Improving Roofs to Reduce Energy and Protect Occupants from Climate Change

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Abstract. Refurbishing existing buildings to reduce energy use is a priority worldwide to reduce greenhouse gas emissions. Millions of buildings have poorly insulated old roofs with large roof surface areas. Covered by photovoltaic (PV) arrays, these roofs could potentially provide significant renewable energy generation. Uninsulated, they increase needs for heating and cooling, while also posing health risks for top-floor occupants during summer heat waves. Such heat waves look to become increasingly common with future climate change. Suspended air conditioning from power interruptions are likely due to excessive system electric demand, earthquake or storm. We analyze an uninsulated apartment building in Milan for several scenarios to save energy while improving occupant comfort in top floor apartments. We evaluate three strategies: added roof insulation, increased roof solar reflectance and covering PV arrays above the roof. We estimate heating and cooling energy savings as well daily temperatures of a roof-adjacent top floor flat under peak summer conditions. We evaluate using current weather TMY 2018 files as well as another morphed to anticipated 2060 weather for the 90% IPCC scenario which represents extreme warming.

Keywords. Roof, insulation, energy, climate change, photovoltaics, comfort.
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1. Introduction

Interest in reducing energy consumption in buildings is recognized worldwide as a priority [1]. Buildings account for about 40% of global energy consumption, and 36% of associated CO_2 emissions [2]. Therefore, retrofit is a key factor to achieve the European (EU) 2030 Energy and Climate targets [4]. At the same time, the need to electrify energy demand to facilitate greenhouse gas emission reductions, and reduce both climate change warming potentials and energy dependance, makes it important to locate new available areas for renewable energy production [5]. Building rooftop solar photovoltaic (PV) arrays are a demonstrated means for addressing building energy use since roof areas experience full solar radiation and are freely available for such utilization [6]. World building floor area and associated roof expanses are enormous (223 x 10^9 m^2 globally) [7].

Renewable energy generation from PV production and designing new buildings at nearly or net zero energy consumption has proved feasible around the world [8]. However, achieving effective energy reduction is much more difficult for existing buildings. Insulation retrofit for envelope elements is a frequent intervention in buildings **Error! Reference source not found.**. In particular, roof retrofit is one of the first options selected in building design optimization [10]. Roofs in existing residential buildings are often old and poorly insulated, increasing needs for heating and cooling [11]. Also, poor levels of roof insulation can lead to overheating of top floor apartments during summer [12]. This issue may become crucial under foreseen climate change scenarios of temperature increase and anticipated heat waves [13]. A harmonized approach for roof retrofit is still missing and many interventions are implemented without a comprehensive knowledge of the potential savings and costs [14].

Accordingly, this paper aims at investigating different common scenarios to save energy adding roof insulation, increasing roof solar reflectance, and covering roof with PV arrays. The connected occupant comfort in top floor apartments is included in the analysis.

2. Methodology

We perform an example analysis for an older five-story apartment complex in Milan, Italy. The prototype building is drawn from previous research examining the potential of roofing insulation [15]. Several parameters are defined: roof insulation with materials and thicknesses, with/without PV). We also examine shading from raised stand-off PV arrays and how this influences heat gains and insulation performance.

We consider a fully-electric apartment complex with both current weather as well as weather files morphed to the year 2060 with the risk of the 90% extreme weather case from the IPCC scenarios. Given the risk of “brown outs” and power interruption during future climate change, we evaluate the risk of high temperatures upper floor apartments in the event of power interruption and not cooling. To address the health risk as well as energy implications, we examined roof insulation, roof reflectance and PV installation to evaluate impacts.

We also examine how improving roof insulation or altering roof surface reflectance might reduce heating and cooling energy consumption while improving comfort in roof-adjacent dwellings. At the same time, we evaluate how much electricity can be generated through combined PV installation at the same time that roofs are thermally improved. For the evaluation, we used the well-accepted EnergyPlus and TRNSYS simulation software, implemented within BEopt, driven by hourly recent weather data, both recent and morphed to the future given expectation of climate change.

