ENERGY CONSUMPTION ANALYSIS & PROPOSED RETROFIT OF A DUKE UNIVERSITY DORMITORY

Bass Connections in Energy
2016-2017

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EXECUTIVE SUMMARY

To investigate the incorporation of green building concepts into college dormitories, we examined the current state of energy consumption in a Duke University dormitory. Our focus was Gilbert-Addoms (GA), a 60 year old, 68,625 square foot building. To mediate inefficient fenestration, window parameters were measured, heat transfer models were developed using principles of physics and thermodynamics, and a thin film and sealant retrofits were proposed and analyzed by the same models. Next, to incorporate renewable energy, solar heat gain was calculated from historic solar resource data, and a solar photovoltaic/thermal hybrid system was proposed. Retrofit variables were plugged into the model, and compared with the building's past energy consumption data. The results proved cost-effective in the long term while simultaneously reducing greenhouse gas emissions, demonstrating that retrofits offer feasible potential as Duke and other universities pursue future sustainability goals.

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INTRODUCTION

Two architectural trends have grown in modern cities and urban centers worldwide. One is the increasing emphasis on human-centered buildings that improve user experience. The other is the increasing emphasis on the building's energy efficiency, particularly regarding LEED certifications. Together, these two trends pose pressing challenges in fenestration design.

Despite the aesthetic and practical benefits, windows and doors are openings in a building that contribute to the structure's heat loss and energy inefficiency. To resolve the conflict between glass's potential to improve user experience and their vulnerability in insulation, we will model the effect of 1. two retrofit measures on windows and 2. implementing a photovoltaic thermal (PV/T) hybrid solar system into the building's electricity provision. Here we focus on the possibility of improving a building's insulation through retrofitting new fenestration technologies. A quantitative comparison between current and post-retrofit potential energy consumption will be provided to demonstrate the economic and environmental incentive to adopt the new model.

The dilemma in incorporating windows into building designs originate from silica's inherent properties that impair insulation but provides natural vs. artificial lighting. To estimate the extent to which current windows in a Duke dormitory contribute to heat loss, we used Gilbert-Addoms (GA) on East Campus as a model. Gilbert-Addoms is a 68,625 gross square feet (=6,475.5 square meter) dormitory that first opened in 1957 and was renovated in 2014 (Collins, 2017). In calculating the heat exchange of the entire building, we assume all dorm windows are identical in material and type, and use back-of-the-envelope approach that establishes a model using one window, which is then scaled to an entire building by multiplication.

In terms of the Solar/Thermal aspects of the report, we chose to investigation this technology because it is relatively new and unique, and research found that it was 20% more energy efficient with respect to traditional Solar Photovoltaics. This is primarily because the PV/T system makes use of water to cool the solar panels to make the cell more efficient, and that heated water could be stored in a boiler. With respect to the logistical aspects of the Gilbert-Addoms Dorm, we find that it is not centrally air-conditioned, but each room has an AC unit, and all the rooms are carpeted.

Our overall analysis aims to pioneer retrofit strategies to improve existing buildings' energy efficiency. These approaches, in addition to making potential modifications on old structures, are applicable to on-going constructions and have valuable indications on future designs. By sharing our results and recommendations in this report, we hope to join the virtual conversation that supports sustainable development on college campuses.

FENESTRATION

THEORY

The net rate of heat transfer for fenestration is modelled by the equation below, taking heat loss as positive and heat gain as negative. This equation is applied for months that require cooling energy, which is taken to be March-August.

$$\dot{Q}_{net} = UA\Delta T + c_p \dot{m} \Delta T - IA\tau$$

The first term in the equation accounts for heat conduction through the glass (Figure 1). Here, U is a measure of the heat loss and heat gain of the glass (provided by the manufacturer), A is the window area, and ΔT is the temperature difference.

$$\dot{Q}_{conduction} = UA\Delta T$$

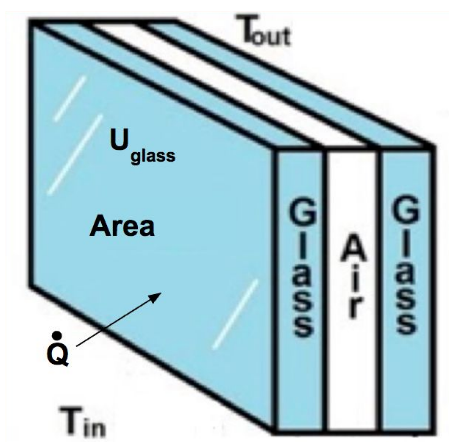


Figure 1. Heat conduction through a double-paned window

Next, the air leakage through the window gaps is accounted for by the leakage term.

$$\dot{Q}_{leakage} = c_p \dot{m} \Delta T$$

Where c_p is the specific heat capacity of air, $\dot{m}$ is the mass transfer rate of air, and ΔT is temperature difference.

In order to calculate the mass transfer rate, the air leakage is modelled as air flowing through a sharp-edged orifice (Figure 2).

$$\dot{m} = KA_2\sqrt{2\rho(p_1 - p_2)}$$

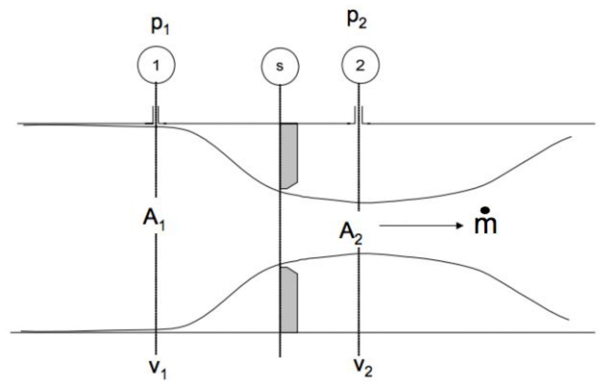


Figure 2. Flow of air through an orifice

Where K is the minor loss coefficient, A_2 is the area of the orifice, ρ is the density of air, and p is the pressure difference.

The mass transfer rate is plugged into the air leakage equation, which provides the amount of heat lost through air leaving the building through window gaps.

