Measured Cooling Energy Savings from Reflective Wall Finishes: Evaluation as an Efficiency Measure across Climates

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ABSTRACT

In past research, reflective roofs have shown significant potential to reduce cooling in buildings. However, there have been few empirical evaluations of cooling reductions from changing *wall* reflectance. In the reported study, several experiments with instrumented scale test buildings are used to provide validation for a detailed simulation analysis across varied North American climates. The simulations establish the potential of reflective walls as an efficiency measure in existing buildings against climate.

Background

In research spanning three decades, solar reflective roofs have been shown to reduce building space cooling (Rosenfeld et al. 1998, Parker et al. 1998, Synnefa et al. 2007, Akbari and Kolokotsa 2016). Cooling energy savings from white reflective roofing in residential buildings have been found to be on the order of 10-20% vs. darker, less reflective colors. Poorly insulated structures with little installed insulation showed even higher savings potential. Comfort implications are also potentially large. Given the impact, the question naturally arises as to how increased wall reflectance might reduce cooling energy. Vernacular architecture with white-washed walls in Portugal and Greece suggests that higher wall reflectance may improve comfort under hot conditions as well as reduce cooling loads (Fernandes et al. 2015).

Millions of concrete block homes in the Southern U.S. have uninsulated concrete masonry unit (CMU) walls which are difficult and expensive to insulate. Indeed, in older research in 1995 conducted by Oak Ridge National Laboratories with the Florida Solar Energy Center (FSEC), we found that the cost to externally insulate such walls with R-5 to R-10 (ft^2- ^oF-hr/Btu) foam insulation and re-apply a stucco outer finish, was ~$10-$12K in 1994, with measured cooling energy savings on the order of only 5-14% depending strongly on interior thermostat settings (Barkaszi and Parker 1995). That study also found that at least three million homes in Florida, alone had uninsulated masonry at that time. In more recent research with a highly monitored residential retrofit program in Florida, high costs against available savings were seen once more (Sutherland et al. 2016). Costs approached $20K against 18% annual savings for cooling or ~1000 kWh.

Low cost solutions are needed for reducing cooling load in homes with uninsulated CMU walls. In this research we sought to see if increasing wall reflectance could provide much of the cooling energy savings of added wall insulation at a fraction of the cost.

Energy simulations such as DOE 2.1E within *EnergyGauge USA* or more recently *EnergyPlus* within *BEopt* or *Open Studio* show a 4-10% reduction in space cooling from making walls in hot climates more reflective (Petrie et al. 2007). However, cooling reduction can be even greater if walls are less insulated or larger in area and less shaded as with two-story buildings.

There have been few experiments where the wall reflectance influence has been directly measured. Past empirical studies include experiments of Moujaes and Brickman (2003), Petrie et al. (2007), Doya et al. (2012) and Zinzi et al. (2016), although no work has tied experimental results to a more extensive effort to simulate impacts across climates.

Experimental Test of Wall Reflectance

We used available small scale experimental buildings at the Florida Solar Energy Center (FSEC) as a ready means for an experimental evaluation of how wall reflectance may influence cooling. The central objective was to estimate such savings empirically and then use results to guide a simulation study of potential across climates.

The buildings used for the experimental evaluation had previously been used to evaluate the potential of night sky radiation for offsetting cooling load. This evaluation showed a limited cooling savings potential of approximately 15% compared to no night cooling at a set point of 78^{o}F, but falling to near zero at 75^{o}F (Parker et al. 2008).

However, given the detailed characterization of the test buildings from earlier research, it became apparent that they could be readily used to evaluate how solar reflective walls might influence measured cooling performance. We chose to use one of the two 12 x 16 foot test structures (192 ft^2 of conditioned area) for our wall reflectance test. These highly instrumented buildings are located at FSEC in Cocoa, Florida. The buildings have slab on grade foundations and R-30 ceiling insulation. The frame walls in both are insulated with R-13 fiberglass batt insulation and sheathed with beige concrete board lapped siding. We used SF_6 tracer gas to test the in-situ infiltration rates of the buildings. The test building measured infiltration rate was 0.34 air changes per hour (ACH).

Each test building has four 32" x 32" double-glazed windows with a rated U-factor of 0.35 Btu/hr-ft^{2o}F, a solar heat gain coefficient of 0.35 and a visible transmittance of 60%. The windows are covered with white interior blinds. The glass area is 28.4 square feet for a glazing to floor ratio of 15%– similar to prevailing residential construction practice in Central Florida. Facing south is 14.2 square feet with 7.1 square feet facing east and west. There is a single 20 ft^2 insulated metal door in each building.

Interior lamps are turned on and off to release an amount of heat to the interior according to a schedule designed to simulate residential occupancy. Latent gains at 18% of total internal heat gain load were provided by small humidifiers in each building. Further details are provided in source reports for the night sky radiative cooling project (Parker et al. 2008).

The buildings are cooled by a small 5,000 Btu/hour, through the wall, air conditioner. The measured temperature inside the 200 square feet control building was maintained at 78.0^{o}F $\underline{+}$0.5^o throughout the entire summer. Internal gains simulating occupancy include moisture generation, which was also kept constant. In summer 2008, we used the heavily instrumented small buildings (1/10 scale of normal floor area) to examine the impact of increasing wall reflectance in an experimental setting.

After collecting data for half the summer with the original beige wall color, on July 8th the walls were re-painted using two coats of *Sherwin Williams* flat white paint (*Luxon: Extra White, A24 W351*). This split the summer season so we could examine how air conditioning energy use changed before and after application of the more reflective white coating.

Figure 1. Walls of each building are painted on 8 July 2008

Figure 1 shows the test building being repainted from tan to white. Two samples of siding were sent for laboratory testing, one with the original coating and one with the white coating. Using ASMT E-903-82, the laboratory measured solar reflectances of 53% for the original coating and 72% for the white coating.

The potential influence of wall gain in the summer thermal performance of the buildings is seen in the comparative visible and infrared thermographic images captured in Figure 2 where the east wall is shown being heated by morning solar irradiance. Here, color is proportional to temperature with white being in excess of 100 ^{o}F.

