Whole-building energy simulation analysis and optimization of residential building equipped with air-duct system in three different regions

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Abstract
This paper examines the retrofitting of low-cost, passive three-dimensionally (3D) printed air-ducts upon the energy usage and production of roof-mounted building integrated photovoltaic (BIPV) systems. BIPV systems are an increasingly popular method of generating electricity, however, the efficiency of photovoltaic (PV) panels is negatively affected by high operating temperatures. Additionally, many residences do not have properly ventilated attics, which increases PV panel temperatures while decreasing airflow. Air-ducts can lower photovoltaic panels operating temperatures and increase airflow in a home’s attic. This study investigates the overall heating and cooling loads after retrofitting an air-duct vs. a baseline building in three climate zones. The results demonstrate a 2.7% energy savings compared to the current baseline design by adding a novel passive BIPV modification.

Keywords: Building Integrated Photovoltaic, Air-Duct System, Natural Ventilation, Energy Modeling.

Key Innovations
- Air-duct attachments increase building performance by reducing cooling loads.
- These attachments work in multiple major climate zones.
- The results demonstrate a 2.7% energy savings by a passive low-cost retrofit.

Practical Implications
Retrofitting an air-duct modification to BIPV helps increase airflow in a residential building’s attic with a passive low-maintenance attachment. This device improves building performance by reducing the attic’s temperature reducing the building’s cooling loads.

Introduction
Reducing energy consumption is an important focus of federal, state, and local policymakers, with residential construction as a primary target, through the use of building codes and weatherization programs to reduce energy usage. An air-duct BIPV system can increase the efficiency of photovoltaic PV panels and lower overall cooling requirements in buildings with the retrofitting of maintenance-free and zero energy 3D printed passive BIPV air-duct attachment (Zarmehr and Kider, 2019). The operating temperature of PV modules is a critical aspect that influences their overall efficiency and lifespan (Power, 2004). Previous research focused on introducing and analyzing an air-flow duct featuring a wind-catcher inspired architectural design to further improve the BIPV efficiency (Zarmehr and Kider, 2019). Zarmehr and Kider introduced a low-cost, maintenance-free wind-catcher duct design intended to increase airflow velocity, thus decreasing the air temperature enhancing performance for PV systems. Lowering the temperature of the backside of a PV panel increases electric output and decreases the thermal degradation. The attachable 3D printed duct demonstrated optimal capture of outdoor air and directing the airflow beneath PV panels utilizing a stack effect driven by buoyancy. The duct system increases airflow on the backside of the PV lowering the overall temperature by increasing the heat transfer. Our previous research demonstrated that computational fluid dynamics (CFD) analysis provided detailed information of airflow behavior (in terms of velocity, temperature, pressure, and humidity), and heat transfer (conduction, convection, and radiation) Zarmehr and Kider (2019).

The proposed system will have two effects on building energy efficiency. First, the air-duct increases the PV power generation by reducing the panel temperatures. Second, the air-duct increases fresh air movement into the attic, by acting like a natural fan (The focus of this paper’s study). By simulating the energy performance of an existing two-story building to measure the impacts of the air-duct design on whole-building energy performance with Energy-Plus, this demonstrates that this simple and low-cost air-duct BIPV system improves energy performance. Furthermore, the duct utilizes airflow to increase building energy efficiency by directing air into the attic or a solar collector. This improved circulation reduces summer ther-
nal loads, permitting the analytical study to show a decrease in the overall cooling load of the building. The optimization metric is energy performance for three different climate zones allowing us to find the ideal functionality. This paper provides constructive advice to increase overall building energy efficiency by adding an air-duct system.

Motivation.
A building’s mechanical heating, ventilation, and air conditioning (HVAC) system uses significant energy to move air. Cooling alone accounts for 15% of the total residential electricity usage (Brown and Koomey, 2003). Natural ventilation (NV) is a promising, rapid, cheap and safe means of improving a structure’s efficiency and reducing demand for energy. NV is an energy-efficient alternative that reduces wasted HVAC energy and improves sustainability (Jiang et al., 2003; Moosavi et al., 2014). However, NV is limited to certain climates (Levermore, 2002). Although NV is a current trend in modern architecture to reduce energy costs, the technique dates back thousands of years, predating mechanical systems in designs of wind-catchers. A wind-catcher is an architectural element mounted to capture fresh air and utilizes physics to increase flow. Solar energy systems, such as roof-mounted photovoltaics, provide renewable electrical power and reduce building energy consumption (Hestnes, 1999; Liu, Duan, and Cai, Liu et al.).