The final term in the net heat transfer equation accounts for solar heat gain through the transparent glass.

$$\dot{Q}_{gain} = IA\tau$$

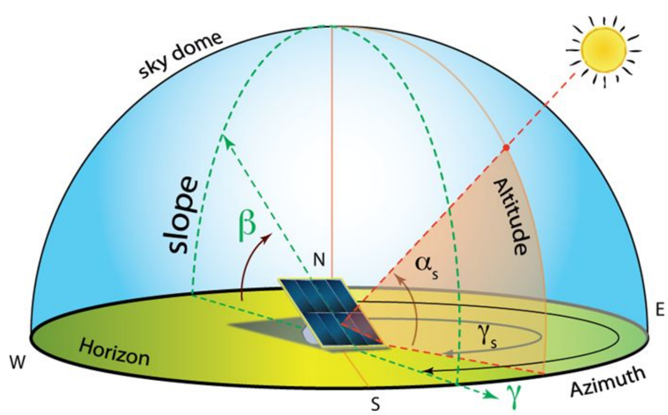


Figure 3. Diagram of solar insolation parameters

Here, I is the isolation, or the total radiation incident on the surface, A is the window area, and τ is the transmissivity of glass for solar radiation. Isolation was calculated based on empirical weather data for Gilbert-Addoms in the month of August. Figure 3 lists the parameters used to calculate insolation (see Table A4 in Appendix for detailed insolation data).

METHODOLOGY

The dilemma in incorporating windows into building designs originate from silica's inherent properties that impair insulation but provides natural vs. artificial lighting. To estimate the extent to which current windows in a Duke's dormitory contribute to heat loss, we use Gilbert-Addoms on East Campus as a model. Gilbert-Addoms is a 68625 gross square feet (=6475.5 square meter) dormitory that first opened in 1957 and was renovated in 2014 (Collins, 2017). In calculating the heat exchange of the entire building, we assume all dorm windows are identical in material and type, and use back-of-the-envelope approach that establishes a model using one window, which is then scaled to an entire building by multiplication.

Loss of efficiency in the heating, ventilation, and air conditioning (HVAC) system generates the central issue with fenestration-related energy consumption. To make a comprehensive estimation of energy loss through fenestration, two possible means of leakage will be considered. Heat exchange through glass (problem 1) and heat exchange through orifices between the glass and the panel (problem 2). For both problem 1 and 2, two sets of calculations will be performed to estimate the amount of energy exchanged across the window, one for status quo and the other after our proposed retrofit.

In addressing problem 1, we propose a retrofit using the Nitto PENJEREX PX-7060N Thermal Insulation Film. Insulating window films offer an affordable, energy-efficient improvements for existing residential windows. By reflecting radiation from outside in summer and retaining heat on the inside in winter, films provide savings on utility bill and reduce carbon emission (Lowe's, 2017). In addressing problem 2, we propose a fixing using 3M Interior Transparent Weather Sealing Tape. While not a long-term solution, weather tapes fill orifices between windows and panels and stop air from traveling between the inside and outside.

The theory and methods sections will elaborate on the two arithmetic model used respectively for fenestration retrofit and solar PV implementation. The Pilkington Architectural Product Guide and Pilkington Graphite Blue™ Datasheet provide baseline parameters for heat exchange across glass windows, and North Carolina Solar Energy Blah blah blah for historic local solar...

Results from fenestration modelling will be compared to *CY2015-CY2016 Campus Energy Data* to provide insights on energy consumption saved. A two-part viability testing will lead the discussion section. The viability section will be followed by a discussion on energy savings in the economical terms, i.e. the business value of our retrofit model, by taking fixed cost taken into consideration. Environmental impact and carbon offset analysis will follow economic impact in order to arrive at a comprehensive evaluation of the proposed model.

RESULTS

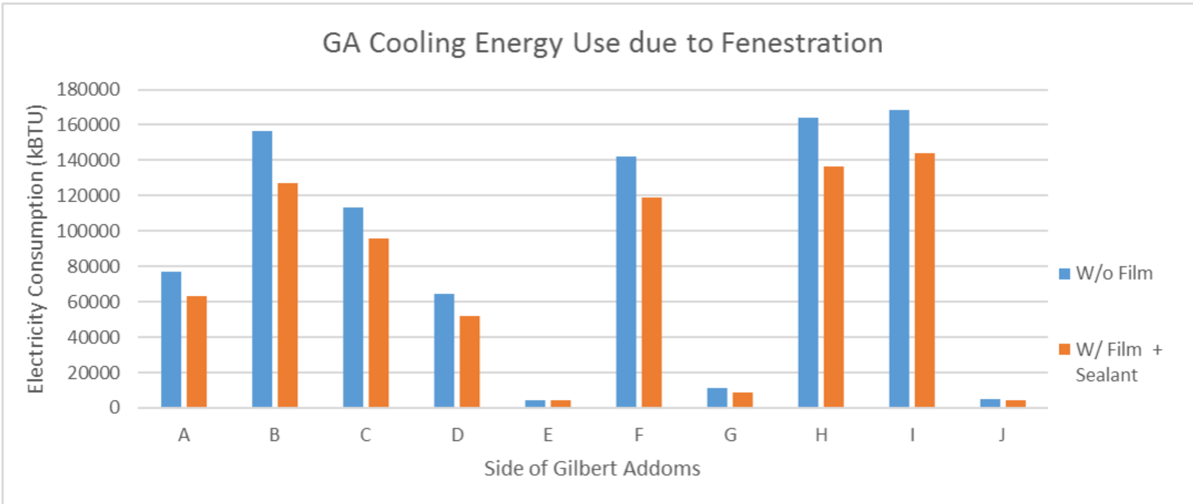
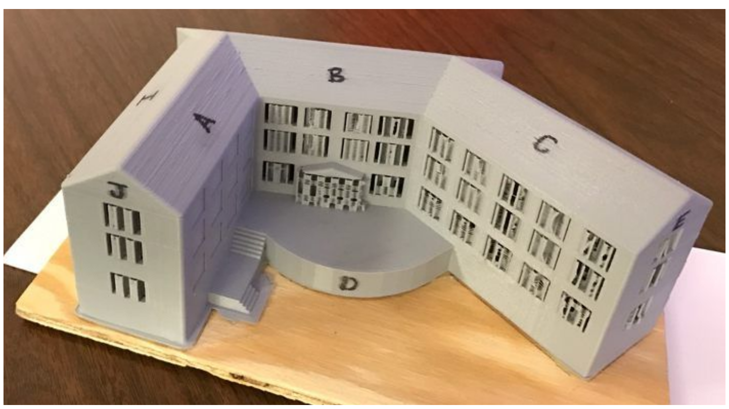
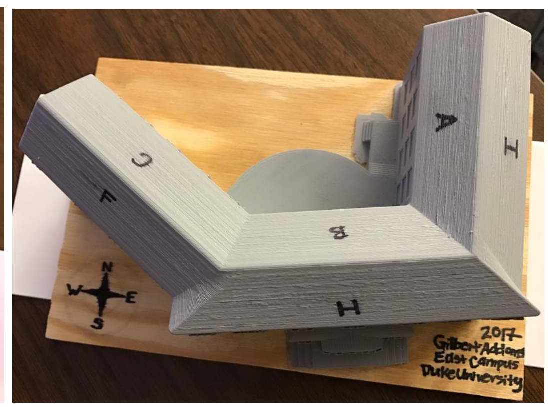


Figure 4. Energy consumption results for Gilbert-Addoms with and without retrofit (See Table A2 in Appendix for sides).