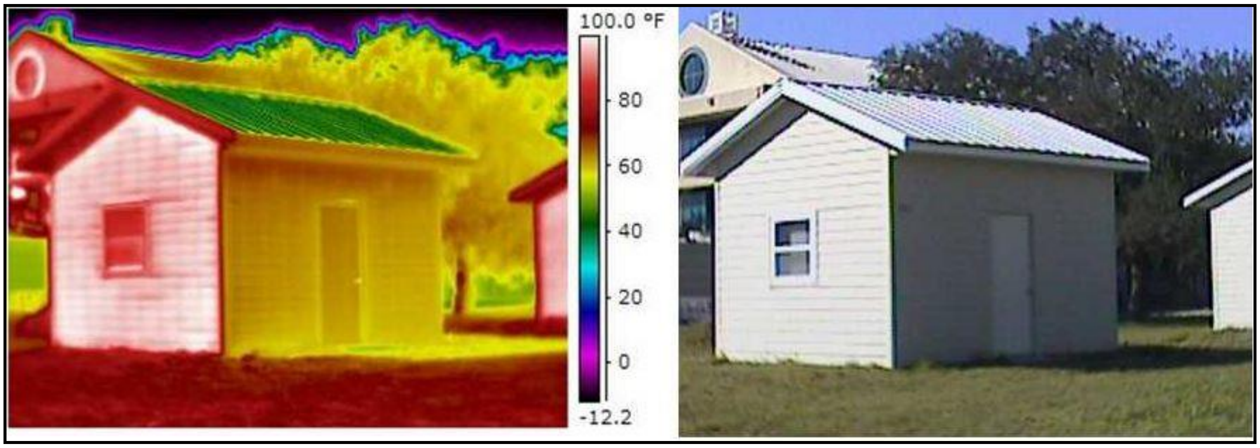


Figure 2: Left: IR thermographic image of East wall of experimental buildings before painting, showing solar related wall heat gain with a visible image of the same (right).

Building Test Results

The test buildings were monitored for cooling continuously for an entire cooling season before and after the walls were altered. Figure 3 shows the measured daily air conditioner energy use (kWh) plotted versus the interior to exterior daily temperature difference for pre and post periods and linear regression lines for the two data sets. The plot shows the expected behavior of cooling energy-- increasing as the average outdoor temperature climbs. The cooling energy reduction from the more reflective wall can be readily seen in the plot. At a 2^{o}F difference between inside and outside temperature (which was the average over the summer period), the regression indicated an 11.6% savings.

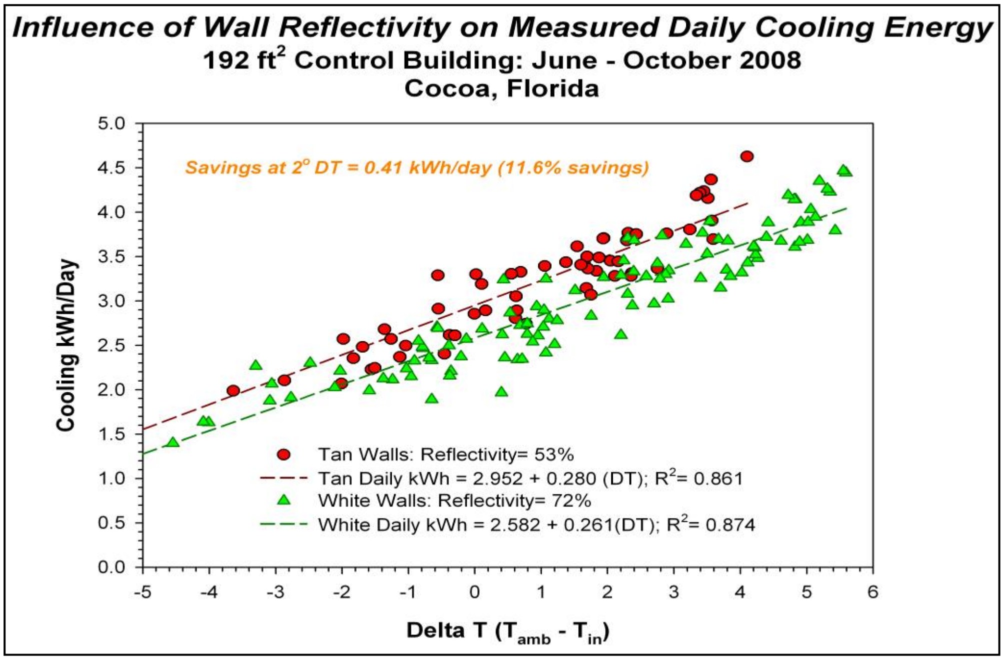


Figure 3. Measured daily cooling energy savings from increasing wall reflectance.

Tan,walls (53% reflectance)
kWh= 2.952 + 0.280(DT) R^2= 0.861

White,walls (72% reflectance)
kWh= 2.582 + 0.261(DT) R^2= 0.874

The relationship shows that although the change was somewhat associated with the daily temperature difference, most of the effect of increasing wall reflectance showed up in the intercept term. This is not surprising as walls with greater solar reflectance will interact most with solar radiation and not necessarily with interior to ambient temperature difference. Evaluating the relationship at a 2 ^{o}F outdoor to indoor temperature difference shows a 0.41 kWh/day difference- a savings of 11-12%.

However, given the fact that the solar insolation varied between the pre and post period it was necessary to do further analysis to evaluate this influence. The average solar horizontal irradiance was 224 W/m2 over the pre-period and 188 W/m2 over the post period. Given that difference, we re-ran the regressions with daily average horizontal solar irradiance as an added term to correct for solar that varied in the pre/post period. The average values for DT (indoor to outdoor temperature difference) was about 1.3°F over the period. The average hourly horizontal irradiance was 203 W/m^2. Evaluating both regressions given these terms gives the following for the control AC kWh. Pre-period (tan walls) = 3.25 kWh/day Post period (white walls) = 2.96 kWh/day The indicated difference after controlling for the varying sun conditions over the period was 8.9% vs. the 11.6% with improved explanatory power of the regressions.

Simulation Analysis

We composed an *EnergyPlus* simulation of the test building using the exact dimensions, construction, internal gains and changed wall reflectances. Using TMY3 data for nearby Melbourne, Florida, we ran the simulation with the measured wall reflectances before and after the change. The simulation indicated a 10.6% annual cooling savings, although indicated savings from June – October, corresponding to the monitoring period, were 7.6% (3.16 vs. 2.92 kWh/day) Given uncertainty, both in the TMY3 weather data to represent specific years and the statistical model, the results (8% simulated against 9% measured) are essentially the same. Unfortunately, the heating season heating penalty could not be measured in Florida given its sporadic winter weather. This suggests similar experimental work in additional temperature climates could both corroborate the cooling reductions seen here, as well as establish impacts on heating season performance.

Meaningful extension of the experimental work by simulation required adjustment in the building characteristics. For real homes, the ratio of wall area to volume will differ significantly from the 1/10th scale buildings in our experimental study. So for further analysis we wished to alter the building prototype to one more typical for residential housing in the U.S. Similar to the analysis of the test building, the *BEopt* program running the *EnergyPlus* simulation engine was also used to evaluate the impact of wall reflectance on energy use for a representative older vintage prototype house. The prototype was more or less typical for the southern U.S.: a 1,790 ft^2 slab-on-grade home with R-30 ceiling insulation, and a leakage rate of 4 ACH50. Windows modeled were single-pane with a U-value of 1.16 Btu/hr-ft2-°F and a solar heat gain coefficient of 0.76. The mechanical system was a 14 SEER, 8.2 HSPF heat pump connected to R-6 attic ducts. Fixed thermostat setpoints of 75°F for cooling and 71°F for heating were simulated. Figure 4 shows an image of the house from BEopt which was simulated facing north-south with adjacent buildings at a 15 foot distance on the important east and west exposures. Most residential homes have adjacent homes, trees or other obstructions nearby such that this became our basecase configuration.