3. Retrofit Potential and PV Array Shading of Roofs

Thermal retrofit to building roof and walls are among most implemented interventions for building energy refurbishment. Improving the building envelope is key to controlling thermal losses to outdoor weather extremes and can have strong influences on resulting space heating and cooling needs [16]. Other research has shown the highly reflective roofs are very effective at cutting summer cooling loads, but with negative benefits in winter during heating conditions [17].

Taking advantage of PV systems to generate renewable energy is of growing importance to both cover building energy needs (e.g. equipment and appliances), and contribute delivery to the grid. PV panels are becoming commonplace worldwide and more often integrated as a building material (Fig.1).

Fig.1. a) Examples of rooftop PV systems in existing buildings in Northern Italy with a) showing solar array shading of apartment roof complex.
b) Visible and IR image illustrating impact of shading from photovoltaics on thermal heat gain. Colour is proportional to temperature: white/ red hottest, and black and blue coolest.

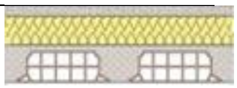
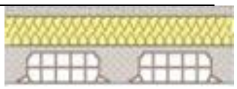
However, a remaining advantage of stand-off PV arrays, with an air space below the panels, comes from roof shading and modification to roof surface long-wave radiation to the sky, that affect thermal transmittance and, consequently, cooling and heating loads. Fig.1b provides an empirical evidence of the PV shading influence on roof heat gain from thermography. The shading impact of a South-facing stand-off PV array is evident: the roof surface is hotter outside the PV array shadow and much lower underneath. Thermal impacts of PV stand-off array on roof heat transfer performance underneath are complex depending on array shadow, spacing, tilt, wind as well as roof view factor to the sky.

Although impacts are small save for insulated roof assemblies, they can be important, however, for existing residential buildings that cannot be easily insulated. Tsurusaki et al. [18] observed an average 26% reduction in monitored space cooling after rooftop PV panels were installed atop Japanese buildings. Dominguez et al. [19] saw a 38% reduction in roof heat gain during the cooling season in San Diego, California. Kapsalis and Karamanis [20] measured and simulated a 17.6% decrease to space cooling in Western Greece. Decreased solar irradiance in winter, can potentially increase heating through lost roof solar absorption, but altered long-wave re-radiance may provide a partially compensating effect. Estimation of impact is accomplished within the EnergyPlus simulation by assuming that the PV array covered portion of the roof has a 90% interruption of incident solar radiation compared to the exposed sections. However, the long-wave emittance of this covered section is also altered from 0.92 for fully exposed sections vs. 0.10 for the covered segments.

3.1 Baseline building prototype

Using the Tabula classification [21], we created a multi-story apartment complex prototype to represent residential urban level density. Characteristics are detailed (Tab. 1).

Tab. 1. Roof description for analysis of the apartment complex.

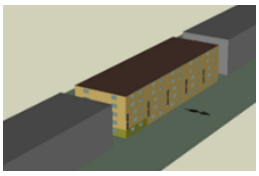
Insulation level	Description	heat transfer coefficient (W/m²K)	Scheme
No	Flat roof with reinforced brick-concrete slab.	2.00	
Low		0.80	
Medium		0.60	
High		0.35	
Very high		0.20	
Extra high		0.15	

Typical roof type for the apartment complex was identified from the Tabula research, differentiated into six different insulation levels (Tab. 2).

The overall U-factor of heat transfer depends on the insulation of the roof/ceiling. Overall conductance varies was estimated from 2.00 and 0.15 W/m^{2}K depending on insulation level. However, buildings older than 1976 had generally lower or no insulation with typical conductance of ~2 W/m^{2}K. Based on previous evaluation of a cost effective retrofit for apartment complexes that considering PV with electrical storage and likely economic parameters, we showed the very high insulation level (0.15 W/m^{2}K) was justified [14]. We thus confined our evaluation for Milan to the uninsulated case or an insulated one with 0.20 W/m^{2}K.

The structure has five floors and a total of 50 apartments (81 m^2 each) separated on either side by an access corridor. In future years, all-electric buildings in Europe will likely be advocated. Recent world events emphasize the need to reduce dependency on natural gas and oil. Thus, we assumed a future with all-electric buildings with efficient heat pumps (COP=3.5 heating/ COP 4.1 for cooling).

Tab. 2. Summary and thermal characteristics of the existing apartment prototype.

