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The impact of the solar absorption coefficient of roof and wall surfaces on energy use and peak demand

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Abstract. Climate change, electrification to decarbonize the building sector, and the rise of renewable energy sources have made reducing the peak demand even more important than solely reducing the overall energy use. Solar radiation can have a significant impact on the energy use of buildings. However, previous studies on solar absorption in building envelopes have focused on cool roofs. Less effort has been made to evaluate the impact of solar radiation on heat loss and gain on walls. This paper summarizes a preliminary study to estimate the magnitude of the benefit low solar absorptance surfaces have on reducing peak demand and focuses on simulating a residential building with two types of U.S. code-compliant wall structures, a standard lightweight wall assembly, and a thermally massive mass timber wall, to evaluate the impact of the solar absorption coefficient of the surfaces on the heating and cooling energy use and peak demand. This effort aimed to identify whether a more comprehensive study should be undertaken to develop further the calculation tools previously developed for estimating the energy benefits for roofing systems in the U.S. by adding a similar tool for wall assemblies. Reducing the solar absorption coefficient from 0.9 to 0.3 resulted in up to 46% lower cooling demand and a 70% increase in heating demand depending on the climate. Peak demand reductions for heating and cooling energy were similar to the reduction in heating or cooling energy use. However, the annual energy use changed up to only 12% as lowering the solar absorption coefficient reduces cooling demand but increases heating demand. Whether the total impact overall is harmful or beneficial depends on the climate and type of structure. Additionally, a cool roof calculator was used to estimate the impact of solar radiation on roofs. The learning from this study is that the exterior color and the solar absorption coefficient should be chosen based on the climate to positively impact the energy use profile and peak demand.

1. Background

A sharp peak in electrical demand can be observed in almost every building during the busiest hours of the day. Although a share of this peak may be attributed to equipment used in the building, a significant portion is caused by increased demand for air conditioning in the late afternoon/early evening. The peak in demand requires additional power plant capacity; causes more demand than supply in the power grid, requires the utility to purchase power at typically higher rates to satisfy the demand; and may result in increased air pollution. Most importantly for the building owner or tenants, unnecessary peak demand may result in monthly charges many times higher than base electrical rates. One of the best approaches to shrink peak demand is to reduce the heat load on a building, especially the solar load that drives the need for air conditioning. Few passive heat reduction strategies can match the energy-saving potential of modern reflective roofing technology. Unfortunately, the energy impacts of solar-reflective walls are less well documented. To help building owners and designers become more cognizant of peak electrical demand’s energy and economic impact, this research quantifies the reductions in peak demand, greenhouse gas emissions, and economic costs associated with cool roof and wall technologies. This information is especially important since few articles to date on building energy savings have adequately addressed peak demand issues. When deciding on the paint color of walls, little consideration is usually placed on how it impacts energy use and peak demand. White brick and black walls have become a fashion statement in recent years. For white and black paint, the solar absorption coefficient can range between 0.3 and 0.9.

2. Impact of solar absorption on walls and building energy use

The whole-building simulation model EnergyPlus^{TM} v22 [5] was used to evaluate the impact of wall solar absorption on the DOE prototype building [6]. The DOE prototype building, following the IECC 2021 energy code [7], used in the simulations is a two-story, single-family building on a slab. A heat pump provides heating and cooling. The conditioned window-to-wall ratio is 15%. The conditioned area is 220 m^2 (2,377 ft^2),

The simulations included two different U.S. code-compliant wall types: a lightweight wall and a solid mass timber wall. The schematics of the walls and the layer thicknesses are shown in Figure 1. The lightweight base wall is a 2x4 wood framed wall (38 mm x 89 mm) with insulation having an R-value of 2.29 m^{2}K/W and 400 mm on-center framing. Table 1 lists the continuous insulation values and mass timber thickness used in the simulations that meet U.S. code requirements for these three climate zones. The three climates used in the simulations are the hot-humid Houston, TX; mild Los Angeles, CA; and cold Golden, CO.