The prototype building was modeled both with frame walls and CMU walls. Cases were developed for three insulation configurations: Uninsulated and with R-5 interior insulation for CMU walls (the uninsulated case representative of millions of existing CMU homes in the Southeastern U.S.), as well as R-5 exterior insulation (retrofit). For frame walls we evaluated R-11 and R-19 with 16 inch on-center framing.

We also created a similar prototype that was two stories tall with frame construction as this configuration should have a larger influence from wall reflectance with the larger expanse of upper story unshaded walls. The simulation focus was on the cooling energy savings from greater wall reflectance in particular, although looking at the negative influences on winter heating as well. For each location, we compared the impact on performance of increased wall reflectance with the much more expensive retrofit of increased wall insulation.

We simulated the impact of wall solar reflectance based on commonly used stucco colors. Table 1 shows the cases considered. We assumed cool colored infrared reflective pigments could have darker colors and still achieve a solar reflectance around 0.5 as described by Petrie at al. (2007 and Levinson et al. 2007). Light colored conventional pigments (e.g. pastels) over a white primer can easily achieve this reflectance level as well. This is readily acceptable to architects and most homeowners since lighter colored walls in residential homes are a conventional expectation. We also simulated a true white stucco which provides greatest solar reflectance, but is often not aesthetically acceptable to designers or home owners. This can be obtained by cool colored IR-reflective pigments (Petrie et al. 2007) and commercially available. These are termed Infrared Control or *IRc* below. We further note ongoing research to significantly increase infrared emittances which may make pastel colors able to reach or exceed our definition of “white” in future cool color paint formulations and coatings (e.g. Mandal et al. 2018).

Table 1. Wall Solar Reflectances for Examined Cases*

Case	Solar Reflectance	Solar Absorptance
Medium/Dark	0.25	0.75
Light or (Med.IRc)	0.50	0.50
White (Light/ IRc)	0.70	0.30

*Reflectances determined by ASTM E-903; hemispheric infrared emittances typically ~0.90.

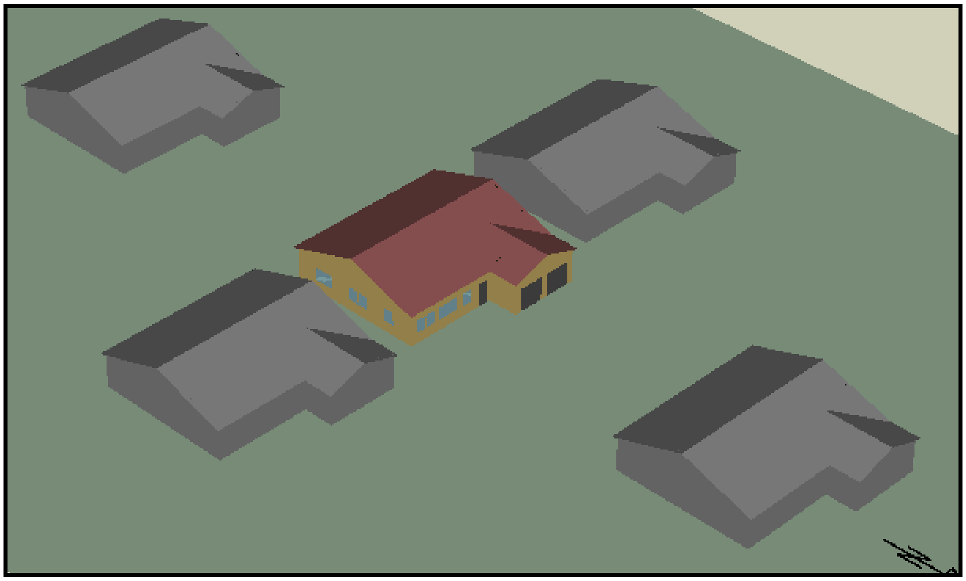


Figure 4. Prototypical 1,790 ft^2 residence rendered in BEopt/EnergyPlus with adjacent buildings

Results were created for three different levels of wall reflectance: Medium/Dark walls (Reflectance = 0.25, Light Walls = 0.50 and White Walls: Reflectance= 0.70). As Petrie et al. (2007) found that heating dominated climates (>3000 heating degree days (HDD) @ 65 ^{o}F) saw negative savings from increased wall reflectance, we concentrated our analysis on cooling dominated locations. Although not specifically analyzed, we note that with climate-related warming, this delineation may become a moving target. Nevertheless, we performed simulations for 15 locations (Table 2) of which Baltimore, MD and Raleigh, NC are mixed climate locations and Los Angeles and San Diego, CA are decidedly mild. We evaluated Minneapolis and New York City to verify that reflective walls are a net negative in the coldest climates. We list the heating and cooling degree days using 15 year average 2018 data from *Climate.Onebuilding.org*.

Table 2.: Simulation Analysis Locations
(Heating Degree Days/Cooling Degree Days; TMY2018 File)