Building type	Apartment complex
Example	
Model rendering	
Area (m^2)	4056
Units	50
Roof area (m^2)	811
Available PV area (m^2)	650
PV power capacity DC (kW)	138
Windows	120m^2 with double clear glass (2.2 W/m^{2}K); 24 m^2 corner apartments
Walls	Low insulation (0.8 W/m^{2}K)
Ceiling	Uninsulated (2 W/m^{2}K)
Doors	Uninsulated (2.86 W/m^{2}K)
Air leakage	4 ACH at 50Pa blower door pressure
Heating system	Air source heat pump; COP= 3.5
Cooling system	COP 4.1 mini-split cooling system
Hot Water	Electric boiler providing 76 l per day at 55^{o}C per unit (50 units)
Mechanical ventilation	13.7 l/s per apartment, continuous with 72% ERV(50 units)

3.2 Installed Rooftop PV Array

The number of high-efficiency PV modules that fit on the building's roof was estimated by calculating the available roof area, assuming that each 21.4% efficient 345 W module has a 1.63 m^2 footprint with 80% of the gross roof area available for array installation and access. The flat apartment complex roof was modelled as a conventional concrete surface with an 80% solar absorptance and a 92% far-infrared emittance. When a 400 module stand-off PV array is placed above the roof, they provide solar shading, and also block the surface-view factor and the far-infrared emittance linked to sky radiative heat transfer. Using the approach by Peng and Yang [22], we accounted for PV shading by altering the roof total solar absorptance and the far-infrared emittance. We assumed that the roof under the PV arrays has no effective view factor with limited solar exposure or long-wave heat transfer.

4. Energy simulations and results

Energy simulations were performed using BEopt, developed by the U.S. National Renewable Energy Laboratory [23]. The tool performs hourly energy calculations using the EnergyPlus simulation developed by the Lawrence Berkeley National Laboratory and the U.S. Department of Energy]. It estimates energy loads related to heating, cooling, water heating and appliances. Renewable energy production from photovoltaic systems is predicted using the state-of-the-art TRNSYS simulation [24]. To evaluate interaction with expected climate change we used TMY 2018 files morphed to expected conditions in the year 2060 under the IPCC 90% scenario that would approximate extreme future warming [25][26]. Results are in Tab. 3.

Tab. 3. Predicted energy performance with and without PV shading using 2018 and 2060 Extreme Weather.

Insulation level	Cooling (kWh)	Heating (kWh)	Total (kWh)	Cooling savings (%)	Heating savings (%)	Heat/cool energy savings (%)
	2018 TMY					
	Without PV shading					
No Insulation	18256	53215	71471	0.0	0.0	0.0
U-0.2W/m²K	14768	36222	50990	19.1%	31.9%	28.7%
Reflective Roof	14710	59332	74042	19.4%	-11.5%	-3.6%
	With PV shading					
No Insulation	15240	53429	68669	16.5%	-4.0%	3.9%
U-0.2W/m²K	14393	36418	50811	21.1%	31.2%	28.9%
	2060 Extreme Weather (90% IPCC Scenario)					
	Without PV shading					
No Insulation	40191	31521	71471	0.0	0.0	0.0
U-0.2W/m²K	33391	19056	50990	16.9%	39.5%	28.7%
Reflective Roof	34308	35308	69616	14.6%	-12.0%	2.6%
	With PV shading					
No Insulation	35783	30947	66730	11.0%	1.8%	6.6%
U-0.2W/m²K	32781	19071	51852	18.4%	31.2%	27.5%

As seen in Tab. 3, the savings derived from added insulation level were 28.7% of total energy for heating and cooling. For the 2018 weather data, the 138 kWDC rooftop PV system is predicted to produce 146817 kWh annually. Total annual energy use for all end-uses (appliances, lighting and miscellaneous in addition to heating and cooling) is estimated at 297233 kWh for the apartment complex, such that with added insulation (consumption falls to 276633) the generated renewable electricity is 46.9% of annual consumption. For the 2060 extreme conditions, similar thermal influences are seen although heating is significantly lower in Milan and cooling is more than doubled. Total predicted annual energy end uses for 2060 are 284338 kWh, down to 263857 with insulation against 164,818 kWh produced by the PV system. PV output is grows with climate change as winter skies are expected to exhibit reduced cloud cover [27].