Figures 5 and 6. Orientation of each side of Gilbert-Addoms.

The results in figure 4 show that sides E, G, and J have the lowest electricity consumption both with and without the retrofit parameters. Sides B, F, H, and I have the highest electricity consumption without the retrofit and the highest energy savings with the retrofit. The sides with the highest savings all have the most windows, and sides F and H are south-facing (Figures 5 and 6). More detailed information about the orientation of each side can be seen in Table A2 of the Appendix.

Table 1. Total energy consumption results from fenestration model

Annual baseline energy consumption (w/o retrofit)	266,000 kWh
Annual energy consumption w/ retrofit	221,000 kWh
Annual energy saved	45,000 kWh
% of energy saved	16.9%

Table 2. Comparison of fenestration model results to empirical energy consumption data for Gilbert-Addoms.

Model baseline energy consumption	266,000 kWh
Actual energy consumption for GA (Mar-Aug 2016)	490,000 kWh
% energy loss due to fenestration (based on model results)	54.4%

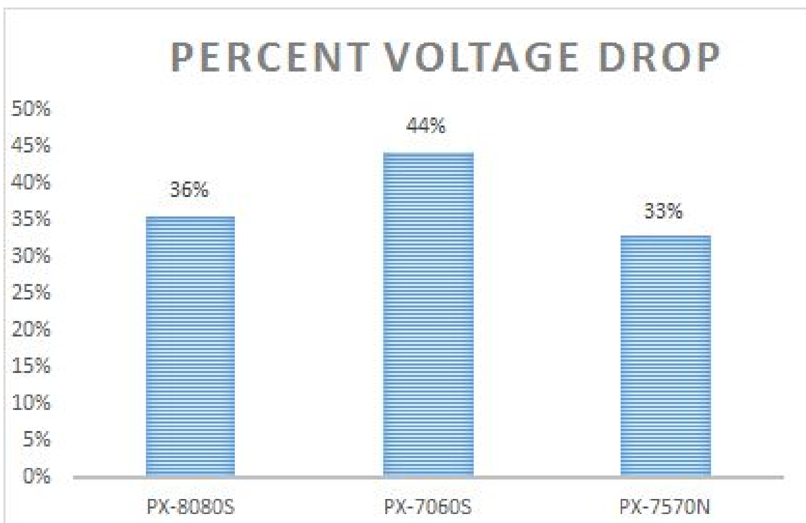


Figure 5. Empirical results for voltage drop for 3 Nitto films from a 7 mV baseline.

DISCUSSION

VERIFICATION OF MODEL

The results from the fenestration model showed a baseline electricity consumption of 266,000 kWh for Gilbert-Addoms for a 6 month cooling season (Table 1 and 2). The actual electricity consumption for GA from March-August 2016 was 490,000 kWh (see Table A3 in appendix). This means our fenestration model accounts for 54.4% of the energy consumption in GA. As lights, heating, and any other general electricity consumption are not factored into the fenestration model calculations, the assumption that about half of electricity consumption in GA would be used for fenestration seems reasonable.

Film testing was also conducted on three Nitto films in order to test the actual energy savings of each film. Out of the three films tested, PX-7060S had the largest voltage drop, meaning it is the most effective at blocking heat gain through the window. This film had a voltage drop of 44%, as seen in Figure 5, which verified Nitto's claim that their films reduce energy consumption by 40%.

The proposed 3M™ Transparent Weather Sealing Tape has not been tested, but data from Energy Star implied a 20% reduction in energy consumption for this product. In order to verify this testing the weather tape would be a potential next step in the process.

ECONOMIC IMPACT

Table 3. The cost analysis of the fenestration retrofit.

Annual energy saved	45,000 kWh
Energy cost	$0.0745/kWh
Annual money saved	$3,350
Total cost of installation	$21,340
Number of years to break even	6.4

As summarized in Table 3, the result from the fenestration modelling calculation showed a 45,000 kWh energy saving per half-year period (March-August). At $0.075/kWh, this reduction in energy consumption can be translated into an annual savings of at least $3,350. When estimating one 2.5m^2 film that covers an entire window panel to be $100,[1] and the sealants needed for a window to reach its sealed condition assumed in our calculations to cost $16 (i.e. total cost at $116/window), the fixed cost will add up to be $21,344. Therefore, retrofitting all the windows in GA has a rate of investment return at 6.4 years. With only the warmer six months of the year taken into consideration, this rate of return is conservative. In general, breaking even at 7th year is considered a reasonable investment. Therefore, quantitatively speaking retrofitting the windows in GA has optimistic economic value.

The economic impact of retrofitting all buildings on Duke's campus, therefore, will potentially see a magnified positive impact on electricity bills in the long term.

[1] Due to Non-Disclosure Agreement, price of PX7060S weather insulation film is an estimation close to its real market price.

ENVIRONMENTAL IMPACT

As seen in Table 1, 45,000 kWh of energy can be saved per half year period (March-August) by applying fenestration retrofits; this means 288,000 kWh can be saved over a conservative rate of investment return of 6.4 years. In environmental benefits, this is the equivalent of carbon dioxide emissions from 215,980 pounds of coal burned, or the carbon sequestered by 192 acres of US forests in one year (US EPA).