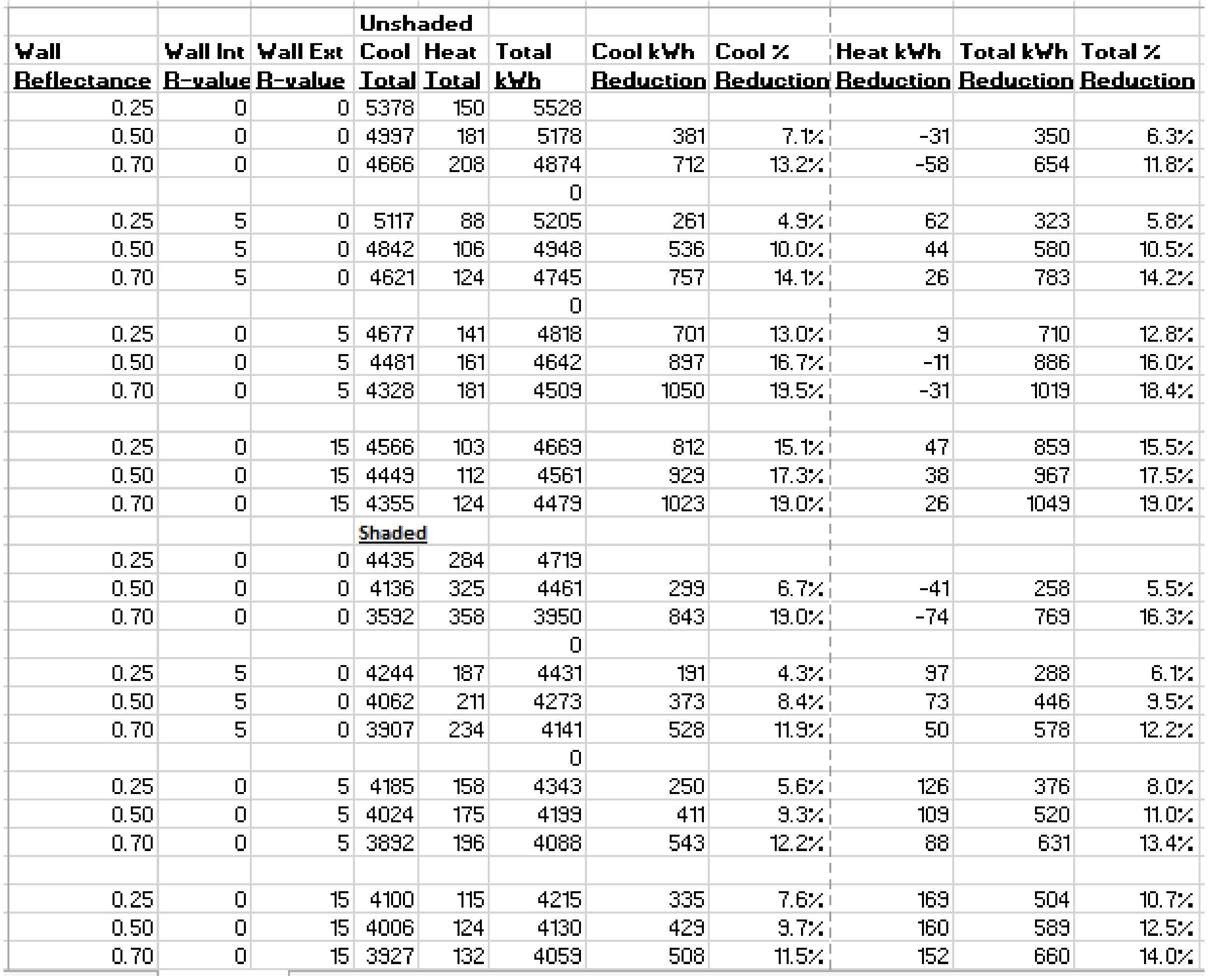
Evaluated	Heating Degree	Cooling Degree	Ratio
Location	Days	Days	CDD/HDD
Cooling Dominated Climates			
Miami, FL	45	2624	58.31
Orlando, FL	221	1889	8.54
Phoenix, AZ	391	2876	7.36
Primarily Cooling Climates			
Houston, TX	798	1817	2.28
Las Vegas, NV	971	2536	2.61
New Orleans, LA	593	1823	3.07
San Antonio, TX	694	1911	2.75
Mild Climates			
Los Angeles, CA	579	404	0.70
San Diego, CA	565	486	0.86
Mixed Climates			
Atlanta, GA	1346	1133	0.84
Sacramento, CA	1324	709	0.54
Raleigh, NC	1492	1054	0.71
Cold Climates			
Baltimore, MD	2326	815	0.35
New York, NY	2312	830	0.36
Minneapolis, MN	3907	545	0.14

Simulation Results and Discussion

After closely replicating with simulation the experimental cooling energy reduction measured in the unshaded test building (9%) against that simulated (8%), we moved to full-scale building simulations. As added wall insulation is a well-known energy savings alternative for residential buildings (although a more expensive), we also simulated this change to provide context for the impacts seen from increasing wall reflectance. The results are shown in Table 3 below in the form of an analysis result table from EnergyPlus/ BEopt.

First, we show an evaluation of the one story CMU prototype in Orlando without any shading, but with R-5 interior insulation which is typical of modern construction in the Central Florida area. Our results for Orlando are shown in Table 3.

Table 3: Wall Reflectance Results for CMU Walls in Orlando, FL



			Unshaded							
Wall Reflectance	**Wall Int R-value**	**Wall Ext R-value**	**Cool Total**	**Heat Total**	**Total kWh**	**Cool kWh Reduction**	**Cool % Reduction**	**Heat kWh Reduction**	**Total kWh Reduction**	**Total % Reduction**
0.25	0	0	5378	150	5528					
0.50	0	0	4997	181	5178	381	7.1%	-31	350	6.3%
0.70	0	0	4666	208	4874	712	13.2%	-58	654	11.8%
					0					
0.25	5	0	5117	88	5205	261	4.9%	62	323	5.8%
0.50	5	0	4842	106	4948	536	10.0%	44	580	10.5%
0.70	5	0	4621	124	4745	757	14.1%	26	783	14.2%
					0					
0.25	0	5	4677	141	4818	701	13.0%	9	710	12.8%
0.50	0	5	4481	161	4642	897	16.7%	-11	886	16.0%
0.70	0	5	4328	181	4509	1050	19.5%	-31	1019	18.4%
0.25	0	15	4566	103	4669	812	15.1%	47	859	15.5%
0.50	0	15	4449	112	4561	929	17.3%	38	967	17.5%
0.70	0	15	4355	124	4479	1023	19.0%	26	1049	19.0%
			Shaded							
0.25	0	0	4435	284	4719					
0.50	0	0	4136	325	4461	299	6.7%	-41	258	5.5%
0.70	0	0	3592	358	3950	843	19.0%	-74	769	16.3%
					0					
0.25	5	0	4244	187	4431	191	4.3%	97	288	6.1%
0.50	5	0	4062	211	4273	373	8.4%	73	446	9.5%
0.70	5	0	3907	234	4141	528	11.9%	50	578	12.2%
					0					
0.25	0	5	4185	158	4343	250	5.6%	126	376	8.0%
0.50	0	5	4024	175	4199	411	9.3%	109	520	11.0%
0.70	0	5	3892	196	4088	543	12.2%	88	631	13.4%
0.25	0	15	4100	115	4215	335	7.6%	169	504	10.7%
0.50	0	15	4006	124	4130	429	9.7%	160	589	12.5%
0.70	0	15	3927	132	4059	508	11.5%	152	660	14.0%

Modeling results show that not only does increased wall reflectance save energy in Central Florida, but that it further augments the savings of wall insulation for insulation retrofitted CMU walls. We show both R-5 interior and exterior as well as R-15 on the exterior. In agreement with earlier research (e.g. Kossecka and Kosny 2002 and Hart et al. 2014), results show the thermal superiority of exterior wall insulation on masonry walls compared with interior application.