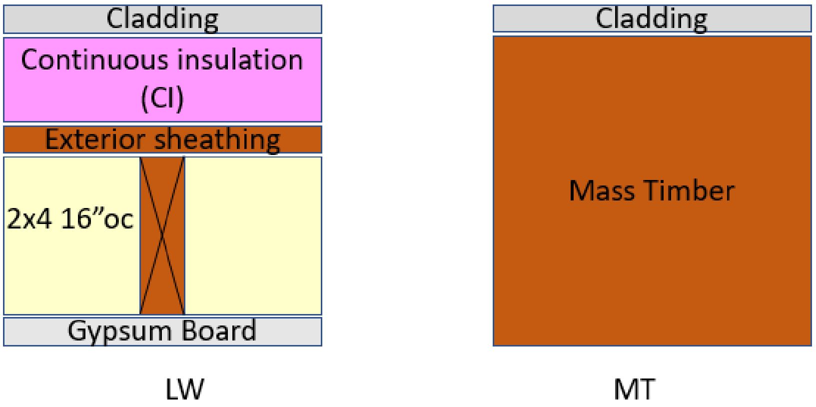

Figure 1. The lightweight (LW) and the mass timber (MT) walls used in the annual simulations.

Table 1. Climate zone, location, and layer descriptions for the lightweight and mass timber walls used in simulations.

Climate zone, city, state	Lightweight wall continuous insulation R-value (m^{2}K/W) and whole wall U-value (W/m^{2}K)	Mass timber wall thickness and U-value (W/m^{2}K)
2A, Houston, TX	No continuous insulation, U-0.47	152 mm mass wood, 0.69
3B, Los Angeles, CA	25 mm extruded polystyrene R-0.88, U-0.35	175 mm mass wood, 0.55
5B, Golden, CO	51 mm extruded polystyrene R-1.76, U-0.27	240 mm mass wood, 0.46

2.1. Impact of wall solar absorption on annual heating and cooling energy use

Table 2 shows the annual heating and cooling energy uses of the lightweight (LW) and mass timber (MT) buildings with different solar absorption coefficients on walls relative to the absorption coefficient of 0.7. The largest impact is in the mild climate of Los Angeles, CA, where the heating and cooling energy use can almost double or cut in half depending on the choice of exterior color of the walls. However, we can also see that the impact on the total energy use is much less due to the opposite impacts of solar absorption on heating and cooling.

Table 2. Annual energy uses relative to building with wall solar absorption coefficient of 0.7. LW=lightweight wall building, MT=mass timber wall building, MT(LW)=mass timber wall building with the same wall U-value as in the lightweight wall.

Energy use	City, state	Wall	Solar absorption coefficient			
			0.3	0.5	0.7	0.9
Heating	Houston, TX	LW	108%	104%	100%	97%
		MT	117%	108%	100%	93%
		MT(LW)	113%	106%	100%	94%
	Los Angeles, CA	LW	115%	107%	100%	94%
		MT	143%	120%	100%	84%
	Golden, CO	LW	107%	103%	100%	97%
		MT	111%	105%	100%	95%
Cooling	Houston, TX	LW	89%	95%	100%	105%
		MT	87%	93%	100%	107%
		MT(LW)	90%	95%	100%	105%
	Los Angeles, CA	LW	74%	87%	100%	114%
		MT	65%	82%	100%	120%
	Golden, CO	LW	87%	94%	100%	106%
		MT	82%	91%	100%	109%
Total, including fan energy	Houston, TX	LW	96%	98%	100%	102%
		MT	97%	99%	100%	102%
		MT(LW)	98%	99%	100%	101%
	Los Angeles, CA	LW	92%	96%	100%	105%
		MT	102%	100%	100%	103%
	Golden, CO	LW	104%	102%	100%	99%
		MT	107%	103%	100%	97%

The impact of the solar absorption coefficient is stronger in the building with mass walls. Table 3 shows the relative performance of the building with mass timber walls as compared to the lightweight wall building. For example, when the solar absorption coefficient is 0.9 on walls, the mass timber building consumes about 18% less heating or cooling energy than the lightweight wall building in Los Angeles, CA. However, when the solar absorption coefficient changes to 0.3, heating energy use is 14% more, and cooling energy use is 31% less in the mass timber building than in the lightweight wall building. The same impact of thermal mass can be seen in Houston, TX: A building with mass walls having the same U-value as in the lightweight building (MT(LW) in Table 2). The lightweight wall building in Houston, TX, was converted into the thermally massive one with the same U-value. The building with thermally massive walls experienced lower annual heating and cooling energy use than the building with lightweight walls. The wall solar absorptance had the same relative change in cooling in both buildings but a higher relative impact on heating in the mass wall building.