Considering the additional, unaccounted savings from the winter period (September-February) would further increase these savings; the films work proactively in the winter, heating the interior. In addition, these retrofits can last upwards of 20-30 years, so the environmental benefits of applying a thin film and sealant are worthwhile to GA. Extrapolating to the whole campus, which has numerous older buildings, the environmental impact of the saved energy would be significant. Recall how Duke Energy relies on four primary energy sources: nuclear, coal-fired, oil- and natural gas-fired, and hydroelectric power plants. The majority comes from coal and nuclear fuel, nonrenewable sources; although Duke has eliminated coal use from campus, natural gas is prevalent. Considering the atmospheric warming potency of natural gas, energy savings would decrease the need of this nonrenewable resource directly benefiting the environment. As Duke strives to become carbon neutral by 2024, applying retrofits would greatly reduce emissions and thus lower the amount of carbon offsets needed to reach the goal.

SOLAR

THEORY

Calculating Tilt Angle

Whenever a solar photovoltaic system is put into place, a decision must be made on the orientation of the panels. In large-scale solar farms in secluded areas like the desert, rotating bases are often used in order to maximize solar yield throughout the day and year. However, most rooftop solar panels are not outfitted with the same level of sophistication due to cost constraints. In the case of the Gilbert-Addoms dormitory (GA), we have decided to move forward with fixed orientation panels. This brings up the question of what angle to tilt the panels at. For most rooftop solar panel outfittings, the tilt angle is set equal to the latitude of the location on the globe. Throughout the paper, we will refer to a panel pointing straight up as zero degrees, with positive degrees tilting the panel towards the equator. For the tilt angle of the solar panels on GA, we have optimized them for summer using a tilt angle of 26˚.

Tilt angle can be optimized for the summer, the winter, or for year-round sun maximization. For year-round solar input maximization, the optimal tilt angle can be determined by the latitude of the building. For reasons that will be discussed in the methods section of this report, we chose to use the summer optimization, which is the tilt angle minus 10˚. These 10˚ ensure that the summer sun's high zenith rays can be taken full advantage of.

Explanation of PV/T system and advantages

A Photovoltaic/Thermal (PV/T) Hybrid system is a system in which solar panels are used and receive a boost to their efficiency through a water cooling system. This water cooling system that increases the solar panels' efficiency due to reducing their temperature also heats up the water that is used in this cooling system. This water is then sent to another rooftop reservoir in which it is heated to residential hot water temperatures, then sent into the building for use. The overall efficiency of this solar PV/T setup is thus far greater than that of a PV or thermal system on its own.

Several variables are of importance when efficiency is called into question: solar panel efficiency and how it scales with temperature, heat transfer between the solar panels and the water, and total volume of water needed for the cooling system all must be taken into account. Additionally, the general calculations for solar PV panels and solar thermal setups must each be performed. In this section, we will discuss the PV/T setup as a whole, while in the next two sections we will look at the photovoltaic and thermal parts of the system in isolation.

The benefits of a PV/T system are rather clear: 1) more energy is harvested from the same area, resulting in a greater overall efficiency, 2) water keeps the solar panel hardware cool, increasing its efficiency and extending its lifetime, and 3) the system can provide both electricity and hot water to a building. However, the disadvantages of PV/T can be rather taxing. The high cost of PV/T panels is a high barrier to investment and can reduce the economic viability of purchasing such panels. Thus, although PV/T systems have great efficiency, the economics of the panels have not yet caught up with the economic viability of standard solar photovoltaic panels. See the discussion section of this report for an economic analysis of the proposed PV/T system.

Provide equation for power generated (to be calculated in results)

In order to calculate the amount of power generated by a solar panel setup, we must take into account several factors: incoming solar radiation (or insolation), as well as solar panel area, tilt angle, and efficiency. Solar panel efficiency is usually given for a certain panel, and the means for calculating tilt angle are discussed above. Thus, the instantaneous power of such a system can be calculated as:

$$P = I \times A \times \eta \, ,$$

where P stand for power, I stands for insolation, A stands for solar panel area, and eta stands for efficiency. This seemingly simple equation is complicated by the difficulty of finding I, the incoming solar radiation (insolation). Seeing as this equation gives instantaneous power, it is clear that the insolation term changes as the sun moves across the sky. In order to figure calculate the insolation for each hour of the day on the solar panels, we downloaded and made use of weather data from the National Renewable Energy Laboratory (NREL). This weather data consisted of the direct normal insolation for each hour of each day of the year. Using this data, we were able to estimate the total insolation hitting our solar panels over the course of the year. Adding this up using the above equation provided us with a final value of energy generated by the photovoltaic part of our solar panel setup. This weather data was used again with a slightly different and more involved process in order to calculate the solar heat gain through the windows for each face of the building. This can be found in the fenestration section of this report.

METHODOLOGY

For the application of the solar panels to the roof of Gilbert-Addoms (GA) dormitory, photovoltaic and thermal hybrid (PVT) solar panels were chosen. The position of panels were chosen as a function of the amount of solar radiation in that particular location. The amount of solar radiation that would hit the roof was determined by using weather data of Durham, NC from NREL. The global position of GA is 36.007139 degrees North by 78.918695 degrees West. To optimize the amount solar energy capture, 24 Solimpek

Volther PhotoVolt panels were placed on the south-east facing facing roof of GA at an angle of 26 degrees with respect to the ground(Optimum, 2017). Solimpek PhotoVolt panels were chosen due to the high efficiency and relatively low price when compared to other hybrid systems(Herrando, 2016). Each 1.7 m^2 PhotoVolt panel will cost $590 each with an additional 20% added to the total cost for the setup and installation. As a result, the PV/T system will cost approximately $18,500.

Explain SAM vs. insolation model

In this project, we were able to take advantage of a software developed by the National Renewable Energy Laboratory (NREL) called System Advisor Model (SAM). This software is designed with several different renewables in mind, and can be used to model systems that comprise of several renewable systems working in tandem. In our case, SAM was used to calculated the amount of electricity generated by our rooftop solar panels. However, as SAM does not have the capability to model a PV/T system, we had to use a simpler PV model as an approximation of the electricity generated by the proposed system. The parameters input into the SAM software are as follows: size of panels, system nameplate capacity, efficiency of panels, tilt angle of panels, azimuth angle of panels (which direction they face), and exact coordinates of the system. These parameters were used along with weather data from NREL in order to come up with a final estimate of solar panel electricity output. The annual electricity generated by our system can be found in the results section of this report.