Increasing wall reflectance from light to white (0.5 to 0.7), as similar in our experimental test, resulted in lower cooling energy savings in a full scale residential building—about 5%. Nevertheless, we note that going from dark uinsulated CMU walls to white results in total energy savings (heating and cooling) that exceed adding either R-5 or R-15 exterior insulation to dark walls. Total annual savings in space conditioning energy are 250 – 650 kWh per year (about 12%) for going from dark walls to white. About half of the advantage is gained from choosing light rather than dark wall coatings however, which means that cool reflective colors might be a viable market, since the market acceptability of white is likely limited.

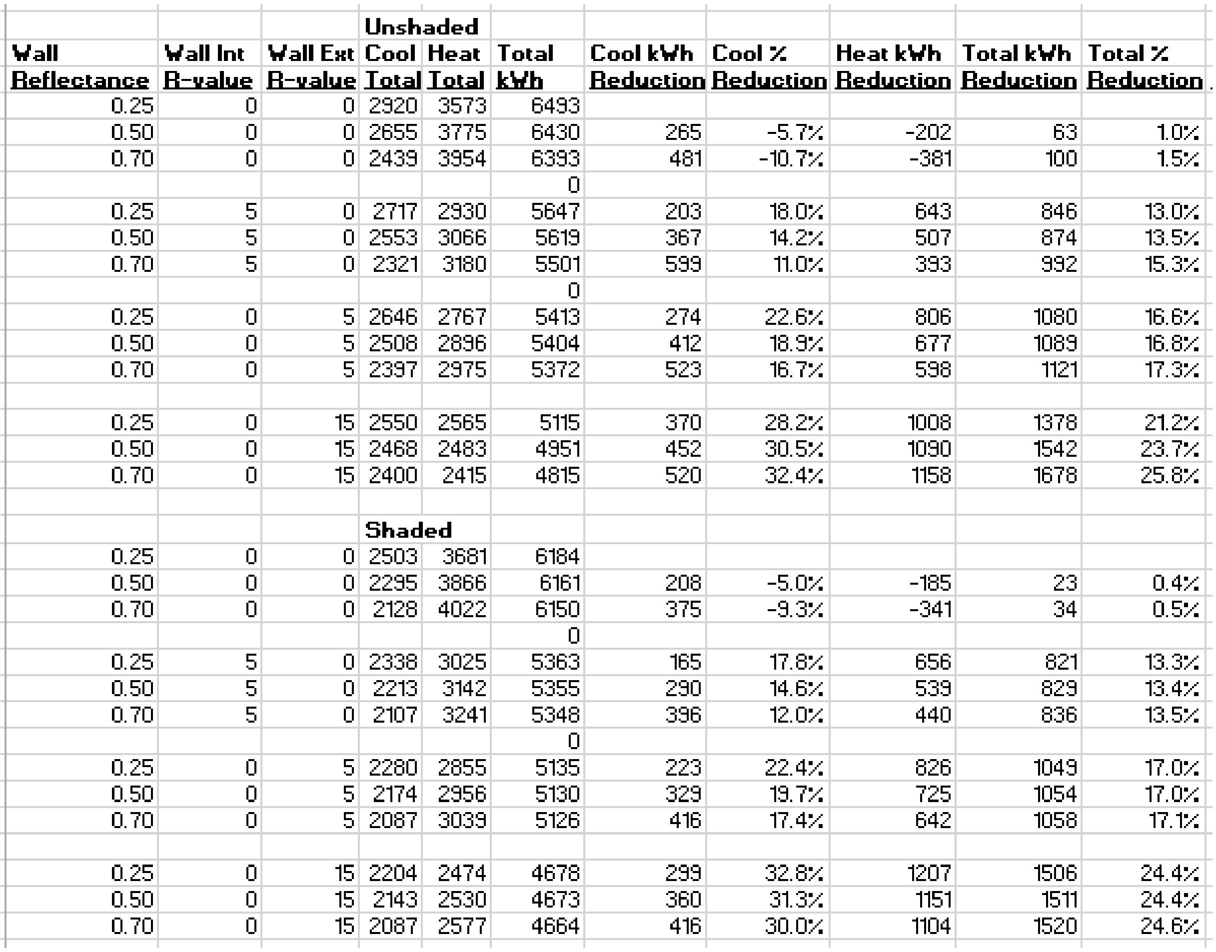
The greater energy savings achieved by the change in wall reflectance is even true in the shaded cases. Increased wall reflectance has a larger impact in the Florida climate than wall insulation even given the heating penalty for increased wall reflectance. This occurs because with internal heat gains from appliances and people, during Florida's mild nights, greater wall heat loss is of benefit to reduce cooling needs. This phenomenon has been widely recognized in evaluating windows in this climate, where lower conductance windows actually slightly increase annual cooling energy for given solar heat gain characteristics (Sullivan et al. 1994).

A similar level of savings to Orlando from reflective walls was also seen in Miami, New Orleans and Houston where annual heating requirements are very low. Such an influence is not the case in more northerly climates, however, where the heating penalty becomes much larger. This was clearly seen in results for Baltimore, New York City and Minneapolis. In these locations higher wall reflectance reduced cooling energy, but additions in heating energy were large enough such that increased wall reflectance does not look to be beneficial on an annual basis. Savings are very slightly negative and increased wall insulation is clearly shown to be more important than wall reflectance.

The same analysis done for the mixed climate of Atlanta, Georgia shows that more reflective walls slightly save conditioning energy, on balance, but while cooling energy savings remain large, reductions to heating counter much of the advantage. (Simulation results for Atlanta are summarized in Table 4.) However, the annual savings are modest, typically 50-100 kWh or 1-2% of space conditioning energy and they are inconsequential when the walls are well insulated. It can be argued, however, that these savings are very cost effective for uninsulated masonry walls since they have very low incremental cost when it entails simply selecting more reflective colors at the time the building façade is to be repainted.

Savings in Sacramento, as with Atlanta, showed modest savings. In all cases, the savings for frame walls - and particularly two story frame walls - were greater, even though the nominal assumed insulation level was R-11. Savings for two-story structures were similar to CMU construction when the frame walls were assumed insulated to R-19.