This research focuses on modeling and simulating the heating and cooling loads of a building that uses this type of air-duct to increase the ventilation in an attic. Because of this increased airflow, the natural ventilation produced by the duct can be used to reduce heating and cooling loads by pulling fresh air into the structure. Additionally, the parametric values needed to affect that the air-duct wind-catcher module and building venting strategy will be assessed during this research to determine their effect on the energy performance of a building. To do so, the thermal changes drive the energy simulation to see the effect of the introduced system on the overall cooling and heating loads. Finally, this study analyzes the overall impact of this airflow forced naturally into an attic.

Currently, approximately 15%-20% of solar radiation is converted to electricity by a PV panel. The other 80%-85% is absorbed by the panels and transferred to nearby surfaces as heat. This increased temperature load needs to be removed from the PV panel to maintain optimal performance. Attaching an air-duct increases the natural ventilation between PV panels and the building. Air will enter the duct and create turbulent flow under the PV enabling superior cooling (Gan, 2009). Past approaches look at the mounting (Wilson and Paul, 2011) or varying the space between PV panels and the roof, by measuring the airflow (Mirzaei and Carmeliet, 2015; Goverde et al., 2015, 2017) to increase the performance of BIPV Kalogirou et al. (2014). Little research has been published on the impact of utilizing a wind-catcher duct system to increase natural ventilation Zarmehr and Kider (2018) in BIPV and on a structure’s heating and cooling loads by ventilating the attic and analyzing the change in building energy performance. Well designed ventilated roofs reduce the summer thermal loads imposed by direct solar radiation.

SIMULATION METHODOLOGY

This study consists of two parts first to model and then simulate the effect of BIPV air-duct system on building overall energy consumption. Modeling the changes in monthly cooling and heating energy use of a building equipped with our proposed air duct structure compare to the baseline design which is patterned after an existing condition. The second is to analyze the impact of three different climates for the use of this configuration and finding the optimum environment to use it.

The BIPV load inputs provide the integrated contribution of shading, thermal performance, and air temperature change in the attic (Kider, 2018). Additionally, the effect of rooftop PV on cooling and heating load is location dependent by season, roof material, PV type, glazing materials, and installation strategies. Kapsalis and Karamanis (2015) found that the effect of rooftop PV on building energy performance should take seasonal strategies into account.

The energy simulations conducted to assess the system’s energy use and savings were compared to a baseline existing building without this system. The following conditions are examined:

1. Modeling the existing building without a PV system as a baseline calibrated model and compare to the building’s energy bills.
2. Simulating PV panels equipped with the air-duct system to study the effect of the introduced system on whole building energy intensity use for the same location of the existing building.

Energy Model Input Criteria. Figure 1 represents the existing building used to evaluate the baseline energy performance. The baseline structure is a two story residential home that comprised of 1227 net square feet under air conditioning with two bedrooms, which was zoned as a single-family home in Orlando, Florida (USA).

Orlando is located in a climate zone 2A which is typically hot and humid. The building has a 645 square foot attic. The structure’s utility confirmed energy consumption was evaluated to validate and calibrate the energy simulation model. Using 2018 energy us-
Figure 1: Case Study: two story single-family house.

age of this building, the energy model is precisely calibrated to validation criteria. All monthly energy consumption data was downloaded from Orlando Utility Commissioning (Orlando Utility Commission (2019)) account associated with the subject building. Figure 2 shows the monthly actual utility consumption.

Figure 2: The monthly energy use of existing building based on real utility bills.

Climate Data. The energy simulation utilized a Typical Meteorological Year (TMYx) weather data file acquired from the nearest weather station, Orlando Executive Ap, FL, USA, TMYx station WMO#722053. The TMYx weather data represents the average monthly values from a period of 15 years, using hourly inputs from 2004 – 2018 (NOAA).