Performing these calculations solely via the SAM software tacitly places a great amount of confidence in the software. However, this level of confidence may not be warranted until secondary verification of the model is conducted. For this reason, we decided to calculate the proposed system's annual electricity output through our own methods. This secondary calculation would serve as a verification that SAM's assumptions and estimates were within reason. To calculate solar electricity gain, we used the equation for instantaneous power discussed in the theory section of this report as well as detailed weather data from NREL. This weather data consisted of the direct normal insolation, through which we could calculate instantaneous power for any moment in the year. Summing up all of these instantaneous powers through integration brought us to our final quantity. The results of these two different methods of calculation can be found in the solar results section of this report.

Calculation of the electricity and heat generated by the panels

For our personal solar model, a simplified efficiency taken by the manufacturer was used as an constant for power generation. For the electricity and heat generated by the PV/T system, an efficiency of 15% and 35% was used as provided by the Solimpek company, respectively(Volther, 2017). The total amount of solar radiation per hour reaching GA was provided by NREL for 2014. In addition to the hour of the year the data was taken, the data provided included the solar zenith angle and the solar intensity at the solar zenith.

Using the insolation data, the solar intensity of the Durham area on a monthly bases was acquired. For each hour, the total solar intensity was multiplied by the total area of the panels, the efficiency of the panels, and a cosine function to account for the deviation of the solar panel relative to the solar zenith. Given each hourly electricity generation by the PVT panels a monthly and yearly electricity production was calculated.

For the heat generated by the PVT system a similar equation was set up using the NREL insolation data. To determine the hourly heat gain, a solar heat efficiency of 35% was used instead of 15% for the electricity generated. To determine the amount of heat that could be harnessed by the system, the hot water would have to reach a certain temperature and run through a storage tank to heat up domestic water. For simplicity of the model and to calculate the ideal scenario, an assumption of 85% heat transfer between the tubing and the storage tank was made. The heat transferred to the water as a result of the cooling of the panels was calculated using the heat transfer equation, $Q=mc\Delta T$. The temperature of the water exiting the storage tank and passing over the solar panels, was taken to be 63 C, the typical bathing water temperature. The heat being transferred to the water from the panels is a factor of the solar intensity and the 35% efficiency of heat capture. The mass of the water is a function of the flow rate of the cooling system. An optimal flow rate of 2.2 L/hour was determined to insure that the temperature of the water within the tubing did not reach to temperatures above 180 degrees celcius. Given the temperature increase of water as it leaves the panels and enters the storage tank, the amount of heat transferred to the tank through the tubing was calculated by reversing the equation previously used.

Calculation of the % electricity that would be offset by the panels

The electricity offset by the panels was calculated by comparing the electricity generated by the PV module and PT module of the panel with the electricity usage of the building. For both modules, the energy generated are calculated in terms of kWh. Both were then compared to their relative areas in the buildings energy usage. The PV module was related to the overall electricity usage, while the PT module was compared to the energy to heat water for the building. The offset of the system was calculated by dividing the energy generated by the panels and dividing each component by its respective price per unit energy. Two different prices are paid for heating and powering the building. With the yearly savings calculated, the payback time for the panels can then be calculated. Under the assumption that major fluctuations in solar radiance and electricity prices will not change in the following decade, an accurate approximation of the payback time could be calculated. Using the installation cost, an approximate lifetime capital cost of the panels was determined. Dividing the lifetime capital cost by the yearly savings of the panels will allow for an approximation on the payback time.

RESULTS

Energy savings

Table 4. Monthly solar energy gain using two different models

	SAM	Insolation	Model
Month	PV (kWh)	PV (kWh)	Thermal (kWh)
Jan	440.5	530.6	929.0
Feb	494.5	351.7	615.8
March	659.6	593.8	1039.7
April	764.1	670.0	1173.0
May	756.2	829.5	1452.4
June	780.3	794.6	1391.2
July	763.1	695.6	1217.9
Aug	737.7	640.3	1121.1
Sept	610.4	452.8	792.8
Oct	577.6	675.0	1181.7
Nov	413.3	472.1	826.5
Dec	418.5	371.3	650.1

From the table above, we could see that the most energy savings we get from SAM is for the months of April, June and July (Table 4). This is notable because this is during the summer which implies the greatest amount of solar radiation during the day. In regards to the insolation model, we note that the greatest energy savings are during the months of May, June and July which also makes sense because it is during the hottest summer months with a larger amount of solar radiation. Finally, when we are looking at our data for the thermal aspect, we find that it is very similar to the other two models in that the greatest energy savings could be found in the months of May, June and July. However, there are some outliers in that the month of October also offers a great deal of energy savings.

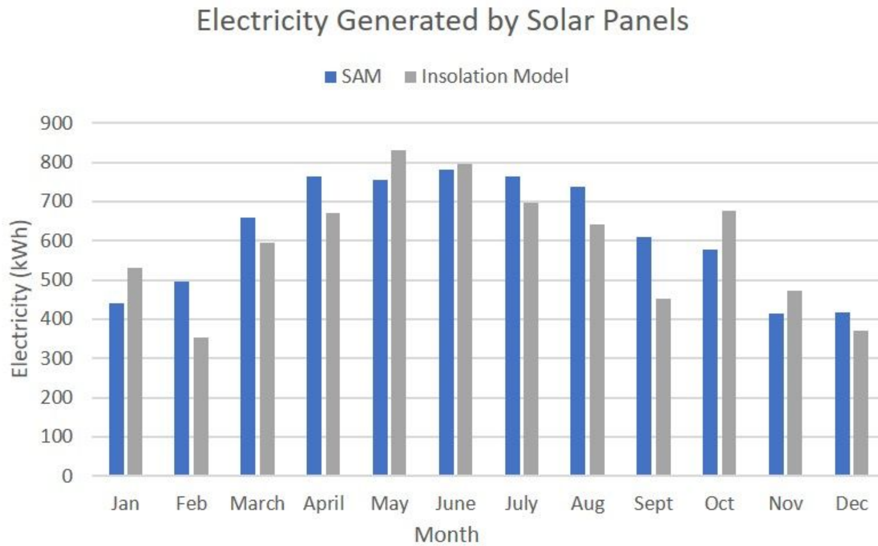


Figure 8. Electricity generated by solar panels

From Figure 8 shown above, we generate our theoretical values for the electricity generation by the SAM and by the insolation Model. We could see by general trend and variance that both models are very close to each other in value. However, there are some outliers that could be found in the month of September. Additionally, we note that the insolation Model electricity generated values is greater than those of the SAM values for some months, and less for other months, seeing that there is no relevant trend to the winter and summer months.