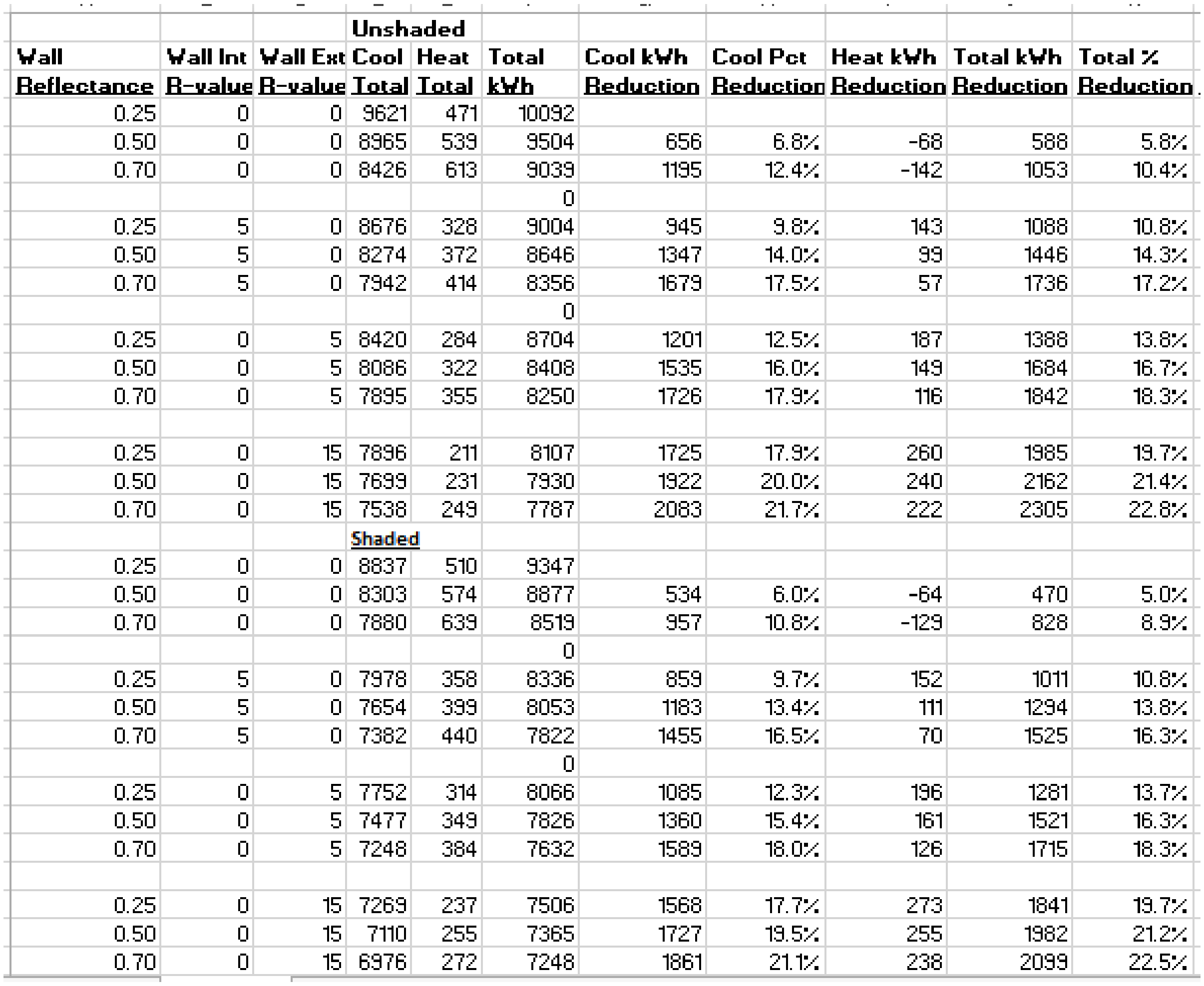
Table 4: Wall Reflectance Results for CMU Walls in Atlanta, GA



			Unshaded							
Wall Reflectance	Wall Int R-value	Wall Ext R-value	Cool Total	Heat Total	Total kWh	Cool kWh Reduction	Cool % Reduction	Heat kWh Reduction	Total kWh Reduction	Total % Reduction
0.25	0	0	2920	3573	6493					
0.50	0	0	2655	3775	6430	265	-5.7%	-202	63	1.0%
0.70	0	0	2439	3954	6393	481	-10.7%	-381	100	1.5%
					0					
0.25	5	0	2717	2930	5647	203	18.0%	643	846	13.0%
0.50	5	0	2553	3066	5619	367	14.2%	507	874	13.5%
0.70	5	0	2321	3180	5501	599	11.0%	393	992	15.3%
					0					
0.25	0	5	2646	2767	5413	274	22.6%	806	1080	16.6%
0.50	0	5	2508	2896	5404	412	18.9%	677	1089	16.8%
0.70	0	5	2397	2975	5372	523	16.7%	598	1121	17.3%
0.25	0	15	2550	2565	5115	370	28.2%	1008	1378	21.2%
0.50	0	15	2468	2483	4951	452	30.5%	1090	1542	23.7%
0.70	0	15	2400	2415	4815	520	32.4%	1158	1678	25.8%
			Shaded							
0.25	0	0	2503	3681	6184					
0.50	0	0	2295	3866	6161	208	-5.0%	-185	23	0.4%
0.70	0	0	2128	4022	6150	375	-9.3%	-341	34	0.5%
					0					
0.25	5	0	2338	3025	5363	165	17.8%	656	821	13.3%
0.50	5	0	2213	3142	5355	290	14.6%	539	829	13.4%
0.70	5	0	2107	3241	5348	396	12.0%	440	836	13.5%
					0					
0.25	0	5	2280	2855	5135	223	22.4%	826	1049	17.0%
0.50	0	5	2174	2956	5130	329	19.7%	725	1054	17.0%
0.70	0	5	2087	3039	5126	416	17.4%	642	1058	17.1%
0.25	0	15	2204	2474	4678	299	32.8%	1207	1506	24.4%
0.50	0	15	2143	2530	4673	360	31.3%	1151	1511	24.4%
0.70	0	15	2087	2577	4664	416	30.0%	1104	1520	24.6%

Table 5 provides simulation results for Phoenix. Not surprisingly, Phoenix showed the highest savings from reflective walls—annual savings of over a 1050 kWh in the unshaded uninsulated case—and over 500 kWh with the shaded and insulated cases. Exterior insulation and reflective walls were able to reduce total space conditioning by over 20% in this sunny, hot and arid climate. However, even when insulated to R-15, reflective walls saved over 250 kWh. Note that reflective walls achieves about half the savings with uninsulated darker walls insulated to R-15. Sunnier climates, including Las Vegas, appear to have a large influence.