Table 3. Relative annual energy performance of the mass timber wall building to the lightweight wall building (annual energy use in the mass timber building/annual energy use in the lightweight building).

		Solar absorption coefficient			
Energy use	City, State	0.3	0.5	0.7	0.9
Heating	Houston, TX	107%	103%	99%	96%
	Los Angeles, CA	114%	103%	91%	82%
	Golden, CO	122%	120%	117%	115%
Cooling	Houston, TX	99%	100%	101%	102%
	Los Angeles, CA	69%	73%	77%	82%
	Golden, CO	82%	85%	88%	90%
Total, including fan energy	Houston, TX	102%	101%	100%	100%
	Los Angeles, CA	94%	89%	85%	83%
	Golden, CO	116%	114%	112%	110%

2.2. *Impact of wall solar absorption on cooling peak demand*

The absorption of solar energy on walls significantly impacts the buildings' peak cooling demand. The largest relative impact in this study was in Los Angeles, CA, which has mild heating and cooling demand. Figure 2 shows the impact of the solar absorption coefficient on the peak cooling demand in the lightweight and mass timber buildings in the three climates. The effect of solar is slightly higher in the mass timber building. Los Angeles, CA, experiences the strongest impact of solar in the relative performance, followed by Houston, TX, and then Golden, CO.

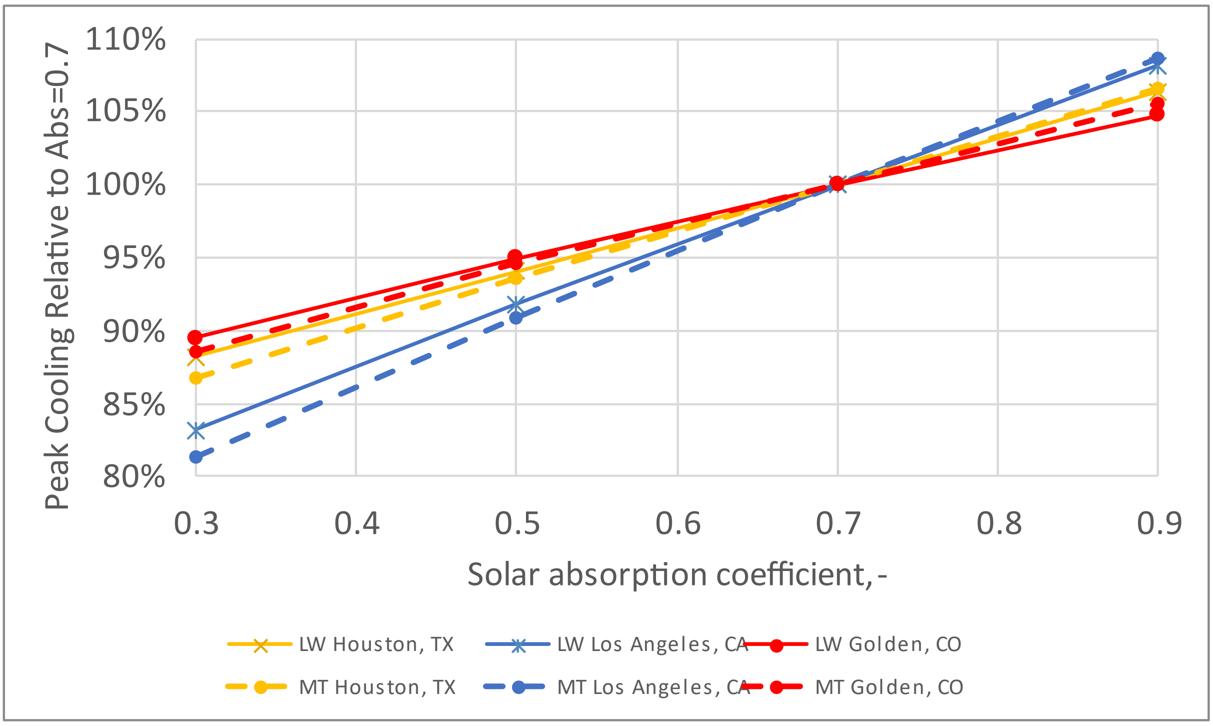

Figure 2. Impact of solar absorption coefficient on cooling power as a function of solar absorption coefficient in three climates and buildings with either lightweight or mass timber wall assemblies. Comparison is relative to the solar absorption coefficient of 0.7.