The solar panels will generate about 7,000 kWh of electricity per year, while GA's average total electricity usage is 840,000 kWh. This amount of electricity amounts to 0.84% of GAs total electricity consumption on the year.

Cost analysis

Table 5. Photovoltaic energy production by the PV/T system. Savings per year with Duke's cost of energy at $.0745 per kWh.

Per Year				
Wh/m^2	kWh/m^2	Area (m^2)	Total kWh	Savings/year
222454.87	222.45487	31.815072	7077.4177	527.267619

Table 6. Photothermal energy production by the PV/T system. Savings per year with Duke's cost of energy at $.0745 per kWh.

Per Year			
kWh/panel	Panels	Total kWh	Savings/year
438.861564	24	10532.6775	784.684476

Table 7. Total energy production by the PV/T system. Payback in years when the cost of energy for Duke is $.0745 per kWh.

Total kWh	Total saving per year ($)	Initial Cost ($)	Payback (years)
17,600	1,300	18,500	14.1

Utilizing the tables above, we denote that from the PV system would save $527.27 a year (Table 5). Additionally, from the thermal aspect of the PV/T, the dorm would save $784.68 a year (Table 6). From this, the PV/T system generates and conserves a total of 17,600 kWh of electricity a year, leading to a total saving of $1300 per year. Because the initial cost is $18,500, we would find a payback of 14.1 years (Table 7). This number though short, does not necessarily offer a feasible payback time. For example, investors look at a payback time of 7 years or less as optimal for the given technology. Because of this, we need to find a more suitable means to have the PV/T system be more economical and efficient device.

DISCUSSION

VERIFICATION OF MODEL

Table 8. Percent error in the difference between the two models for each month's electricity output.

Month	Percent Error (%)
Jan	20.5
Feb	28.9
March	10.0
April	12.3
May	9.7
June	1.8

July	8.8
Aug	13.2
Sept	25.8
Oct	16.9
Nov	14.2
Dec	11.3
Year	4.6

In order to quantitatively check that our model verification was successful, we calculated the percent error between the SAM and insolation models' monthly electricity estimates. The percent errors for each month can be seen in the table above (Table 8). The largest percent errors are around the 25% range, and represent relatively high deviation between the two models. However, there are also percent errors as low as 1.8% in June for example. When these percent errors are taken as a whole, their mean is 12%, while their median is 11.8%. The fact that these values are close shows that this distribution is not heavily skewed. Although a 12% error rate is not ideal, it is close enough to add confidence that SAM and our own insolation model in fact agree to a reasonable degree. Even this rough correlation of 12% mean error rate is not low enough for a rigorous model, it is low enough to give increased confidence in the models' agreement. For instance, if either of these two models were taken alone, we would know nothing of their errors and thus their credibility. This shows the power of results verification to increase confidence in both results and conclusions of the report.

ECONOMIC IMPACT

One of the main reasons why we find that our model has a payback time of 14.1 years is because of the very low price. The price of electricity for the GA dorm is $.0745 per kWh, which is much cheaper compared to the average in the US which is around $0.12 per kWh. Additionally, another reason why we are facing a long payback time is because of the high initial cost of $18,500. We would be able to find more affordable solar panels that could be as efficient. We were initially interested with utilizing the Photovoltaic and Thermal system because it was a relatively new and unique technology that is very popular in Europe. However, working throughout the entire year on studying the theoretical and structural complexities of the PV/T system, and also considering the higher costs it entails, we could potentially look to a more economic low cost PV system. This in hope would allow us to reach a shorter payback time closer to the optimal number of 7 years, and make the technology more marketable. Moreover, the PV/T system brings in many more complications and intricacies, and it would make the system more difficult to set up and maintain in the GA dorm, as it entails added variables like an added boiler.

ENVIRONMENTAL IMPACT

Based on the two models used to calculate the energy generated by the solar panels, we can presume a range of 7,000 to 7,300 kWh of electricity per year. Where this looks like a significant amount of energy produced in a year, it is insignificant when compared to the energy use of the building. This amount of energy generated by the panels accounts for less than one percent of the total building's electricity usage. The hope of the GA retro-fit was to substantially reduce the energy need of the building, but this does not seem to be the case for this building. In addition to the relatively minimal energy generation, the extra energy generated by the thermal component would not be easily incorporated into the building. GA does not use a in building boiler to circulate hot water, like other domestic buildings. This would mean to incorporate the thermal energy savings of the hybrid system, a complete remodeling of the building would be required. For this reason, the energy savings that could have been offset by the heated water would not be able to be easily implemented. Even though the solar system is not demonstrating substantial improvements to GA, the pursuit for alternative solar power should not be dropped. The solar panels may not have a substantial energy generation, but it could have an effect on the students that inhabit the dorm. Duke is in the pursuit of obtaining carbon neutrality and visual demonstrations toward this goal on a first-year campus could encourage greener behaviors. In this regard, the application of solar panels could influence energy savings within the dorm in a habitual nature.

The hybrid system that we chose was done to increase the efficiency of the panels, while also increasing additional offset by capturing thermal energy. With technology constantly improving, newer, cheaper and more efficient PV systems are being developed and built. With this in mind, future analysis should be done with a PV system instead of the hybrid system explored in this paper. By setting up a PV system, costs could be reduced on all fronts.

CONCLUSION

Based on the rate of return analysis and in pace with Duke University's Sustainability Strategic Plan to reach campus-wide carbon neutral by 2020 (Sustainable Duke, 2016), retrofitting GA fenestrations with PX7060S weather insulation films as well as 3M™ Transparent Weather Sealing Tape has the potential to move from theoretical calculation to practical implementation. In order to initiate this with Duke Administration, a separate model for non-summer months should be developed to take winter data into consideration. Then, we can approach Facilities Management and propose our retrofits.

When analyzing the feasibility of a solar retrofit on GA, our report found that the payback time for the proposed solar PV/T panels was far too long to be economically viable. The main factor causing elongation of the payback time is the great capital cost of the sophisticated PV/T panels from the Volther company based in Germany. Before starting this report, we figured that a PV/T system would be ideal for the summer due to its high efficiency even in high temperatures. It is of course more efficient than standard PV panels at high outdoor temperatures as it is constantly cooled by flowing water. However, it has been shown that in most cases rooftop solar panels can pay for themselves in around 7-10 years. Thus, if a simpler PV setup was implemented, the payback time of the project as a whole would decrease substantially. If we were to give a recommendation to the Duke administration to retrofit GA or any other dorm buildings on campus, we would suggest a simple PV setup rather than the overly complex PV/T setup that we explored in this project.