Table 5: Wall Reflectance Results for CMU Walls in Phoenix, AZ



			Unshaded							
Wall Reflectance	**Wall Int R-value**	**Wall Ext R-value**	**Cool Total**	**Heat Total**	**Total kWh**	**Cool kWh Reduction**	**Cool Pct Reduction**	**Heat kWh Reduction**	**Total kWh Reduction**	**Total % Reduction**
0.25	0	0	9621	471	10092					
0.50	0	0	8965	539	9504	656	6.8%	-68	588	5.8%
0.70	0	0	8426	613	9039	1195	12.4%	-142	1053	10.4%
					0					
0.25	5	0	8676	328	9004	945	9.8%	143	1088	10.8%
0.50	5	0	8274	372	8646	1347	14.0%	99	1446	14.3%
0.70	5	0	7942	414	8356	1679	17.5%	57	1736	17.2%
					0					
0.25	0	5	8420	284	8704	1201	12.5%	187	1388	13.8%
0.50	0	5	8086	322	8408	1535	16.0%	149	1684	16.7%
0.70	0	5	7895	355	8250	1726	17.9%	116	1842	18.3%
0.25	0	15	7896	211	8107	1725	17.9%	260	1985	19.7%
0.50	0	15	7699	231	7930	1922	20.0%	240	2162	21.4%
0.70	0	15	7538	249	7787	2083	21.7%	222	2305	22.8%
			Shaded							
0.25	0	0	8837	510	9347					
0.50	0	0	8303	574	8877	534	6.0%	-64	470	5.0%
0.70	0	0	7880	639	8519	957	10.8%	-129	828	8.9%
					0					
0.25	5	0	7978	358	8336	859	9.7%	152	1011	10.8%
0.50	5	0	7654	399	8053	1183	13.4%	111	1294	13.8%
0.70	5	0	7382	440	7822	1455	16.5%	70	1525	16.3%
					0					
0.25	0	5	7752	314	8066	1085	12.3%	196	1281	13.7%
0.50	0	5	7477	349	7826	1360	15.4%	161	1521	16.3%
0.70	0	5	7248	384	7632	1589	18.0%	126	1715	18.3%
0.25	0	15	7269	237	7506	1568	17.7%	273	1841	19.7%
0.50	0	15	7110	255	7365	1727	19.5%	255	1982	21.2%
0.70	0	15	6976	272	7248	1861	21.1%	238	2099	22.5%

Figure 5 illustrates the impact of increasing wall reflectance on annual heating and cooling energy use for shaded, uninsulated CMU buildings in all modeled climate locations. While going from medium colored walls to white walls produces cooling energy savings in all locations—from 957 (Phoenix) to 161 kWh (New York), the annual savings are strongly reduced by increases to heating energy. In climates such as Florida, there is very little heating such that the cooling advantages prevail. However, in many more temperate locations such as Atlanta or Sacramento, cooling energy savings are partially offset by increased heating energy use from reduced passive heating. In colder locations such as New York and Minneapolis, the cooling advantage of reflective walls is completely offset by increases to heating energy, resulting in negative annual savings. Sunnier locations such as Phoenix and Las Vegas show the largest benefit from reflective paints. Mild locations in California (San Diego and Los Angeles), show modest savings, but still show overall benefit from more reflective walls.

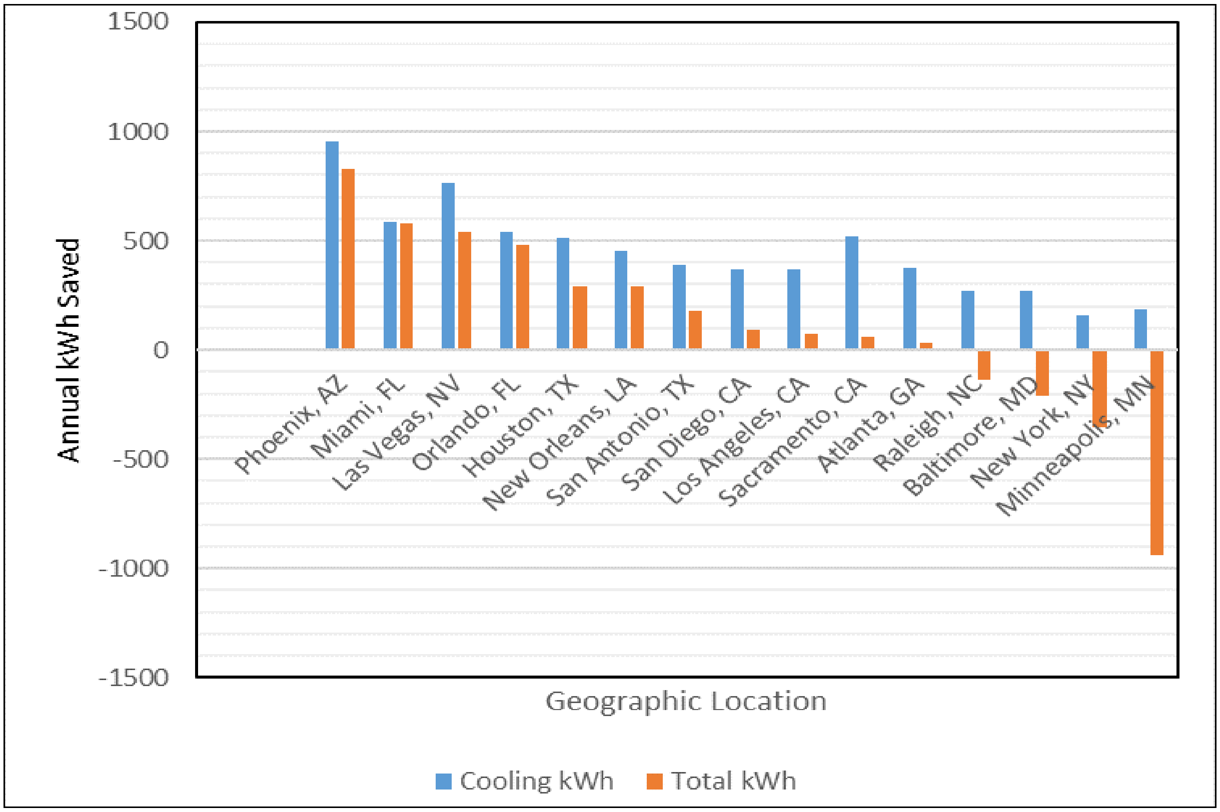


Figure 5: Annual savings of changing wall reflectance from 0.25 to 0.70 for shaded case, uninsulated CMU

Peak Savings

Summer peak impacts of reflective walls were also evaluated. Results indicated reflective walls saved in every evaluated case, although savings were reduced for cases with highly insulated walls. Reductions to air conditioning peak energy tended to parallel the cooling savings results seen in Figure 5 with the highest peak reductions in the sunniest locations (e.g. Phoenix and Las Vegas). Figure 6 shows the estimated performance of various reflectance and insulation options on the summer peak day in Orlando. This was August 6,th which had a maximum daytime temperature of 94.4 ^{o}F. These results were from the shaded case with much of the east and west exposure shielded by other buildings which makes for conservative results. Impacts were greater in buildings oriented east /west or with two story structures.