Next, two different outdoor parameters are compared which have significant effects on the cooling and heating loads of the buildings. The first key parameter is outdoor dry-bulb temperature. Figure 3 (A) compares the outdoor temperature of the case study region (Orlando) and Washington, DC. The data indicates that Florida has more warm days than DC. So, DC has more heating load than cooling load. Figure 3 (B) compares Orlando and Las Vegas, NV. Nevada has hot days in summer but has more cooler days compared with Orlando, which leads to the determination that Nevada has a greater heating load compared to Orlando but less than the DC region.

The second key parameter is humidity. Like many NV approaches, the air-duct permits entry of untreated humid air into the building. As Figure 4 visualizes, Florida and DC have a greater relative humidity compared to the arid climate of Nevada.

Figure 3: Annual hourly outdoor dry-bulb temperature Analysis

Figure 4: Annual hourly outdoor RH for all three region

Geometry/Thermal Zones. The building was modeled in SketchUp Pro for geometry, material parameters, and defined boundary conditions of this energy simulation. The simulation utilized Energy Plus 9.3 (Crawley et al., 2001) to conduct whole-building energy modeling and simulations. All building envelopes, HVAC systems, electrical equipment, lighting loads are simulated as the existing condition of this specific residential building. The simulation model of this building is a representation of the actual building architectural design with the same orientation and dwelling area of the actual structure (See Figure 5). The case study building was built at 1989, with the building envelope criteria based upon existing conditions (See Table 1). This model configuration was used to perform simulations to assess the energy consumption allowing us to understand the impact and capability of achieving a low energy design target with the proposed BIPV air-duct system.

Operation Schedules. A building’s annual opera-
Figure 5: SketchUp geometry model of existing Building (North Face)

Table 1: Building envelopes criteria based on case study existing conditions.

<table>
<thead>
<tr>
<th>Roof Construction</th>
<th>Asphalt Shingle+Stud+Air-Gap+6”Insulation+Gyp, R-36</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wall Construction</td>
<td>1 1/2” Brick + 1 1/2” Insulation+Stud Wall+Gyp, R-15</td>
</tr>
<tr>
<td>Vertical Fenestration</td>
<td>Single Pane + 1, U-0.36, SHGC=0.36</td>
</tr>
</tbody>
</table>

Table 2: Lighting and Plug Loads settings.

<table>
<thead>
<tr>
<th>Lighting Power Density (W/ft²)</th>
<th>Miscellaneous Equipment Power (W/ft²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.15</td>
<td>0.5</td>
</tr>
</tbody>
</table>

HVAC System. Heating, ventilation, and air conditioning systems have different requirements for various types of climates. The case study building is located in a hot and humid area in the southeastern United States. At the time of simulation, the building is equipped with a 2 ton 14 SEER packaged terminal heat pump unit (PTHP). This system was installed in 2017. PTHP has a constant volume fan, direct expansion cooling type, and electric heat pump for heating type.

Existing Building Energy modeling and calibration The simulation model is calibrated against the utility billing data, utilizing the procedures and error metrics for model error found in ASHRAE Guideline 14 – Measurement of Energy and Demand Savings. The model must agree with the utility data to within a 5% Normalized Mean Bias Error (NMBE) and to within a 15% Coefficient of Variation of the Root Mean Square Error (CVRMSE) for each fuel type considered.

Building outfitted with PV and air-duct system energy model. This section presents the methodology for the building energy simulation under effect of the introduced air-duct BIPV system (See Figure 7 and 8). Analyzing the effect of the duct’s design on building performance by measuring the cooling load, and heating load, and quantifying the difference between the existing building energy model’s results (baseline) and the proposed case model is the goal to assess impact. The study of BIPV air-duct system is mainly divided into two categories. Previous CFD performance analysis of building Zarmehr and Kider (2019), and whole-building energy simulation which is the focus in this paper.

Another important aspect measured and examined (based on climate zone and outside environmental conditions) is that the model pressurizes the attic by utilizing air-duct ventilation. Increasing the pressure of the attic is necessary to calculate unconditioned air leaks from the attic into the conditioned spaces of the building, as no home builder constructs a leak-free structure. Adding increased pressure in the attic helps to visualize and measure changes in the infiltration rate of the building due to this pressurizing of the zone. When the wind-catcher increases the airflow into the duct, the movement of air in the attic will rise. It means the pressure of fluid in some parts
of the duct would be considerable.