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APPENDIX

Table A1. Parameters used in fenestration model based on Pilkington data

Window Type	Uncoated clear flow glass; air insulation
Window Dimensions (cm)	166x152
Window Area (m2)	2.54
Orifice Size (m)	0.0031877
Summer U-value (W/sq m/K)	3.1229
Film U-value (W/m2/K)	3.46
Combined U-value (W/m2/K)	1.641409409
Tinside (K)	304.7
Toutside (K)	296.9
K (sharp-edged orifice)	0.5
Δp (Pa)	3400
ρair (kg/m3)	1.18
cp (J/kg-K)	1000
Window Transmittance	0.67
Film Transmittance	0.45
Combined Transmittance	0.3015
AC Unit SEER (Electricity)	10
Central AC SEER (Chilled Water)	11.5

Table A2. Fenestration electricity calculations for model baseline and retrofit

Side	A.C. Source	Face	Windows	Type	Qconduction (W)	mdot (kg/s)	Qleakage (W)	Insolation (W/m2)	Qgain (W)	Total Heat Loss (W)	Total Heat Loss (kBTU)	Input Electrical Energy Required (kBtu)	Seasonal Energy Required-Cooling (kBtu)
				Without Film	928.063422	0.1427719551	16704.31875	58.63978148	1496.897702	16135.48447	37719.083	12869.75112	77218.50671
A	Electricity	N.W.	15	With Film + sealant	487.7940482	0.1427719551	13363.455	58.63978148	673.6039658	13177.64508	30804.69567	10510.56216	63063.37297
				Without Film	1856.126844	0.1427719551	33408.6375	49.27620772	2515.747509	32749.01683	76555.6737	26120.79587	156724.7752
B	Electricity	North	30	With Film + sealant	975.5880965	0.1427719551	26726.91	49.27620772	1132.086379	26570.41172	62112.26981	21192.70646	127156.2387
				Without Film	1423.03058	0.1427719551	25613.28875	65.69600785	3354.043985	23682.27534	55360.82359	18889.11301	113334.6781
C	Electricity	N.E.	23	With Film + sealant	747.950874	0.1427719551	20490.631	65.69600785	1157.145175	20081.4367	46943.33033	16017.06431	96102.38586
				Without Film	866.1925272	0.1427719551	15590.6975	37.78296372	900.1866671	15556.70336	36366.09649	10789.66272	64737.9763
D	Chilled Water	North	14	With Film + sealant	455.274445	0.1427719551	12472.558	37.78296372	405.0840002	12522.74844	29273.77785	8685.402612	52112.41567
				Without Film	61.8708948	0.1427719551	1113.62125	58.63978148	99.79318012	1075.698965	2514.605533	746.0725286	4476.435172
E	Electricity	N.W.	1	With Film + sealant	32.51960322	0.1427719551	890.8969999	58.63978148	44.90693106	878.5096721	2053.646378	700.7041442	4204.224865
				Without Film	1794.255949	0.1427719551	32295.01625	87.69455133	4327.919036	29761.35316	69571.56769	23737.8189	142426.9134
F	Electricity	S.W.	29	With Film + sealant	943.0684933	0.1427719551	25836.013	87.69455133	1947.563566	24831.51792	58047.34821	19805.75521	118834.5313
				Without Film	123.7417896	0.1427719551	2227.2425	5.397566245	18.37115647	2332.613133	5452.828425	1860.505059	11163.03035
G	Electricity	N.W.	2	With Film + sealant	65.03920643	0.1427719551	1781.794	5.397566245	8.267020412	1838.566186	4297.920567	1466.450498	8798.702985
				Without Film	2057.207252	0.1427719551	37027.90656	83.73119425	4737.917067	34347.19674	80291.65578	27395.51295	164373.0777
H	Electricity	S.E.	33.25	With Film + sealant	1081.276807	0.1427719551	29622.32525	83.73119425	2132.06268	28571.53937	66790.20188	22788.81688	136732.9013
				Without Film	2227.352213	0.1427719551	40090.365	115.6179932	7083.31323	35234.40398	82365.63399	28103.15432	168618.9259
I	Electricity	East	36	With Film + sealant	1170.705716	0.1427719551	32072.292	115.6179932	3187.490953	30055.50676	70259.19527	23972.43742	143834.6245
				Without Film	61.8708948	0.1427719551	1113.62125	49.27620772	83.8582503	1091.633894	2551.85579	870.6931955	5224.159173
J	Electricity	North	1	With Film + sealant	32.51960322	0.1427719551	890.8969999	49.27620772	37.73621263	885.6803905	2070.408994	706.4235486	4238.541292
				Without Film	11399.71237	1.427719551	205184.7153	497.2507903	24618.04778	191966.3799	448749.824	151383.0797	908298.478
Total			184.25	With Film + sealant	5991.736892	1.427719551	164147.7722	497.2507903	10725.94688	159413.5622	372652.795	125846.3232	755077.9395

Table A3. GA empirical energy data for March-September 2016

BldgName	GSF	UtilityType	MeterName	3/1/16 12:00	4/1/16 12:00	5/1/16 12:00	6/1/16 12:00	7/1/16 12:00	8/1/16 12:00	9/1/16 12:00
Gilbert-Addoms [7230]	**6862**	**Chilled Water**	**CV7230AR -Gilbert Addoms**	**7,105**	**31,339**	**19,811**	**21,837**	**25,658**	**31,019**	**29,761**
		Electric	**EV7230AR -Gilbert-Addoms**	**197,906**	**221,111**	**257,125**	**179,130**	**155,556**	**522,834**	**412,060**

Table A4. Solar and Thermal energy calculations for insolation model.