As PV-related shading in 2018 reduced cooling by 16.5% (3016 kWh savings) when added to the uninsulated apartment complex (Tab. 3). Little impact on heating was observed (+214 kWh/year). The impact of shading fell sharply when insulation was added. Shading reduced cooling by 2.5% (375 kWh) when added to a well-insulated roof, it increased heating by 0.5% (196 kWh). A reflective membrane (70% reflectance) added to the uninsulated roof is very effective to reduce space cooling, but significantly increased space heating in winter.
Accordingly, this option does not appear well suited for Milan. It may do very well, however, in other Mediterranean locations with negligible winter heating—particularly within future climate.

4.1 Rooftop PV shading as aid to lack of cooling or summertime power interruption

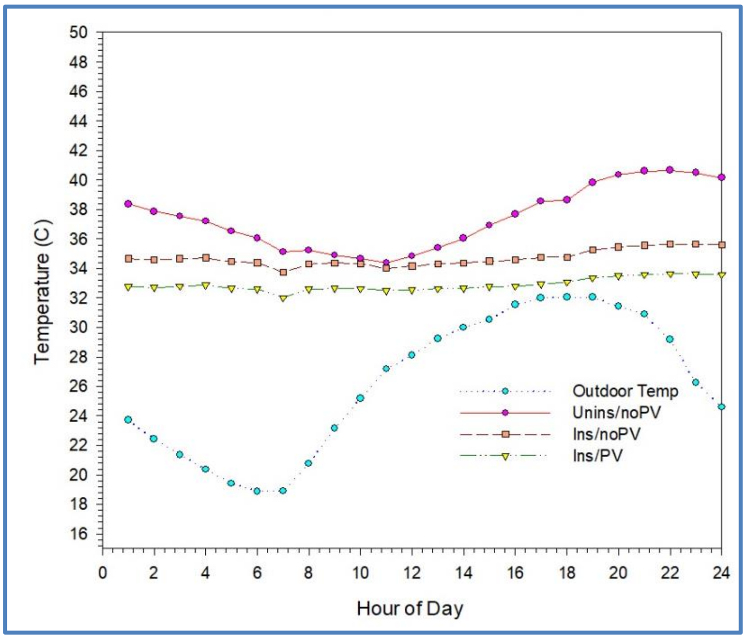
Roof insulation retrofit with added PV can also have large potential impacts on comfort and safety in existing apartment buildings during summer heat waves. Many flats in older apartment buildings with low levels of insulation in Europe lack cooling systems. With increased summertime heat waves expected from climate-related warming, the top floor apartments adjacent to the roof deck under full sun can experience much higher levels of heat accumulation during summer heat waves that can endanger the health of occupants, particularly the elderly [28][29][30].

Even in flats with cooling systems, there is the possibility of equipment failure. Also with increased heatwaves in the future, there are increased chances that utilities may experience “brownouts” where power for cooling and or heating systems are temporarily unavailable [31][32]. Under full sun, the upper floor apartments can become exceedingy hot and are notoriously difficult to ventilate with limited cross ventilation [33] [34].

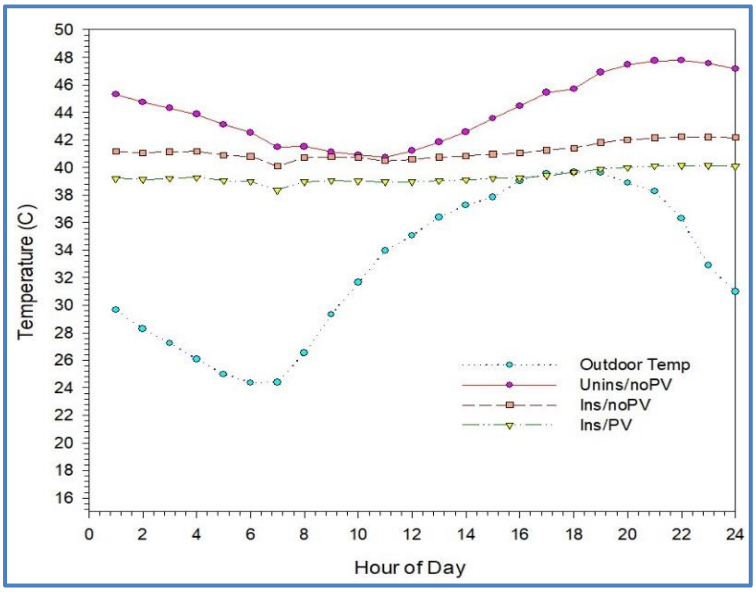
With simulation, we examined the air temperatures within the top floor apartment flats with the cooling system disabled on the hottest summer day. We examined predicted performance both with and without insulation and a shading cover from an expansive rooftop PV system (Fig.2).