3. Impact of solar radiation on roofs

To better understand the benefits of low-slope cool roofs in reducing peak energy demand, researchers at Oak Ridge National Laboratory performed a cursory examination of the seasonal variation in peak electric demand for a variety of different climates across North America using a web-based interactive tool dubbed the "DOE Cool Roof Calculator" [1,2] which was developed and validated using models [3] and field data [4]. We evaluated the energy benefit of a cool roof applied to an 1860 m^2 (20,000 ft^2) roof with IECC 2021-compliant insulation levels [7]. Energy costs [8,9] and equipment efficiencies (air conditioning COP of 2.5 and furnace efficiency of 85 percent) were typical for 2021, and we assumed a peak demand charge of $25/kW. We modeled the energy and cost differences between roof surfaces having a solar reflectance of 0.05 and 0.60 with a thermal emittance of 0.90. Their findings suggest that even though usage savings may be higher in hot climates than in cooler climates, almost all climates exhibit a seasonal variation in the peaks for roof-related air conditioning demand. A summary of their findings is shown in Table 4.

Table 4. The annual energy cost savings in eight climate zones and cities in the U.S. when solar reflectance is changed from 0.05 to 0.60.

Climate Zone	City	R-value		Annual Savings, US$		
		m^2 K/ W	hr ft^2 F/Btu	Usage	Demand	Total
1	Miami, FL	4.4	25	$1,060	$860	$1,920
2	Houston, TX	4.4	25	$400	$820	$1,220
3	Atlanta, GA	4.4	25	$380	$840	$1,220
4	Baltimore, MD	5.3	30	$120	$680	$800
5	Chicago, IL	5.3	30	-$140	$680	$540
6	Minneapolis, MN	5.3	30	-$100	$680	$580
7	Fargo, ND	6.2	35	-$200	$580	$380
8	Fairbanks, AK	6.2	35	-$1,320	$500	-$820

As illustrated in Table 4, the total value of usage plus demand energy savings offered by the cool roof is sizable, averaging more than $800 annually in many climate zones for a typical commercial building. Consequently, cool surfaces may offer a significant opportunity for net energy cost savings even at the highest levels of insulation mandated by the latest building codes. Moreover, the savings value of cool surfaces is further reinforced because modern cool surfaces frequently cost no more than darker non-cool surfaces. As a result, all the savings identified in the analysis tend to drop to the bottom line without additional cost encumbrances.

One of the most striking results from this analysis is that the estimated cost savings due to peak energy demand reduction provide a substantial majority of the net heating and cooling energy cost savings throughout all climate zones studied. In fact, peak demand savings account for over 40% of total cost savings in the warmest climate zones and up to 100% in the coldest climate zones. In addition, while energy use cost savings vary widely by climate zone (falling to negative values in the coldest climates), peak demand cost savings tend to be more significant and consistent throughout all climate zones. Similarly, in a field study, Parker et al. [10] found 10% savings in cooling energy use, while peak demand was reduced by 35% when increasing the solar reflectance of a commercial roof from 0.23 to 0.68. Consequently, the analysis suggests that any projection of cool roof cost savings that neglects to include peak demand reduction has little chance of providing an accurate estimate.

4. Conclusions

The authors investigated a limited set of assemblies and climates for this paper. The simulations for walls and roofs with a range of solar absorption coefficients show a significant impact of solar radiation on the roofs and the walls on the heating and cooling energy use and peak demand. In addition to the immediate economics of peak demand, other savings associated with peak demand need to be considered. Because additional electrical generating capacity is required to meet peak demand levels, this will likely lead to increased air pollution and environmental impacts due to the need to construct new generating facilities and the less-than-efficient operation of existing facilities. Peak power demand is also strongly associated with the overall heating of large cities and urban areas, commonly referred to as the urban heat island effect (UHIE). Increased warming of urban areas may lead to increased production and accumulation of ground-level ozone, which may lead to increased health risks and a growing number of “Ozone Action Days” in cities and towns. Finally, increasing peak electricity demand may increase the potential for “brownouts,” especially during unusually hot weather events. Using cool surfaces to prevent these impacts can contribute to environmental justice efforts since pollution from peak power plants, the UHI effect, and brownouts and blackouts disproportionately affect lower-income areas and communities of color.

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