PV Design Calculation. The simulation uses the National Renewable Energy PV-Watts Calculator NRE (2019) to determine the amount of energy that is possible to generate based on the location and capacity of the roof (See table 3). These energy input rates are based on an analysis of 30 years of historical weather data and are intended to provide an indication of possible inter-annual variability in the generation for a fixed (open rack) PV system at this site. The specification of PV design based on location, available roof area, and modules criteria are defined in Table 4. PV panels are chosen from common industry brands which is SunPower SPR 122-360. Each of these panels produces ~ 360 watts of energy and their efficiency is ~ 22%.

RESULTS

The results of the case study were analyzed utilizing various parameters. A whole building energy model (BEM) was created to simulate the design using Energy Plus v.9.2 Crawley et al. (2001). Annual energy simulations were performed to assess the energy use and savings as compared to the building’s baseline existing condition, following the input criteria described in the last section. An existing building was simulated for 8670 hours of operation and 1227.12 net conditioned square feet and a total of 1840.68 square feet of total building area. The results are validated with actual annual energy bills of the building for the whole year of 2018. The results show most of the electricity consumption is for cooling and service hot water of building. This data demonstrates that reducing the cooling load is key to improve performance. The design not only will reduce cooling load, but will also increase power generation by increasing the performance of PV. The next energy usage is the hot water system (See Figure 9). Utility bills show the average monthly water use of 2,142 Gal and annual of 25,704 Gal and the energy simulation estimated annual water use of 25,687 Gal for this building. Figure 10 presents the difference between the simulation and measured energy consumption for the building with actual energy bills of the existing case study building. This effort will validate the simulation results.

Table 3: Monthly PV energy values at the location of case study model based on the NREL PV-Watts Calculator.

<table>
<thead>
<tr>
<th>Month</th>
<th>Solar Radiation (kWh/m2/Day)</th>
<th>AC Energy (kWh)</th>
<th>Value ($)</th>
</tr>
</thead>
<tbody>
<tr>
<td>January</td>
<td>3.25</td>
<td>219</td>
<td>24</td>
</tr>
<tr>
<td>February</td>
<td>3.71</td>
<td>271</td>
<td>30</td>
</tr>
<tr>
<td>March</td>
<td>4.04</td>
<td>304</td>
<td>34</td>
</tr>
<tr>
<td>April</td>
<td>6.44</td>
<td>831</td>
<td>92</td>
</tr>
<tr>
<td>May</td>
<td>6.07</td>
<td>804</td>
<td>100</td>
</tr>
<tr>
<td>June</td>
<td>5.80</td>
<td>882</td>
<td>102</td>
</tr>
<tr>
<td>July</td>
<td>6.20</td>
<td>874</td>
<td>105</td>
</tr>
<tr>
<td>August</td>
<td>5.88</td>
<td>711</td>
<td>77</td>
</tr>
<tr>
<td>September</td>
<td>4.94</td>
<td>578</td>
<td>62</td>
</tr>
<tr>
<td>October</td>
<td>4.64</td>
<td>591</td>
<td>65</td>
</tr>
<tr>
<td>November</td>
<td>3.85</td>
<td>518</td>
<td>57</td>
</tr>
<tr>
<td>December</td>
<td>3.35</td>
<td>452</td>
<td>51</td>
</tr>
<tr>
<td>Annual</td>
<td>5.09</td>
<td>8048</td>
<td>892</td>
</tr>
</tbody>
</table>

Table 4: Specific PV design parameters.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Roof Gross Area [SF]</td>
<td>329.38</td>
</tr>
<tr>
<td>PV module gross area [SF]</td>
<td>18.4</td>
</tr>
<tr>
<td>Percentage of south face roof covered by PV [%]</td>
<td>95</td>
</tr>
<tr>
<td>Number of modules can be installed</td>
<td>16</td>
</tr>
<tr>
<td>Total power to generate kWh-year</td>
<td>8041</td>
</tr>
</tbody>
</table>

Figure 9: End-use breaks down of the existing building simulation result
load is the amount of heat energy that would need to be added to a space to maintain the same setpoint. A simulated cooling load shows how energy consumption increased in the summer. There is a small cooling load in the winter because of weather conditions in Florida. In the summer, the cooling load reaches a high of 700 kWh. In the winter, it decreased to almost 100 kWh (Figure 11). The simulation of energy for heating load shows a maximum of 140 kWh in January and zero for the summer (See Figure 11). Comparison of heating and cooling load shows the seasonal consumption of energy in the building. This provides the energy consumption of the baseline model.