		w/m2	w/m2													
Day of Year	Hour	DNI	Solar Zenith Angle	Solar Hour	Hour Angle	Sin Theta	Theta	Sin Phi	Phi	Relative Azimuth Angle	Incidence Factor	Solar +	Panel electricity per	Insolation	Solar electricity	Heat (kWh)
1	0	0	166.7798377	-3	-172.5	-0.969275779	-75.7603426	-0.487225546	-29.15834686	-15.84165314	0.236634287	0	0	0	0	0
1	1	0	159.8744854	-2.75	-157.5	-0.919092368	-66.79365822	-0.891728918	-63.09122491	18.09122491	0.374561958	0	0	0	0	0
1	2	0	148.8793782	-2.5	-142.5	-0.822144626	-55.2999821	-0.981883882	-79.0772398	34.0772398	0.471523576	0	0	0	0	0
1	3	0	136.933111	-2.25	-127.5	-0.6850394	-43.23864578	-0.999936349	-89.35341553	44.35341553	0.520911349	0	0	0	0	0
1	4	0	124.8139367	-2	-112.5	-0.51712021	-31.13923514	-0.991117671	-82.35760402	37.35760402	0.680333642	0	0	0	0	0
1	5	0	112.8312656	-1.75	-97.5	-0.329830503	-19.25846133	-0.964312581	-74.64682373	29.64682373	0.820456456	0	0	0	0	0
1	6	0	101.2053299	-1.5	-82.5	-0.135933799	-7.81260958	-0.918879444	-66.76271749	21.76271749	0.920106568	0	0	0	0	0
1	7	0	90.16823884	-1.25	-67.5	0.051356126	2.943780185	-0.849432723	-58.14994197	13.14994197	0.97249297	0	0	0	0	0
1	8	180	80.04486027	-1	-52.5	0.219275739	12.66647964	-0.746632946	-48.29948198	3.299481984	0.974045604	142.5395682	21.38093523	105.6873452	15.93765166	0.036990571
1	9	554	71.25477411	-0.75	-37.5	0.356381563	20.87811196	-0.598249494	-36.7445785	-8.255421498	0.924658661	519.5402818	77.93104227	389.9914839	58.81071577	0.136497019
1	10	635	64.38370981	-0.5	-22.5	0.453330037	26.95749982	-0.394217025	-23.21711865	-21.78288135	0.827697788	521.7369546	78.26054319	497.7575627	75.06184046	0.174215147
1	11	603	60.11504757	-0.25	-7.5	0.503514265	30.23273355	-0.138717412	-7.97362417	-37.02637583	0.689770728	596.9258476	89.53887714	499.2316506	75.28413291	0.174731078
1	12	524	59.02766833	0	7.5	0.503514265	30.23273355	0.138717412	7.97362417	-52.97362417	0.520277007	486.3588689	72.95383034	439.325569	66.25029581	0.153763949
1	13	513	61.29374191	0.25	22.5	0.453330037	26.95749982	0.394217025	23.21711865	-68.21711865	0.330767374	511.2286173	76.68429259	418.711025	63.14162257	0.146548859
1	14	375	66.56665646	0.5	37.5	0.356381563	20.87811196	0.598249494	36.7445785	-81.7445785	0.134156633	239.5199008	35.92798512	284.8687742	42.95821115	0.099704071
1	15	104	74.19638579	0.75	52.5	0.219275739	12.66647964	0.746632946	48.29948198	-93.29948198	0.056156482	103.0745628	15.46118443	69.32429063	10.45410303	0.024263502
1	16	0	83.52091654	1	67.5	0.051356126	2.943780185	0.849432723	58.14994197	-103.149942	0.22720241	0	0	0	0	0
1	17	0	94.01396181	1.25	82.5	-0.135933799	-7.81260958	0.918879444	66.76271749	-111.7627175	0.367324623	0	0	0	0	0
1	18	0	105.2879425	1.5	97.5	-0.329830503	-19.25846133	0.964312581	74.64682373	-119.6468237	0.466973997	0	0	0	0	0
1	19	0	117.0650146	1.75	112.5	-0.51712021	-31.13923514	0.991117671	82.35760402	-127.357604	0.519359572	0	0	0	0	0
1	20	0	129.1209739	2	127.5	-0.6850394	-43.23864578	0.999936349	89.35341553	-134.3534155	0.50928729	0	0	0	0	0
1	21	0	141.2201983	2.25	142.5	-0.822144626	-55.2999821	0.981883882	79.0772398	-124.0772398	0.31897396	0	0	0	0	0
1	22	0	152.958036	2.5	157.5	-0.919092368	-66.79365822	0.891728918	63.09122491	-108.0912249	0.122363226	0	0	0	0	0
1	23	0	163.0840659	2.75	172.5	-0.969275779	-75.7603426	0.487225546	29.15834686	-74.15834686	0.067146179	0	0	0	0	0
2	0	0	166.7131613	-3	-172.5	-0.969025476	-75.70215562	-0.485518757	-29.04642523	-15.95357477	0.237448989	0	0	0	0	0
2	1	0	159.8912768	-2.75	-157.5	-0.918817766	-66.75376214	-0.890714267	-62.96305162	17.96305162	0.375443446	0	0	0	0	0
2	2	0	148.9243691	-2.5	-142.5	-0.821823081	-55.26763306	-0.981559125	-78.97947259	33.97947259	0.472452014	0	0	0	0	0
2	3	0	136.985698	-2.25	-127.5	-0.684651468	-43.20814326	-0.999920101	-89.27558791	44.27558791	0.521863701	0	0	0	0	0
2	4	0	124.866152	-2	-112.5	-0.51665097	-31.10782895	-0.991269444	-82.42327353	37.42327353	0.679962941	0	0	0	0	0
2	5	0	112.8786254	-1.75	-97.5	-0.329270577	-19.22448178	-0.964579814	-74.70475983	29.70475983	0.820153604	0	0	0	0	0
2	6	0	101.2442594	-1.5	-82.5	-0.135279986	-7.774799665	-0.91924134	-66.81532903	21.81532903	0.919851967	0	0	0	0	0
2	7	0	90.1950479	-1.25	-67.5	0.052100626	2.986494005	-0.849876841	-58.19819572	13.19819572	0.972263735	0	0	0	0	0
2	8	0	80.05542242	-1	-52.5	0.220101546	12.71497972	-0.747136877	-48.34290319	3.34290319	0.973817121	0	0	0	0	0
2	9	0	71.24417931	-0.75	-37.5	0.357273758	20.93283319	-0.598757563	-36.78091536	-8.219084643	0.924406264	0	0	0	0	0
2	10	2	64.34703184	-0.5	-22.5	0.454269175	27.01788402	-0.394619646	-23.24222222	-21.75777778	0.827398442	1.67136415	0.250704623	1.568535005	0.236535079	0.000548987

Figure A1. Screenshots of the SAM software showing input parameters and DC/AC calculations.