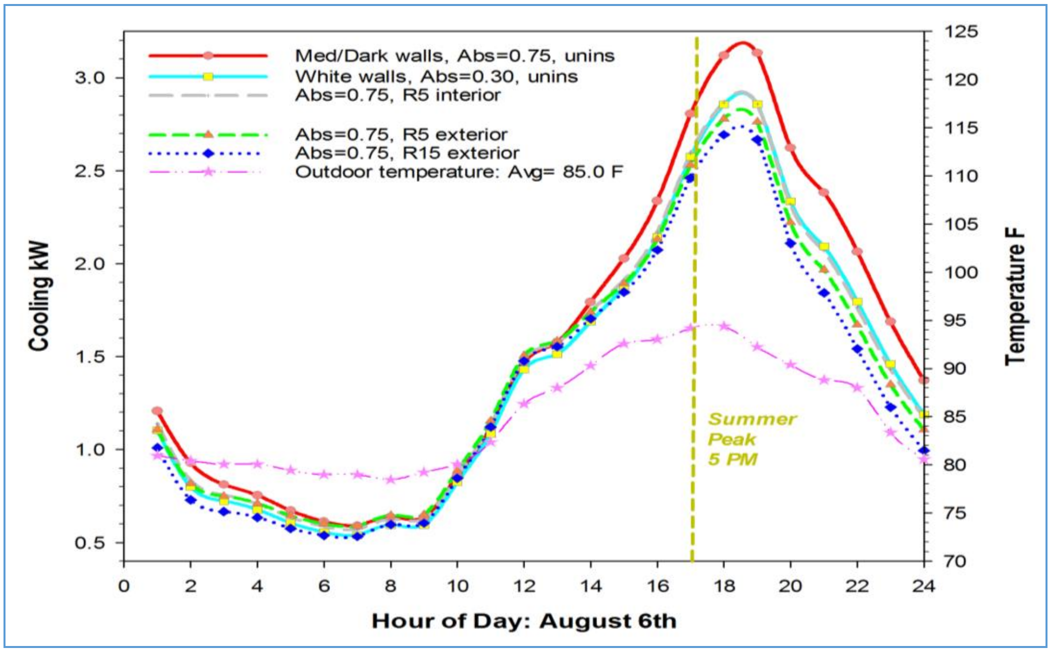


Figure 6: Comparative cooling summer peak demand in Orlando, FL for shaded case.

With medium colored uinsulated walls with a reflectance of 0.25, the estimated peak air conditioning demand at the time of utility coincident peak (5 PM or hour 17) was 2.81 kW. The uninsulated case with white walls (reflectance=0.70) saw an air conditioning demand of 2.58 kW-- a 0.23 kW or 8.2% reduction. For the R-5 insulated interior case with medium colored walls, the demand was essentially the same: 2.59 kW (0.22 kW reduction or 7.8%). With R-5 insulation installed on the wall exterior the demand was slightly lower 2.53 kW. A case with R-15 installed on the exterior showed a demand of 2.46 kW or a 12.5% reduction.

We conclude that white reflective walls perform about as well as R-5 insulation in Orlando in controlling summer peak gains as well as producing annual savings. Repainting walls is a much lower cost option than retrofitting R-5 to R-15 exterior insulation. The cost of retrofitting insulation has been estimated at $20K for a typical residence (Sutherland et al. 2016).

Unlike white roofs, which suffer significant degradation over time, vertical light colored walls are more aesthetically acceptable and typically experience less decline in reflectance save in urban environments (Paolini et al. 2017). For residences, repainting normally occurs every ten years at which point reflectances are renewed. For cooling climates, this is a no cost measure.

Conclusions

Test results obtained from a small (1/10th scale) building in Central Florida suggested that increasing wall reflectance produced an 8% reduction in air conditioner energy use over the summer monitoring period. An EnergyPlus simulation of the small test building closely replicated this result using Orlando TMY3 weather data.

There are millions of existing houses with uninsulated concrete masonry construction, largely in southern latitudes in the US. Research has shown these structures are very expensive to retrofit with insulation. We desired to see if an inexpensive increase in building wall reflectance would compare to adding expensive wall insulation in various climates. While retrofitting insulation has been found to be very expensive, houses are typically repainted every decade providing an essentially no-cost opportunity to improve wall reflectance.

To extend experimental results, we simulated a typically sized 1,790 square foot residence upon which to evaluate reducing wall reflectance around the U.S. With the realistic assumption of shading from adjacent buildings (or vegetation), cooling energy savings were about 7% in Orlando when moving from dark wall to a medium color with moderate reflectance.

We found sizable heating/cooling savings from wall reflectance in cooling-dominated climates, such as Florida, New Orleans, Houston particularly in sunny locations such as Phoenix and Las Vegas. Mild climates such as Los Angeles and San Diego showed advantage of reflective walls, but savings were modest since both heating and cooling needs are low.

With simulations we corroborated the finding of Petrie et al. (2007) that reflective walls are unhelpful in heating dominated climates such as Baltimore, Minneapolis and New York City. Essentially, if the ratio of cooling degree days to heating degree days is less than 0.9, there seems little advantage for more reflective wall surfaces. These ratios are seen in Table 2. If the ratio falls to less than 0.7, we find reflective walls to increase annual space conditioning energy. We caution, however, that as climate changes, heating needs will fall while cooling needs increase. This may result in locations showing marginal advantage now (e.g. Atlanta and Sacramento) moving to climatic circumstances with advantage to greater wall reflectance.

However, in cooling dominated locations such as Orlando, we found that reflective walls produced more energy savings than R-5 wall insulation for retrofitting existing buildings. Future technology developments with wall pigments that are IR selective with ambient temperature could play a role in reducing the heating penalty seen in most locations.

- In cooling-dominated climates such as Miami, Orlando, Las Vegas and Phoenix with very low heating, reflective walls perform nearly as well in reducing annual conditioning energy as added wall insulation (specific values in Tables 3 and 5).
- Added wall insulation provides better savings than increased wall reflectance in all climates with significant heating. In mixed climates, such as Atlanta, Raleigh, and Sacramento, the wall insulation level is much more significant than wall reflectance.
- Pre-existing wall insulation has a large impact on reflective wall cooling energy savings, although increased wall reflectance helps reduce cooling even with high insulation.
- Mixed climates with significant heating (e.g. Atlanta), show modest savings from increased wall reflectance given the winter heating penalty. Added wall insulation is more effective in such locations. However, cooling peak savings remain large.
- Pre-existing shading from adjacent buildings and other obstructions such as vegetation reduces savings, but they still remain significant even when walls are insulated.
- Two-story buildings show the greatest influence from increasing wall reflectance due to their greater exposed façade area within the building envelope.
- Even though annual energy savings with pre-existing shading are typically only 50 – 500 kWh with insulated walls, these savings are highly cost effective due to the negligible costs to alter wall reflectance.

The potential for reflective finishes to reduce cooling loads vary strongly with climates around the U.S. We show that reflective wall finishes a powerful means of reducing cooling in existing buildings in hot climates with uninsulated concrete masonry construction. Two-story structures are likely beneficial applications given large un-shaded wall expanses.

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