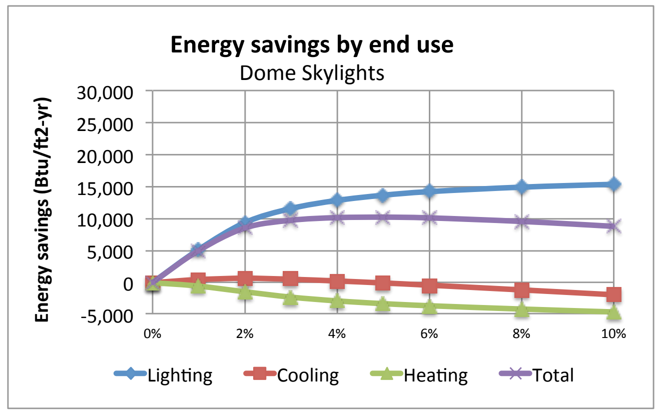

Fig. 14: Total energy savings by end use, dome skylight

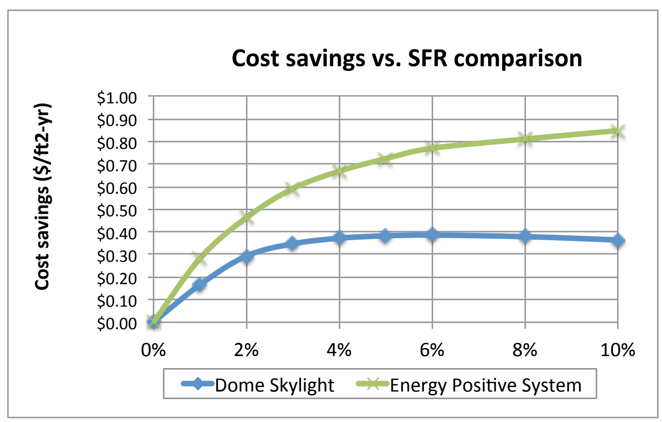

Fig. 15: Cost savings comparison

The fact that the alternative skylights continue to increase changes the economically optimum SFR level. Assuming Maryland statewide average energy costs (10.5/kWh electric and $11/mcf for gas), and common financial criteria, the optimal module density for the energy positive system is 5.5%, which provides an energy savings of 24 kBtu/ft^2-yr, 2.4 times the maximum possible energy savings with dome skylights. A cost savings comparison is shown in Figure 15.

Fig. 15: Fifty module system installed on roof in Baltimore

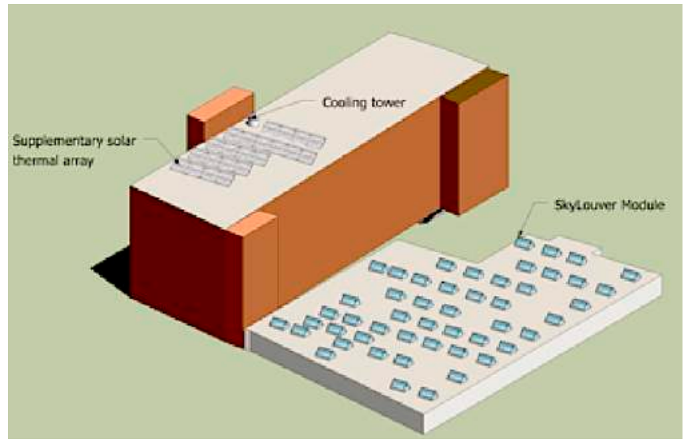

Fig. 16: Full system layout of pilot system at MBC Ventures, Baltimore, MD

5. FULL SYSTEM IMPLEMENTATION

A full scale pilot system using energy positive skylights was installed on a factory building in Baltimore, Maryland, completed in early 2012. The system design is consistent with the system diagram in Figure 10; rooftop layout of the modules is shown in Figures 15; and the site layout is shown in Figure 16.

The 50 modules supply daylighting to an operational single story factory building with an area of 18,000 ft^2. To supplement the heat generated by the hybrid modules, a 900 ft^2 evacuated tube array was installed to ensure that the absorption chiller would have adequate heat to operate. The heating and cooling generated by the system is being used to condition a previously vacant floor of the multistory factory building that is being used for the manufacture of the modules.

The system was developed under a grant from the Maryland Energy Agency(CEEDI-2011-04-531FA). The grant funded the purchase of tooling for building a high volume production line for the modules as will as the manufacturing and installation of the 50 units and ancillary equipment. A full report on the installation is available in Reference (9).

(1) US Department of Energy, Buildings Energy Data Book, Table 1.1.3

(2) Ibid., Table 3.2.3.

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