Shading from the rooftop PV system appeared effective in controlling excess heat accumulation in the top floor dwellings, particularly when matched with insulation. On 18 July, the hottest day on the Milan weather file, the elevated indoor temperatures in simulated inside flat 47 next to the uninsulated roof were much more moderate with the PV system overhead. During evening hours around 10 pm on this very hot day, the peak inside air temperature in the uncooled and uninsulated flat was predicted at 40.7 °C against 35.6 °C with insulation added.

However, providing PV shading over the top of the roof in the apartment complex with insulation as well was predicted to drop the inside flat temperature without cooling to 33.6 °C, only slightly above the outdoor temperature. While not comfortable, is indicates a very significant improvement in interior comfort and one to less dangerous to vulnerable occupants. As seen with the much hotter extreme weather for 2060 (peak outdoor temperature is 40 °C), the differences in heat accumulation could easily impact occupant mortality as the differences in insulation and shading represent a 7 °C difference in peak room temperatures without mechanical cooling.



a)



b)

Fig.2. Comparison of simulated top floor apartment air temperatures adjacent to roof on summer peak day with and without roof shading from PV arrays and insulation (*Unins/Ins*). Blue dotted line and symbols are the outdoor temperatures on 18 July on the 2018 TMY Milan weather file. Fig. 2b shows the same date for a weather file morphed to the 90% IPCC condition in 2060.

5. Conclusions

Roof retrofit for existing buildings becomes a priority compared to other measures when considering potentials to reduce energy use, generate PV electricity and improve power interruption resiliency. Around the world, poor roof insulation can lead to considerable overheating of top-floor apartments during summer heat waves with increased mortality for some occupants paricularly the health-challenged. Full electrication is also desireble along with efficiency to prevent interruption of natural gas supplies from threating comfort and well being.

We conducted an evaluation of potential energy savings from combining roof insulation with PV electricity generation. For the first time, the overhead shading of solar and long-wave roof irradiance associated with stand-off PV arrays was approximated as part of the evaluation.

Our example analysis for Milan, Italy evaluated a roof insulation retrofit to the roof of an apartment complex combined with or without the installation of rooftop PV. Simulations show that adding insulation to uninsulated apartment prototype was shown to cut heating by 31.9% and cooling by 19.1%. Meanwhile, PV generation can provide up to 46% or more of annual energy needs for a fully electrified complex. We summarize key conclusions:

- Shading from stand-off PV arrays can reduce overheating of uninsulated roofs during summer. Predicted energy required for cooling can be reduced by up to 16.5%.
- PV arrays that cover and shade building rooftops can improve interior comfort in top floor dwellings which may not have cooling systems or whose cooling systems may not be functional. In particular, this provides important protection for health and safety of top-floor apartment dwellers. We saw decreases in temperature in roof adjacent flat without mechanical cooling of 5-7 °C —depending on the presence of insulation and shading from an overhead PV system. These differences are potentially significant to occupant safety, particularly for the elderly.
- Weather files morphed to represent extreme future climate suggest insulation and shading of upper floor apartment roofs may be important to public safety during heat waves if power is interrupted.

In summary, ourresults suggest adding insulation and rooftop PV arrays can not only save energy and produce significant electricity (nearly half for a an electrified apartment complex), but can also help protect building occupant health and safety. in the event of energy interruption.

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Data Statement

The datasets generated during and/or analysed during the current study are not available because not yet published, but the authors will make every reasonable effort to publish them in near future.