We studied three different locations to understand the effect of adding this BIPV air-duct system to building performance. The goal is to understand which climate zones the system will provide the highest efficiency. The three different cases that were analyzed are:

- **Climate Zone 1**: 2A, Orlando, Florida: Existing BEM vs. Proposed Air-Duct Design.
- **Climate Zone 2**: 3B, Las Vegas, NV: Existing BEM vs. Proposed Air-Duct Design.
- **Climate Zone 1**: 4A, Washington, DC: Existing BEM vs. Proposed Air-Duct Design.

**Energy Use Intensity Analysis**

**Cooling and Heating Load Analysis**

The results are presented in this section first by ranking the heating and cooling loads for the proposed model versus the base-case model and then by graphically displaying the HVAC energy usage for the various region. The most energy-saving were achieved for the Florida region. Results showed a 2.7% energy reduction by outfitting the building with the PV air-duct system and moving the static attic air. (This saving does not include the PV power generation). Monthly cooling and heating energy consumption is compared to understand energy consumption. Figure 13 shows how the duct design can reduce 15.6% of annual cooling energy consumption (14456.08 kBTU/Yr. to 12192.1 kBTU/Yr.).

**Adding untreated air into the attic area in the winter increases the heating load of the building. Figure 14 displays plots of monthly heating load comparison. The graph indicates how adding cold air can increase the heating load of the building, which suggests that very hot regions are the ideal potential locations for the proposed duct design. Additionally, this paper proposes two mitigation strategies to minimize the effect of this cold air. First, the vent can be closed during these months when the temperature dips below a set point. Second, it is possible to reduce this negative effect by adding superior insulation. The heating load becomes greater in the D.C. and Nevada regions since they have longer and colder winters compared to Florida’s climate zone. The implemented measures**
determined the resulting energy consumption in a hot climate like Orlando, FL, USA. This concludes that this climate zone has excellent potential for the tested vent design.

![Figure 14: Monthly Heating Analysis (Climate: Orlando, FL)](image)

**Interior Humidity Analysis**

Interior humidity is another important parameter of entering untreated air into the building body. That pressurizing the attic will expose air leaks increasingly on the second level of the building. Therefore, it is important to monitor the interior air humidity ratio to detect additional humid air intrusion. Figure 15(A) plots the mean humidity ratio of L2. The max humidity ratio during hot seasons increased from 0.018364 to 0.01720, and because it is not significantly different the approach complies with the indoor air quality requirements.

**Attic Temperature Analysis**

Analyzing the indoor mean air temperature of the attic is the parameter to see the most effects of the air-duct design on the building energy efficiency. The baseline BEM model and the modified cases cooling and heating set points are identical defined. Figure 16 compares the baseline and proposed model mean temperature in the attic. The attic is the first place to be affected by the air-duct system. Results show that a building equipped with an air-duct system has a 4.5% lower average mean temperature in the attic from a purely passive, low-cost strategy.

**CONCLUSION**

This paper demonstrated the air-duct’s positive effect on building energy performance. By introducing a low-maintenance wind-catcher duct system design, an architect or engineer can easily enhance BIPV installations. The better airflow velocity and decreased air temperature results in increased performance. The design can further improve energy performance by utilizing the increased airflow from the duct system to naturally ventilate an attic which can increase building performance. This system could easily be retrofitted and enhance many BIPV systems with little effort. The design is a low-cost and efficient addition to solar installations. Also, this paper performed an optimization study to see the effectiveness of the system in three different regions. Additional site locations will expand the analysis of the system in more weather conditions and locations. Future work includes calculating the exact electrical output of the PV panels to determine the electrical energy change. This will allow us to factor the change of PV panel energy production into the overall energy simulation to determine the overall impact of the building sys-
Our next phase is to 3D print and install the air-duct model and measure the impact in the field.

References


